Is it possible to save the environment and satisify consumers with artificial meat?

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Review

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COVER

In August 2013, the world's first hamburger cultured from bovine skeletal muscle stem cells was presented in a televised press conference. Thirty billion cells forming 10 000 muscle fibers were used to create the hamburger. The cost of production was 300 000 USD. It was cooked and tasted by two food journalists who commented that it was definitely recognizable as meat in contradistinction to the many vegetable protein-based burgers they had experienced. They found the burger dry, which was anticipated because it did not contain fat yet. Evidently, cultured meat has still some way to go before it can be launched as a consumer product. In addition to improving quality and adding fat tissue, the price has to come down to a reasonable level. For that, scaling up production and making it an efficient process are absolute requirements. Possible methods for scaling are discussed in this issue. The photo was provided by Prof. Mark J Post from the Department of Physiology, Maastricht University.

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EDITORIAL

Is it possible to save the environment and satisify consumers with artificial meat?

Our modern society is facing major challenges such as reducing world hunger by increasing protein resources despite an increase in protein demands due to the presence of more and more human beings on the earth. Other challenges include reducing potential environmental degradation due to human activities and also due to livestock. In addition to that, some people are concerned by reducing potential discomfort of animals on modern farms or maybe avoiding killing animals to eat them. For all these reasons, alternatives to traditional livestock production have continuously emerged and any type of meat substitutes seems more and more interesting to contribute to solve the above mentioned major challenges of our society.

According to a recent report (http://www.marketsandmarkets.com/Market-Reports/meat-substitutes-market-979.html), meat substitutes include mainly soy-based products, but also wheat-based products and mycoproteins. The meat substitutes market was estimated at $3 185.8 million in 2013. Consumers are more and more aware of the potential health benefits of these substitutes, and therefore the demand for these products has increased based mainly on potential good health and wellness associated with consumption of meat substitutes. The meat substitutes market is also characterized by a high level of innovation. Some of the key players include Quorn Foods Ltd. (U.K.), Blue Chip Group (U.S.), VBites Foods (U.K.), Amy's Kitchen Inc. (U.S.), and Cauldron Foods (U.K.). The top five players mentioned above accounted for about 40% of the market in 2013 according to market value.

Another meat substitute is artificial meat made from stem cells. The technique to produce muscle cells from stem cells was described a long time ago, but has only recently been highly publicized when a cultured beef hamburger was tasted on August 5, 2013 in London. From that point, artificial meat from stem cells has been considered by the public media as a new type of meat with a great potential. Therefore, the *Journal of Integrative Agriculture* invited famous scientists throughout the world to give their opinions about *in vitro* meat produced from cell cultures.

As guest editor, I am pleased to see that ten of the manuscripts were accepted by the Editor-in-Chief of the *Journal of Integrative Agriculture* for publication in this special focus. The ten papers are organized into the following three sections.

Section 1: Technical aspects of artificial meat production

The first technical review by Moritz *et al*. (2015) describes the principles of producing artificial meat from stem cells. They indicate that, for large-scale production of cultured meat, *in vitro* techniques still need to be more efficient than current available techniques. These authors also describe needs of technical research to increase the efficiency of large-scale production of artificial meat. However, they are rather optimistic that the optimization of large-scale cell culture will result in efficient production of artificial meat at low cost.

A second short review by Orzechowski (2015) also describes principles of muscle cell culture and interactions between different cell types present in the muscle tissue. This author concluded that artificial meat should be produced at an affordable price to be commercialized. He thinks this is not achievable, except if a new type of alternative low-cost technology is discovered.

This opinion was confirmed by Kadim *et al*. (2015) who think that the *in vitro* meat technology is at an early stage. Although huge progress has been made during recent years, important issues remain to be solved, including technical, social and ethical problems. Consumer acceptance and confidence might be a major issue.

Section 2: The potential of artificial meat to solve societal problems associated with conventional meat production

China has major concerns concerning the growth in its population and environmental degradation. Therefore, according to Sun *et al*. (2015) meat substitutes are required. They concluded that the overall substitution of meat from livestock by artificial meat would be beneficial for China's

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environment and food security because less land is needed to produce meat from cell culture than from livestock.

Bhat *et al*. (2015) from India confirmed the potential benefits of artificial meat to reduce suffering of livestock, nutrition-related diseases, foodborne illnesses, resource use, and greenhouse gas emissions. However, a great deal of research is still needed to reduce the cost of artificial meat technology and to solve societal issues before large scale production and commercialization of artificial meat.

Mattick *et al*. (2015) agree that artificial meat has the potential to increase food security and human well-being, reduce animal suffering, and mitigate some of the environmental impacts associated with meat production. However, these advantages are associated with a great uncertainty and to unintended and unanticipated consequences. Many of the consequences of artificial meat production are unforeseeable and therefore more research is needed to study interactions between technological and societal issues.

Bonny *et al*. (2015) confirm that conventional meat production cannot continue to respond to an increase in animal protein demand. New solutions regarding animal welfare, health and sustainability must indeed be found. However, in their present stage, new technologies including artificial meat and meat from genetically modified organisms cannot be a substitute to conventional meat production. However, meat substitutes manufactured from plant proteins and mycoproteins have a greater potential to be developed in the near future.

Section 3: Societal perceptions of artificial meat production

One manuscript by Hopkins (2015) described media coverage of artificial meat. The author concluded that the "online coverage gives an inaccurate sense of what obstacles are really in the path of cultured meat acceptance". In fact, media coverage tends to "overemphasize the importance of the reception of cultured meat among vegetarians". More generally, the high media coverage creates a skewed impression that everyone may be aware of, especially the promoters of artificial meat.

A worldwide survey demonstrated that the majority of educated respondents (such as scientists) believed that artificial meat will not be accepted by consumers in the future, except for a few of them. The conclusion from Hocquette *et al*. (2015) was that people trust scientists to continuously discover new technologies potentially useful in a long term future, but that respondents are not convinced that artificial meat will be tasty, safe and healthy enough to be accepted by consumers.

In fact, consumer acceptance of cultured meat depends on a wide diversity of determinants which have been reviewed by Verbeke and co-authors. These determinants include how technology is perceived by consumers, media coverage and public involvement. Other important factors include trust in science, policy and the society by consumers and citizens. The actual high price but also sensory trait expectations may be major difficulties to solve for the potential success of artificial meat. These authors confirmed that vegetarians may not be the first target group for artificial meat.

Conclusion

One challenge for cultured meat is to mimic traditional meat in terms of sensory quality at an affordable price in order to become acceptable for future consumers. However, beyond these technological and economical aspects, artificial meat should convince citizens and consumers that it may bring both personal benefits (taste, safety, healthiness) and societal benefits (food security, no environmental degradation, better animal wellbeing, etc.) and this is uncertain.

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REVIEW

Alternatives for large-scale production of cultured beef: A review

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Abstract

Cultured beef is a method where stem cells from skeletal muscle of cows are cultured *in vitro* to gain edible muscle tissue. For large-scale production of cultured beef, the culture technique needs to become more efficient than today's 2-dimensional (2D) standard technique that was used to make the first cultured hamburger. Options for efficient large-scale production of stem cells are to culture cells on microcarriers, either in suspension or in a packed bed bioreactor, or to culture aggregated cells in suspension. We discuss the pros and cons of these systems as well as the possibilities to use the systems for tissue culture. Either of the production systems needs to be optimized to achieve an efficient production of cultured beef. It is anticipated that the optimization of large-scale cell culture as performed for other stem cells can be translated into successful protocols for bovine satellite cells resulting in resource and cost efficient cultured beef.

Keywords: cultured beef, microcarriers, aggregated cells, packed bed bioreactor, cell culture

1. Introduction

In August 2013 we provided proof of principle that consumption meat can be cultured using fairly standard tissue engineering technology. Cells are typically grown in flasks with a flat bottom and nourished with fluid containing essential nutrients, the so-called medium. Tissue engineering technology for cultured beef in particular relies on the self-organizing capacity of skeletal muscle stem cells (i.e., satellite cells) when provided with a conducive hydrogel and polar anchor points. The small-scale production of less than 5×10^{10} cells has been separated in a proliferation phase and a differentiation phase and each of these phases has specific requirements to be fulfilled for commercial application. The separation into these two phases is dictated by different medium requirements and by different anchoring of cells and muscle fibers and resultant mechanical conditioning. During the proliferation phase, the cells grow in sheets (2-dimensional, 2D) anchored to a surface, for instance the layers of commercially available cell-factories. Satellite cells proliferate well in a medium containing exceptionally high serum concentrations of 30%. The differentiation phase starts with reducing serum to 2% and placing the differentiating cells, a.k.a myotubes, in a hydrogel that allows self-organization into muscle fibers (myooids, bioartificial muscle) between two fixed, rigid anchor points to which the cells can attach. Protein synthesis, an important goal of meat engineering, is stimulated by tension between the anchor points of the bio-artificial muscle (Vandenburgh *et al.* 1999).

The three major conditions for cultured beef to become successful in replacing current livestock produced beef are, 1) better efficiency, 2) sustainability and 3) mimicry. In

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order to reduce resources required for beef production, the culture system needs to be more efficient than livestock produced beef in converting vegetable proteins from feed into edible animal proteins. This so-called bioconversion rate is estimated to be a meager 15% for cattle (Egbert and Borders 2006), which is the lowest for domesticated animals providing staple meats. Sustainability is also an absolute requirement. In the particular case of cultured beef, this means that the production cannot involve animal products such as fetal bovine serum or bovine collagen hydrogel, because we will not be able to source them if cultured beef becomes successful and global livestock volume is greatly reduced. Mimicry, meaning that the eventual product needs to be sufficiently similar in taste, texture and appearance to livestock beef that it can serve as a widely acceptable alternative, is also a condition for success.

Cell and tissue culture in their current states are not efficient processes in terms of energy, water and feedstock expenditure as they have been primarily employed for scientific and medical applications, and were considered less dependent on cost and resources effectiveness than any food application. Also, the scale of cell and tissue manufacturing for food would trump scientific and medical tissue production by several orders of magnitude offering a new perspective on current production, resource management and pricing (Post and van der Weele 2014).

In this review, we focus on scale and efficiency of cell and tissue production for cultured beef applications. Considerations on the other requirements, sustainability and mimicry, are beyond the scope of this review. First, we will discuss systems to scale up cell and tissue production and second we will focus on the resource efficiency of cell culture in general and that of the large-scale systems for anchor dependent cells in particular.

2. Large scale cell production systems

The goal of a large-scale cell production system is to generate a large amount of cells with the smallest possible amount of resources (i.e., culture medium) and minimal handling and preferably in a short time. For the very large-scale cultivation of stem cells for food, suspension cultures in bioreactors are required. To achieve high density cultures in suspensions there are two alternatives: 1) cultivation on microcarriers or 2) cultivation in aggregated form as cell aggregates (Reuveny 1990; Steiner *et al.* 2010; Abbasalizadeh *et al.* 2012). Microcarriers are beads to which cells can adhere and grow in apposition. Cell aggregates are clumps of cells that grow in 3D and serve as anchors for their neighbors, while the aggregates themselves remain in suspension. Microcarriers or beads can also be static in a bioreactor with fluidized media in a system called a packed bed bioreactor (PBR). A basic overview of the three large-scale production systems can be seen in Fig. 1.

2.1. Microcarriers in suspension

Microcarriers are beads to which cells can attach and grow by apposition, much the same way as if they are grown on flat surfaces. They are typically 100–200 μm in diameter

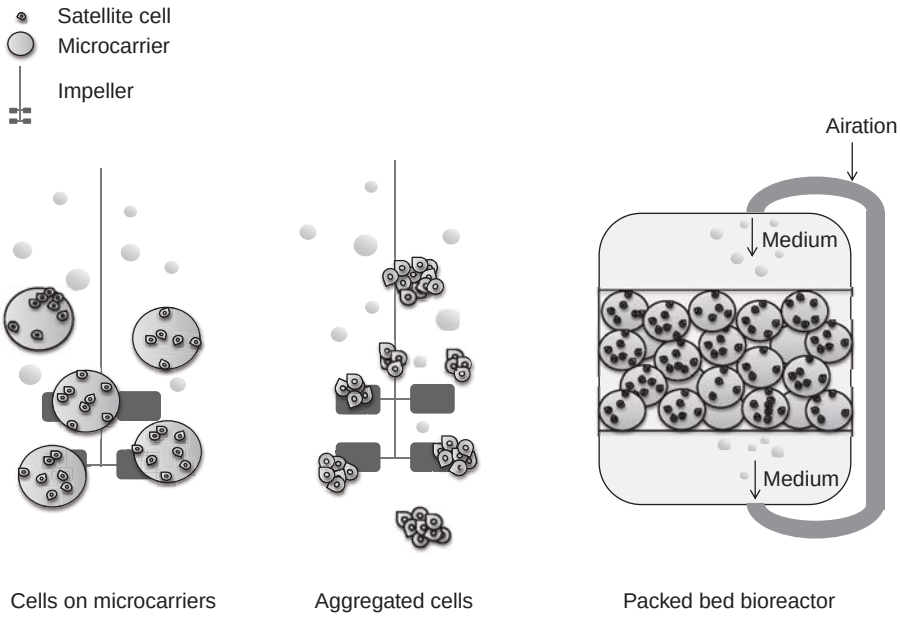

Fig. 1 Overview of the three possible large-scale systems for cultured beef.

and made of polystyrene so that they float in the medium. To ensure mixture of nutrients and gases, the medium is agitated by an impeller, gas flow or rotation of the bioreactor.

There are several factors that need to be considered for retaining the proliferation phase of satellite cells in cell suspension. One important aspect is inter-dependency of cells through their proximity. Cells in culture depend on growth factors that come from the medium but also from the cells themselves. The growth factors and cytokines produced during metabolic activity trigger neighboring cells resulting in increased growth (Greene and Allen 1991; Tatsumi *et al.* 1998; Troy *et al.* 2012). For microcarrier cell culture this means that a low initial seeding concentration (cells per bead) can cause a lower growth rate compared to high seeding concentration but there is also a maximum density of cells when they reach confluency on the beads. The cells also seem to form aggregates, which on microcarriers can build big clusters (Molnar *et al.* 1997). To overcome clusters, new beads can be added which make the cells transfer and colonize the new beads as well, a phenomenon known as bead-to-bead transfer (Wang and Ouyang 1999a; Dürrschmid *et al.* 2003). To add new beads for bead-to-bead transfer of cells also offers a convenient scalable production of cells on microcarriers. Mesenchymal and pluripotent stem cells cultured on microcarriers, earlier reviewed by Sart *et al.* (2013), can be produced this way in large-scale.

Satellite cells grow, proliferate and differentiate on microcarriers (Molnar *et al.* 1997). By just changing the medium in the bioreactor differentiation was initialized, however with less myotube formation, a hallmark of the initial stage of differentiation into muscle cells. Molnar *et al.* (1997) concluded therefore that satellite cells show slower expansion in bioreactor cultures compared to layered cell factories. Optimization is therefore still necessary.

A mouse cell line of muscle cells have also been tested to grow, proliferate and differentiate on microcarriers (Torgan *et al.* 2000). In this study, cells were cultured either in a microgravity bioreactor or in a teflon bag. In both systems, myotubes developed showing that the differentiation phase can occur on microcarriers in much the same way it occurs on flat surfaces. Results differed in the two culture conditions with less myotube formation in the microgravity bioreactor, probably as a result of different hydrodynamics that influenced the cells. In this study, it was also observed aggregate formation of the cells on microcarriers. Prevention of aggregation might be necessary for myotube formation. As aggregation is never observed in flat surface cell factories, it is reasonable to assume that increasing the diameter of the microcarriers will prevent aggregate formation.

The observation that differentiation on beads occurs however suggests that proliferation and differentiation phase do not have to be separated, which would save additional handling of the cell culture. One of the important parameters in microcarrier-based cell culture is shear stress imparted on the cells by medium agitation.

The formation of muscle skeletal tissue on microcarriers may be possible since the coating of the microcarrier reassembles the hydrogel that is needed for self-organization. If the microcarriers are spherical or cylindrical, bioartificial muscle (BAMs) might also be formed around the microcarriers through self-anchoring, in much the same way as we cultured BAMs for the hamburger. It has previously been reported that myoblasts cultured on microcarriers cannot only differentiate into myotubes, but they also mature to muscles in a static condition (Bardouille *et al.* 2001). It remains to be determined if these muscle fibers are sufficiently oriented and anchored to develop in full-fledged muscle fibers like in separate dedicated differentiation bioreactors. In addition, muscle fibers need to be harvested from the microcarriers, which imposes another level of complexity on the design of the beads. Harvest from microcarriers could be done by changing temperature (Tamura *et al.* 2012), or through electronically induced shape change of the microcarriers (Persson *et al.* 2011). Alternatively, the beads themselves are edible and become an integrated and perhaps partly degraded part of the skeletal muscle tissue, obviating the need for harvesting the muscle by sequestering them from the microcarriers.

Thus, it is anticipated that for optimal cell production, microcarriers have to be tailored for bovine satellite cells by coating, surface modification, size and perhaps composition (Sart *et al.* 2013).

2.2. Cell aggregates

Successful suspension cultures with aggregated stem cells have been developed (Cormier *et al.* 2006). Many studies of stem cells in suspension are on human embryonic stem cells (hESC) or human induced pluripotent stem cells (hiPSC) reprogrammed to allow suspension culture by treatment with cytokines that delay differentiation or with a Rho-associated protein kinase-inhibitor (ROCKi) to delay apoptosis (Amit *et al.* 2010; Larijani *et al.* 2011; Fluri *et al.* 2012).

For aggregated cells in suspension, cell density is of utmost importance, as well as medium composition and parameters of mixing through agitation (Abbasalizadeh *et al.* 2012; Chen *et al.* 2012). Metabolic activities of the cells in aggregates depend on the initial cell density with high initial cell densities being preferable to assure colonization of all cells (Abbasalizadeh *et al.* 2012). Growth media formulation is also an important aspect, which can change properties of cell cultures. The ROCKi is commonly used to inhibit apoptosis and increase proliferation in cell aggregates suspended in medium (Watanabe *et al.* 2007).

ROCKi treatment is not ideal for cells in food applications since protein expression is diminished even after withdrawal of the treatment (Krawetz *et al.* 2011).

Size of the aggregates is an important determinant of successful culture. Ideally, aggregates are not too large with a fairly homogeneous size distribution. By changing the agitation of the medium, size can be contained and shear stress on the cells decreased (Zweigerdt *et al.* 2011; Abbasalizadeh *et al.* 2012). Another method to prevent the occurrence of large aggregates is to split the cell aggregates at regular intervals by passaging methods, although inevitable cell loss with each passage might off-set the benefits from reducing aggregate size (Singh *et al.* 2010; Amit *et al.* 2011; Chen *et al.* 2012). Passaging refers to the dissociating cells from the surface and redistributing them at lower densities in fresh medium to boost the next phase of growth. Higher cell densities have been described for aggregate systems than for microcarrier systems (Table 1).

A combination of aggregated cells on microcarriers have also been tested and seem better than single cells on microcarriers (Phillips *et al.* 2008), although reported cell expansion was still lower than with aggregates or non-aggregate microcarriers alone (Amit *et al.* 2011; Park *et al.* 2014). It appears however, that aggregates on microcarriers could be an option for expansion to large-scale because the aggregated state protected the cells from stress and decreased the lag phase during bead-to-bead transfer (Boudreault *et al.* 2001).

A synthetic, biodegradable scaffold that serves as support for the cells is required for differentiation and myofiber formation. After having proliferated, the cells have to be transferred to a second bioreactor system for differentiation and tissue generation. One option might be to use added microcarriers for further tissue development after aggregate culture. Since aggregated cells can attach to microcarriers, the cells could still stay in the same bioreactor by just changing the medium and adding microcarriers. Another option could be to add a scaffolds wherein the cells can organize and mature (Neumann *et al.* 2003). Both procedures would result in less operational handling of the cells and therefore less risk of contamination.

2.3. Packed bed bioreactors

Packed bed bioreactor (PBR) is a bioreactor with a bed of microcarriers on which the cells are immobilized. This type of reactor has a flow of growth medium down-stream, up-stream, or radially across cells in a static position within the packed bed while the nutrients and gases are evenly distributed.

PBRs have proved to increase viability of the cells because of the static immobilization and the flow of nutrients and oxygen that can reach the cells (Park and Stephanopoulos 1993; Cong *et al.* 2001). A packed bed with a flow of medium has the advantage that the medium is oxygenated before entering the bioreactor which improves oxygen distribution to the cells (Chiou *et al.* 1991). The system of a continuous radial flow of growth medium seems to be the most promising type of PBR (Bohmann *et al.* 1992). PBR for use in mammalian cell culture has earlier been reviewed and proven to achieve high cell densities (Table 1) but is not common for large volumes: 30 L is the largest reported PBR (Meuwly *et al.* 2007).

Since the packed bed in a PBR can serve as a scaffold, further tissue development might be combined in one system. Both proliferation and differentiation on a scaffold in a PBR has shown to work efficiently (de Peppo *et al.* 2013).

High cell density during the proliferation phase is an important parameter that determines efficiency of the production system. Optimal conditions for each type of system need to be defined for bovine satellite cells as these are not well studied for large-scale cell production. A comparison between the three possible scale-up strategies can be seen that it is possible to recycle culture medium through replenishment of utilized nutrients, such as glucose and glutamine, and removal of waste-products, such as lactate and ammonia. It might be beneficial to reuse part of the medium as growth factors and cytokines produced by the

Table 1 Cell densities previously reported for 3-dimensional (3D) suspension cultures

System	Cell type[1)]	Cell density per mL medium	Reference
Microcarriers in suspension	Human myoblasts	1.5×10^6	Boudreault *et al*. 2001
	hESC	3.5×10^6	Oh *et al*. 2009
	hfMSCs	8.3×10^5	Goh *et al*. 2013
	Ear-MSC	1.7×10^6	Sart *et al*. 2009
Packed bed bioreactor	CHO (Chinese hamster ovary cells)	2×10^7	Cong *et al*. 2001
	γ-CHO	6.8×10^7	Chiou *et al*. 1991
Aggregated cells	hiPSC (ROCKi-treated)	1.23×10^7	Abbasalizadeh *et al*. 2012
	hESC (ROCKi-treated)	1.27×10^7	Abbasalizadeh *et al*. 2012

[1)] hESC, human embryonic stem cells; MSC, mesenchymal stem cells; hiPSC, human induced pluripotent stem cells; ROCKi, Rho-associated protein kinase-inhibitor.

cells can stimulate subsequent cell growth. It has been reported that recycling of growth medium when culturing algae was not efficient since centrifugation was needed to separate the biomass. Other problems were the inhibitory factors in the medium that were still present during further cell culture (Rodolfi *et al.* 2003). For stem cell culture, these reported problems can be solved. Recycling of media can be done in a similar way as for PBRs meaning that the cells stay in the reactor and the medium is recycled "on-line". A purification step can be added to get rid of unwanted waste-products, for example by chromatography. If nutrients needed for growth of satellite cells can be established, an optimization of nutrients supplements can be calculated or monitored during recycling. The reuse of other materials, for example microcarriers, will be important. For instance, it has been reported that washed cytodex-3 microcarriers are reusable for mammalian cell culture without affecting cell growth (Wang and Ouyang 1999). If necessary, microcarrier beads can be recoated before usage.

Cell culture is a technology where many variables determine its efficiency, and most of these variables can be optimized. This is a time consuming effort, but there it is fair to assume that a resource efficient method can be developed (Table 2).

3. Efficiency

Efficient production is of utmost importance for large-scale production of cultured beef as it drives the potential food-security and environmental benefits over livestock beef. Resource efficiency is also important to keep the cost of production low as materials are by far the largest cost component. Production cost will translate in consumer price and this is the most important criterion in consumer preference. To reach a high efficiency, culture conditions need to be optimized for culture medium utilization. Metabolic monitoring during cell growth is an integral part of most large-scale cell culture systems, but monitoring may need to be refined to optimize metabolism so that most nutrients are being converted to animal edible proteins. Even with optimized medium utilization it is still likely that not all components of the medium are equally consumed, suggesting that additional resource efficiency can be gained by recycling the medium and microcarriers (Wang and Ouyang 1999). Recycling of medium or carriers is not routinely practiced because there is no economical or environmental need for it with small or intermediate scale cell production for medical applications. For food application however, recycling may be essential to cost- and resource-efficient cell production.

3.1. Optimization of culture conditions

Culturing cells in large-scale can be done by step-wise increasing the size of the cell culture, meaning that after cells are isolated from a cow, they are transferred to 2D surface plates and then to bioreactors, going from small to large volume tanks. These transferring steps, i.e., passages, need to be optimized. For cultivation of cells on microcarriers or in aggregates, high density of cells can be achieved by step-wise increasing the number of beads and cells per bead or by splitting the aggregates during culture. This technique involves minimal handling. Another condition that is required for high cell density is efficient distribution of oxygen and nutrients and here, culture medium agitation is a factor of importance (Zhao *et al.* 2005).

Cells need to be temporarily dissociated from their environment to assume a new growth promoting state. Different methods for dissociation of cells have been developed, such as enzymatic treatment, chemical treatment, and mechanical disruption (Collins *et al.* 2005; Suemori *et al.* 2006; Amit *et al.* 2010). Each of these methods may affect viability and genetic stability of the cells (Mitalipova *et al.* 2005), so a balance needs to be found between efficient cell dispersion and potential side effects. For cells in aggregated form the homogeneity of the aggregates can also be affected by the splitting treatment (Amit *et al.* 2010). Even though mild dissociation treatments exists, optimization of

Table 2 Challenges and prospects of the three scale-up systems, microcarrier suspension culture, aggregated cells in suspension, and packed bed bioreactor (PBR)

System	Prospects	Challenges
Microcarriers	Many different possibilities of characteristics on microcarriers	Can aggregate and build clusters
	Reuse of microcarriers possible	Shear forces from microcarriers or clusters
	Easy to scale-up by adding new microcarriers	
Aggregates	Cheap because of no extra material needed	Could be difficult to achieve on satellite cells without any cell modifications
	Simple harvest	Hard to control aggregate size
PBR	Protective for the cells from shear forces	Difficult to scale up
	Good oxygenation	
	Easy recycling of growth media possible	

passaging is important and has previously been done for human embryonic stem cells and human pluripotent stem cells (Amit *et al.* 2011; Chen *et al.* 2012). They need to be repeated for satellite cells.

Bead-to-bead transfer is affected by stirring conditions and for efficient scale-up of cells on microcarriers, this has to be optimized. Intermittent agitation compared to continuous agitation has shown positive effect on bead-to-bead transfer (Wang and Ouyang 1999). Different intermittent agitation conditions have also been studied and showed that resting time and stirring time were both important in addition to the interaction between stirring time and resting time, and stirrer speed and resting time (Luo *et al.* 2008). Experience with myoblasts showed more efficient culture with continuous agitation, however with a lag-phase during which no increase in cell density occurred. In this study, different initial cell densities were also tested and the conclusion was that by changing initial cell density efficient cell culture with continuous agitation is better than static 2D-layered culture (Boudreault *et al.* 2001). Another study showed different cell-attachment on different types of microcarriers. For the microcarrier Cytodex-1, continuous agitation was preferable for cell attachment while for the microcarrier Cultispher-G, intermittent agitation was superior (Ng *et al.* 1996).

A good distribution of oxygen and CO_2 is required to support high cell densities. Homogenous mixing and agitation without harming the cells are difficult tasks to achieve for large-scale mammalian cell culture, even though different kind of impellers, and control systems are available (Marks 2003). Conventionally, stirred tank bioreactors are used in which the fluid is mixed by large impellers but recently other mixing technologies have been designed including orbital shaken disposal bioreactors, rotating wall vessels and wave reactors (Pierce and Shabram 2004; Chen *et al.* 2006; Zhang *et al.* 2010). Only rotating wall vessel has been tested for satellite cells so far (Molnar *et al.* 1997).

A scale-up strategy by step-wise optimization of parameters such as oxygen influx, agitation, and initial cell density is necessary for transforming adherent cultures to suspensions (Abbasalizadeh *et al.* 2012). Since earlier mentioned studies have been on other type of cells, new optimized systems have to be established for satellite cells used for cultured beef.

3.2. Metabolic control

To increase efficiency, controlling metabolites utilized and produced during cell culture is also required. Eukaryotic cells produce energy (ATP) by aerobic or anaerobic respiration. Through glycolysis, glucose is modified to ATP. The up-take of glucose is transported by proteins in the plasma membrane to mitochondria where the conversion takes place. Different fatty acids and amino acids are also converted in the cell.

In vivo, many stem cells are situated in areas where the oxygen pressure is lower than the “normoxic” state (20–21% pO_2) for culture practice, which might be an indication that lower oxygen pressure could be preferable in cell culture. In low oxygen concentrations, so-called hypoxia state (2–6% pO_2), muscle cells have shown to increase glucose consumption. Myotubes in cell culture showed a large increase in glucose utilization and increased lactic acid production already after 24 h of culture compared to normoxia (Bashan *et al.* 1992). Other studies have shown an increase in both myoblasts and myotubes in hypoxic conditions (Chakravarthy *et al.* 2001). For human mesenchymal stem cells (hMSC) cultured on a 3D scaffold hypoxia proved to increased proliferation and enhanced tissue formation (Grayson *et al.* 2006). Hypoxic culture of hMSC have also resulted in increased cell density during hypoxic culture, suggesting better efficiency (Grayson *et al.* 2007). Thus, oxygen regulation during stem cell cultivation is an important aspect that needs to be considered and optimized as previously reviewed (Csete 2005).

Lactic acid is a byproduct produced by the cells when consuming glucose. When there is no glucose or very little available, a metabolic switch occurs and lactate can serve as a carbon source and produce energy for the cell, but high concentrations lactate can also inhibit growth of cells. By on-line monitoring of glucose and lactate content, the feeding with new medium can be regulated to maximize glucose consumption and minimize lactate production (Ozturk *et al.* 1997).

Glutamine is an important amino acid for the cells and ammonia is a byproduct produced when consuming glutamine. Ammonia can inhibit cells already in small concentrations therefore regulation of glutamine is preferred to decrease ammonia concentration. It also seem that glutamine concentration can regulate lactate consumption, when glutamate was decreased lactate degradation started (Zagari *et al.* 2013). Both glucose, glutamine, lactate and ammonia production/consumption can be regulated by optimizing refreshment of culture medium (Schop *et al.* 2008), therefore a feeding profile for the cell system is required to optimize metabolite utilization/inhibition.

3.3. Recycling

It is possible to recycle culture medium through replenishment of utilized nutrients, such as glucose and glutamine, and removal of waste-products, such as lactate and ammonia. It might be beneficial to reuse part of the medium as growth factors and cytokines produced by the cells can stimulate subsequent cell growth. It has been reported that

recycling of growth medium when culturing algae was not efficient since centrifugation was needed to separate the biomass. Other problems were the inhibitory factors in the medium that were still present during further cell culture (Rodolfi *et al.* 2003). For stem cell culture, these reported problems can be solved. Recycling of media can be done in a similar way as for PBRs meaning that the cells stay in the reactor and the medium is recycled "on-line". A purification step can be added to get rid of unwanted waste-products, for example by chromatography. If nutrients needed for growth of satellite cells can be established, an optimization of nutrients supplements can be calculated or monitored during recycling. The reuse of other materials, for example microcarriers, will be important. For instance, it has been reported that washed cytodex-3 microcarriers are reusable for mammalian cell culture without affecting cell growth (Wang and Ouyang 1999). If necessary, microcarrier beads can be recoated before usage.

Cell culture is a technology where many variables determine its efficiency, and most of these variables can be optimized. This is a time-consuming effort, but there it is fair to assume that a resource efficient method can be developed

4. Conclusion

Tissue engineering in large-scale is a difficult task and the scale of cell and tissue culture needed for food applications is orders of magnitude higher than for medical applications. Commercially available systems, microcarrier or cell-aggregate based are a good start but need to be optimized for bovine satellite cells, including but not limited to, specialized microcarriers. The highest cell densities and therefore the highest efficiencies have been reported for packed bed bioreactors but they are still in an experimental stage. Limitations in up-scaling systems discussed are costs (microcarriers), apoptotic cells (aggregates) and lack of commercial availability (PBR). It is anticipated however, that the optimization of large-scale cell culture as performed for other stem cells can be translated into successful protocols for bovine satellite cells resulting in resource and cost efficient cultured beef.

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REVIEW

Artificial meat? Feasible approach based on the experience from cell culture studies

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Abstract

This short review is to list pros and cons which are based on the literature and personal experience in cell culture studies related to possible commercial production of artificial meat as functional food. The general view of muscle composition and determinants of meat quality are shortly described. Principles of muscle cell propagation in culture and mutual relationships between different cell types present in this organ are briefly discussed. Additionally, the effects of some cytokines and growth factors for muscle cell growth and muscle tissue development are indicated. Finally, conclusion remarks related to detrimental consequences of meat production to natural environment as well as personal opinion of author on the prospects of artificial meat production are declared.

Keywords: artificial meat, cell and tissue cultures, muscle growth, muscle composition

1. Introduction

Meat is expensive source of animal protein. Almost two-thirds of agricultural land is used for cultivating livestock, whereas remaining one-third hardly meets human requirements for plant-based foods (Welin and van der Wende 2012). Moreover, economical pressure to increase meat production leads to progressive devastation and unprecedented contamination of natural environment. It is linked to extensive deforestration and greenhouse gases (GHG) emissions (carbon dioxide and methane—the latter 25-fold more harmful to ozone layer than the former one). Today, livestock produces more GHG than all known transportation systems taken together, and could be clearly pointed as causal factor of the so-called global warming effect (GWE). Last year (2013), almost 56 billion animals were slaughtered for meat production (this number does not take into account hunting and fishery). Additionally, meat is also rich in animal fat, thus offering alternative energy supply to carbohydrates (Hocquette *et al.* 1999). High energy content of meat and meat-based diet is also blamed for the epidemy of overweight and obesity in human population. This is especially evident in nations where traditional plant-based cuisine is replaced by fast-foods popular in western societies. Excessive meat consumption in modern societies is also widely believed as hazardous to human health (atherosclerosis, cancer, Fergusson 2010; Corpet 2011; Buscemi *et al.* 2013; Kim *et al.* 2013). Some efforts were undertaken to modify the composition of meat to make it healthy as functional

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food of high nutritional value. Major activities were directed to feed farm animals crude feeds of high quality pasture (Jurie *et al.* 2006) or natural supplies of polyunsaturated fatty acids (Krasicka *et al.* 2000). Regardless of species, these methods are expensive and offer meat of sometimes questioned taste and flavor. Some methods, as calf feeding with only one food item are banned as offensive (Webster 2011). The latter issue points to the growing importance of animal welfare and increased sensitivity of human population to animal abuse (Pluhar 2010). Animals used in animal production by certain cultures are often considered as pets or sacred animals (horses in western societies or cattle in India). It should be stressed, however, that irrespective to apparent species' differences, the physiology of higher animals is almost identical regardless of human attitude driven by cultural or religious reasons. Animal activists often emphasize that breeding animals for meat is unethical as these animals do not differ much from pets. On the other hand, in certain cultures popular pets (dogs and cats) are exploited as source of meat. Thus, citing George Orwell from the *Animal Farm* "All animals are equal, but some animals are more equal than others". Another ethical issue of paramount importance is the act of slaughter, controversial and associated with violence when animals are killed or sacrificed. As the Nobel Price winner in the literature of 1978, Isaac Bashevis Singer wrote in *The Letter Writer* "In relation to [animals], all people are Nazis; for the animals, it is an eternal Treblinka". These are apparently strong words, but they aren't so if one could imagine the horror of holocaust and animal slaughter. At least for social and educational reasons the truth about the animal slaughter needs to be uncovered (Driessen and Korthals 2012).

Nowadays, an attractive alternative to traditional livestock production has just emerged (Post 2013). Decades of cell culture of muscle cells, adipocytes, and fibroblasts for research purposes brought the prospects to exploit the collected knowledge for artificial meat manufacturing.

There is growing interest in commercial use of human/animal cell culture techniques. Most widely known examples of muscle cells applications are frequently heralded as achievements in regenerative medicine and tissue engineering (Leobon *et al.* 2003; Beier *et al.* 2006; Niagara *et al.* 2007; Burdzińska *et al*. 2009). Efforts also speak to biotechnology driven production of muscle animal cells in substantial quantity for other than medical applications (Post 2012). Recently, cultured meat from stem cells has been demonstrated together with public presentation and organoleptic test (www.theguardian.com/science/video/2013/aug/05/synthetic-beef-hamburger-tastes-meat-video; Post 2013). The idea to produce cultured meat is not new (even Winston Churchill mentioned such future possibility) though knowledge about the processing and technical details of meat generated in lab remains enigmatic to general public. Fears are emerging when consumers have no idea how the artificial meat is produced (van der Welle and Driessen 2013). At the initial stage of artificial meat production there is need to educate people and make them more familiar with the procedures. Once they accept the concept of cultured meat no more objections will be met (Post 2012). Today, we can give free rein to applications such as 3D cultures (muscle cells grown on natural scaffolds made from extracellular matrix proteins), or even the use of 3D printing devices (on the basis of different cell-type suspensions injected on preformed scaffolds) in order to produce muscle rather than mixture of muscle fibers. In fact, this idea is not barely a fiction as 3D printing becomes affordable in commercial use. Another attractive concept is the home processed meat, similarly to home made bread, or other foods. At the moment, the afore-mentioned simulations might be futuristic but it is really hard to predict the outcomes of human imagination.

2. Principles of muscle growth

Meat is mainly represented by skeletal muscles located at different body regions (carcass). In turn, skeletal muscle is phylogenetically old and complex organ essential for locomotion and evolved in vertebrates ample of millions years ago. Differences in muscle composition are more quantitative than qualitative with major dissimilarities being when this tissue is evaluated as processed food. Anyway, it is generally accepted that the complexity of skeletal muscle composition determines its quality as food. Adipocytes as a main fat deposits would make the meat a rich source of flavor and taste during processing. Stroma represented by connective tissue determines the texture of meat, probably one of the most important parameters for consumers. Finally, depending on the muscle type, meat value results from biochemical processes undergoing prior and after slaughter. One, however, who see skeletal muscle as a raw meat should be aware that muscle development (myogenesis) is of paramount importance to meat quality and meat derived foods (Collins and Partridge 2005). Myogenesis starts at embryonic life, continues in fetal life and is almost completed at birth (Sabourin and Rudnicki 2000). Further episodes of myogenesis are observed during muscle regeneration after injury or as adaptation to workload (Adams *et al.* 1999). Muscle growth and development is under control of nervous, hormone and growth factor/cytokine activities. There is a continuous "crosstalk" between different cell types (muscle cells, adipocytes, fibroblasts, endothelial cells, and leukocytes) making muscle an organ of high cellular interrelatedness (Bonnet *et al.* 2010; Raschke and Eckel 2013). Some of these influences are trophic (to stimulate muscle growth) whereas other are atrophic (to retard muscle growth)

being either of endocrine, paracrine or autocrine origin. Nowadays, several examples were brought to light after detailed scrutiny of myogenesis (Lancaster and Febbraio 2009). Despite endothelial and immune cells, derivation of some potent cytokine modulators controlling muscle growth are muscle fibers (myokines), adipocytes (adipokines) or both (adipo-myokines; Raschke and Eckel 2013). Recent study on myostatin, member of TGF-β superfamily, and most powerful known atrophic agent indicate it is adipokine rather than myokine (Lehr *et al.* 2012). Increased secretion of adipokines (leptin, TNF-α, chemerin, monocyte chemoatractant protein 1 (MCP-1), dipeptidyl peptidase 4 (DPP4)) were reported in obese patients (Trayhurn and Beattie 2001). Apparently leptin and TNF-α are mitogenic to myoblasts (undifferentiated muscle cells – descendants of muscle satellite cells), but given alone they are not capable to rise muscle fibers (Pijet B *et al.* 2013, Pijet M *et al.* 2013). Similarly, secretion of hepatocyte growth factor/scatter factor (HGF/SF), the most powerful mitogen for muscle satellite cells (muscle progenitors) points to polymorphonuclear cells as source of signals (PMN-s; McCourt *et al.* 2001). These cytokines may play an important role in muscle regeneration in response to muscle damage.

3. Outcome of cell culture studies—pros and cons

Muscle cells can be easily grown on plastics as routine "*in vitro*" model of muscle cell culture. For decades, this method was used, and is widely accepted model to examine the molecular mechanisms of muscle development and muscle decay. Nowadays, this approach became attractive alternative to animal production as a source of meat. Muscle cells can be cultured and fully controlled during growth and differentiation (pros). Moreover, muscle cell monolayer differs considerably from muscle tissue as the latter is highly complex organ (cons). In skeletal muscle there is representation of adipose and connective tissue as well as vascular bed. One might ask if, and if yes, which of these components determine muscle properties attractive for the meat consumers? Obviously, each constituent contributes differently to the taste, olfactory and nutritional value of meat. Moreover, significance of organoleptic and processed assets of meat varies according to the habit and preferences of the consumers. There is high competition and challenge to meet the consumer viewpoint.

Great advantage of cell culture method is the homogeneity of cells and almost full control of myogenesis (pros). Additionally, satellite cells (muscle progenitors; Mauro 1961) are capable to perform at least 20 doublings when kept in optimal conditions (10^6 cells). Thus, from a relatively small population of isolated cells (obtained through muscle biopsy), one might obtain considerable quantity of muscle fibers (pros). Future endavours are pointing to somatic cell nuclear transfer into oocytes (cloning), embryonic stem cells (ESC) or through the ectopic expression of defined factors in inducible pluripotent stem cells (iPSC) as endlessly dividing cells that can be successfully differentiated into muscle cells, myotubes and muscle fibers (Wilmut *et al.* 1997; Takahashi and Yamanaka 2006; Mizuno *et al.* 2010; Stadtfeld and Hochedlinger 2010; Yamanaka and Blau 2010). Recently, a brand-new and promising methods of pluripotent stem cell induction from mouse somatic cells was reported (Hou *et al.* 2013; Obokata *et al.* 2014). The chemically induced pluripotent stem cells (CiPSC) are epigenetically reprogrammed by cocktail of certain previously screened substances, thus exogenous "master genes" such as *Oct4*, *Sox2*, *Klf4*, and *c-Myc* are dispensable (Hou *et al.* 2013). Simple and promising stress-induced epigenetic reprogramming to pluripotency was demonstrated in different somatic cells by Obokata *et al.* (2014). The latter method allows to generate stimulus-triggered acquisition of pluripotency (STAP) stem cells from plated mouse adult somatic cells which can be further differentiated into any germ layer or tissue type including skeletal muscles. Efficient "breeding" of artificial meat is to be accomplished by additional requirements met by the recombinant growth factors and cytokines. Some mitogens (PDGF, EGF, IGF-1, insulin) and differentiation factors (TGF-β) are used in miniature concentrations for muscle tissue engineering (mitogenesis *vs*. myogenesis). For decades it was known that skeletal muscle tissue is also an endocrine organ with number of bioactive substances secreted or ceased in secretion depending on the type of stimuli as withdrawal of mitogens leads to extensive secretion of differentiation (IGF-II; Sarbassov *et al.* 1997; Sarbassov and Petersen 1998) and survival factors (myonectin, follistatin like 1; Chan *et al.* 2007; Henningsen *et al.* 2010). In order to create functional food, growth media might be subjected to certain modifications. By keeping basic homeostatic parameters (isoionia, isoosmia, isohydria) within acceptable limits, some changes in composition will be possible by enrichment with PUFA (n-3) or other important determinants of nutritional value (minerals, vitamins, pros). Texture, taste and flavor of the artificial meat are also possible for adjustments (pros). As we have scant experience in muscle tissue engineering other than that of medical applications new field of research is open for extensive studies (Table 1).

4. Challenges of artificial meat production

Prospects to generate artificial meat are apparently optimistic, however, there are numerous challenges and pitfalls. The most important are epidemology and economy issues. There is urgent need to develop commercial technology for

Table 1 Pros and cons of artificial meat production are listed below

Selected issue	Pros	Cons
Control of growth and differentiation	+	
Homogeneity of cell culture	+	
Multiplication of cells	+	
Functional food	+	
Organoleptic features	+	
Semi-open systems of growth	+	
Lack of microbial contamination	+	
Complexity of muscle		+
Economy of cell culture		+

culturing meat reasonably prized and free of any hazard of animal-born disease (pros). Although, it seems to be speculative at the moment, one might adopt biotechnology methods based on bioreactors coupled to dialysing systems. It would allow for continuous growth of muscle cells in semi-open system. Muscle cells could be propagated and recovered for further steps of differentiation into muscle fibers in aseptic conditions. Similarly, other components of meat could be managed. Adipocytes are successfully produced from adipose tissue derived stem cells (ADC), or from other mesenchymal cells (fibroblasts). The latter cells can easily be isolated through skin biopsy. Materials used to grow cells in culture are rather expensive and some of them are of animal origin (sera) having risk of contamination (cons). Beside, it would be hard to use term “cruelty-free meat” if muscle tissue is grown on sera collected from fetal or newborn calves. The answer could be a synthetic substitute (mixture of substances that mimic serum activity) or natural product of plant origin with identical assets as serum. Affordable prize of growth media can be achieved when large volumes are produced and system is semi-open as it is in dialysed bioreactors (pros).

5. Conclusion

Recent advances in biotechnology together with routine cell and tissue culture techniques as well as public appearance of artificial meat grown in lab followed by processing, and triumphant taste valuation are milestones in support the viewpoint that meat can be manufactured artificially. In author’s opinion, main complications come forward as economic and moral issues. To sell the artificial meat the latter should be produced at affordable prize. This is not achievable, unless alternative low-cost technology is put into practice for massive production of artificial meat. The ethical barrier is equally important as many non-meat eaters would not accept the artificial meat unless the manufacturing is devoid of any substrates of animal origin (except the starting material obtained from unharmed animal donors). These challenges are however to be overcome if the high throughput screening for plant-derived materials to formulate low-priced media and modified biotechnology techniques for continuous production of artificial meat are successful.

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REVIEW

Cultured meat from muscle stem cells: A review of challenges and prospects

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Abstract

Growing muscle tissue in culture from animal stem cells to produce meat theoretically eliminates the need to sacrifice animals. So-called "cultured" or "synthetic" or "*in vitro*" meat could in theory be constructed with different characteristics and be produced faster and more efficiently than traditional meat. The technique to generate cultured muscle tissues from stem cells was described long ago, but has not yet been developed for the commercial production of cultured meat products. The technology is at an early stage and prerequisites of implementation include a reasonably high level of consumer acceptance, and the development of commercially-viable means of large scale production. Recent advancements in tissue culture techniques suggest that production may be economically feasible, provided it has physical properties in terms of colour, flavour, aroma, texture and palatability that are comparable to conventional meat. Although considerable progress has been made during recent years, important issues remain to be resolved, including the characterization of social and ethical constraints, the fine-tuning of culture conditions, and the development of culture media that are cost-effective and free of animal products. Consumer acceptance and confidence in *in vitro* produced cultured meat might be a significant impediment that hinders the marketing process.

Keywords: cultured meat, conventional meat, environmental impact, stem cells

1. Introduction

Winston Churchill predicted that it would eventually be possible to grow chicken muscles more efficiently without rearing live chickens (Churchill 1932). Since then, many researchers have investigated the possibility of culturing meat. Catts and Zurr (2002) managed to keep biopsy muscle samples from frogs alive and growing in culture dishes. Cultured muscles have been generated from skeletal muscle stem cells for the last 15 years to be used in potential medical implants (Dennis and Kosnik 2000; Wang and Rudnicki 2012). In the 1990s, the first cultured stem cells from animals were used including the production of small quantities of tissue. The National Aeronautics and Space Administration of USA (NASA) conducted research on muscle culture from turkey cells (Edelman *et al.* 2005; Webb 2006), while the first edible cultured fish filet was generated from goldfish cells. van Eelen (2007) stated that by includ-

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ing a collagen matrix with stem cells they could proliferate to generate muscle strips. Culture medium requirements and the design of bioreactors have been described by van Eelen (2007). The creation of the cultured meat consortium led to the first cultured meat symposium held in Norway in 2008 at the Norwegian Food Research Institute to discuss commercial possibilities of cultured muscle (IVMC 2008). Many techniques have been developed that make it possible to generate skeletal muscle, bone, cartilage, fat and fibrous tissue (Post 2012). In 2013, the world's first burger was made from cultured meat produced from bovine stem cells (Post 2014), but this cost many thousands of dollars and involved the combining of at least 10 000 individual muscle strips. Although, muscle strips and cultured meat products have been produced, there are still many technical difficulties that will need to be resolved for the large scale production of products acceptable as alternatives to conventional meat for discerning consumers. Some of these challenges are discussed below.

The principal steps in the production of a cultured meat product are set out in Fig. 1 in order to provide an overview of the requirements, with all of these steps needing to be working well, from both commercial as well as biological points of view, in order for the system to be viable.

In this review, some aspects of cultured meat production are discussed along with the benefits and challenges related to the technology used. Cell culturing technology may solve some pressing problems but new issues may emerge. Some drawbacks and limitations of the methodology will be discussed.

Some recent reviews concerning the production of cultured meat are summarized in Table 1 with regard to their content and conclusions. The term "cultured meat" will be used here as it seems to be the most widely used and accepted term, but alternative terms used for the same product include "synthetic meat", "*in vitro* meat", and sometimes "artificial meat". These are generally interchangeable, but are distinct from the term "simulated meat", which encompasses products that are similar in some respects to meat, but are made from non-animal proteins such as those from plants (especially soya bean) and fungi (e.g., Quorn®).

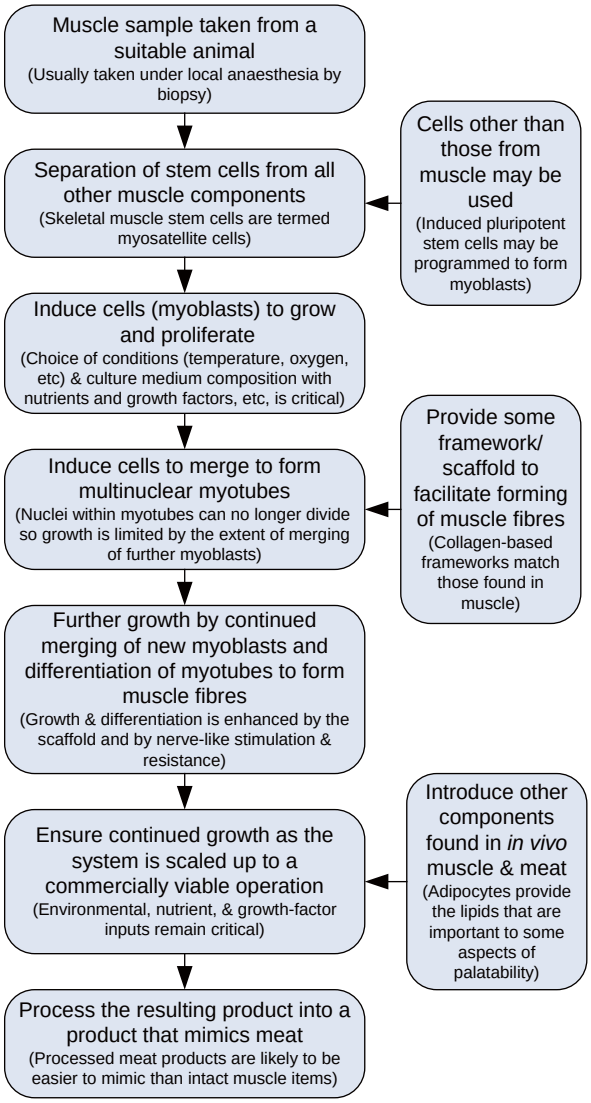

Fig. 1 A flow diagram illustrating in general terms some of the steps in the production of a cultured meat product.

2. Type of cells

Muscle growth *in vivo* during early embryogenesis begins with limited proliferation of the mono-nucleated myoblasts (Benjaminson *et al.* 2002), which then merge and differentiate into a non-proliferative multinuclear cell known as a muscle fiber or myofiber (Campion 1984). The equivalent of the embryonic myoblast in muscle after birth is the myosatellite cell (Kuang and Rudnicki 2008).

The potential of several cell types for initiating the production of cultured meat have been investigated, with the most promising being myosatellite cells, which are the primary adult stem cells for muscle. These were first identified by Mauro (1961) as playing a crucial role in muscle regeneration following injury as they efficiently differentiate into myotubes, which then develop into muscle fibers, a key process for muscle regeneration *in vivo* (Benjaminson *et al.* 2002; Le Grand and Rudnicki 2007). Characteristics of stem cells generally, and some examples of different types of stem cells are outlined in Table 2.

Post (2012) noted that the isolation, culturing and maintenance of a vibrant proliferative state of myosatellite cells is possible, but is challenging. It has been suggested that embryonic stem cells (Table 2) would be an alternative possible starting source for cultured meat given their pluripotent

Table 1 A summary of the content and conclusions of recent reviews (arranged by date) about the production of cultured meat from stem cells of muscle (myosatellite cells)

Author(s) & reference (affiliation)	Title of article	Topics covered & conclusions
Langelaan *et al.* 2010. *Trends in Food Science & Technology*, **21**, 59–66. (Eindhoven University of Technology, The Netherlands)	"Meet the new meat: Tissue engineered skeletal muscle"	• A review of the requirements in order for the economic production of cultured meat to be viable from an engineering perspective • The main hurdles were seen as the finding of the best stem cell source, and the development of commercially viable methods to grow three-dimensional structures within a bioreactor
Stephens. 2010. *Scripted*, **7**, 394–401. (Cardiff University, Wales)	"*In vitro* meat: zombies on the menu?"	• Considers the possibility of *in vitro* meat production with respect to emergent social, ethical, and regulatory issues • The author does not favour the use of the term suggested by others that *in vitro* meat is "zombie meat"
Bhat and Fayez. 2011. *Journal of Food Science & Technology*, **48**, 125–140. (Sher-e-Kashmir University, India)	"Prospectus of cultured meat—Advancing meat alternatives"	• The authors note that the production of a meat-like product that is chemically safe, disease-free, and with a favourable nutritional profile will be more easily achieved than the production of a product with all the physical and sensory characteristics of unprocessed meat • Potential strong points of cultured meat products are listed • Conclude with a list of 6 essential requirements for the future together with the opinion that *in vitro* meat holds great promise
Tuomisto and de Mattos. 2011. *Environmental Science & Technology*, **45**, 6117–6123. (University of Oxford, UK)	"Environmental impacts of cultured meat production"	• The authors used a modelling approach and a range of assumptions to compare cultured meat production with several conventional systems (beef, sheep, pork, & chicken) in terms of energy use, greenhouse gas emissions, land use, and water use per kg of edible meat • Results showed that cultured meat production was superior for all these parameters except that energy use was better for chicken production • They concluded that despite high uncertainty "…the overall environmental impacts of cultured meat production are substantially lower than those of conventionally produced meat"
Dodson. 2012. *Journal of Genomics*, **1**, 39–44. (Washington State University, USA)	"Cell supermarket: Adipose tissue as a source of stem cells"	• This review is not directly concerned with cultured meat, but successful cultured meat will probably need to include adipocytes to ensure satisfactory palatability • The types of cells that may be induced to develop from adipose tissue sources are described
Post. 2012. *Meat Science*, **92**, 297–301. (Maastricht University, The Netherlands)	"Cultured meat from stem cells"	• A review of the need for cultured meat and some of the problems to be overcome • Identified the three main motivations behind the development of commercially viable cultured meat production systems as being: 1) to cater for the predicted increased demand for meat; 2) concerns about environment impacts of meat production from livestock; and 3) concerns about ethical aspects • Emphasises the need for the product to mimic conventional meat as closely as possible • Notes that cultured meat products can be produced, but challenges remaining include: 1) fine-tuning the harvesting of satellite cells, 2) optimising culture media for efficiency (economic and biological) and effectiveness, 3) developing the "tissue engineering" aspects, and 4) ensuring that the product is acceptable to consumers
Welin *et al.* 2012. In the book entitled "*The Philosophy of Food*". pp. 292–304. (Linkoping University, Sweden)	"*In vitro* meat: What are the moral issues?"	• Reviews the production of cultured meat with respect to the moral issues involved • They conclude that we are moving towards the acceptance of *in vitro* meat but: "It will take some time to get there, and it will take people quite some time to adjust" • It is pointed out that an important driver in the development of cultured meat is the medical interest in tissue engineering
Young *et al.* 2013. *Meat Science*, **95**, 904–911. (Aarhus University, Denmark)	"Novel aspects of health-promoting compounds in meat"	• As the title indicates this review focusses on health-promoting "functional" or "bioactive" compounds in meat, but the potential of cultured meat is also reviewed briefly • The authors considered the four main challenges to cultured or *in vitro* meat production to be: 1) identifying the best source of seed cells and a suitable cost-effective growing medium; 2) developing a suitable framework for the cells to grow and differentiate on; 3) scaling up of procedures to an industrial level; and 4) ensuring that nutritional value, health-promoting properties and consumer acceptance is at least equivalent to conventional meat
Goodwin and Shoulders. 2013. *Meat Science*, **95**, 445–450. (University of Florida, USA)	"The future of meat: A qualitative analysis of cultured meat media coverage"	• A summary and discussion of ways in which the media in many counties have run stories concerning the potential and problems for cultured meat • It is noted that the likely time before cultured meat products are on the market is likely to be much less for ground and processed meat than for products similar to current intact meat items such as steaks and roasts

(Continued on next page)

Table 1 (Continued from preceding page)

Author(s) & reference (affiliation)	Title of article	Topics covered & conclusions
Post. 2014. *Journal of the Science of Food & Agriculture*, **94**, 1039–1041. (Maastricht University, The Netherlands)	"Cultured beef: Medical technology to produce food"	• This brief review was written after the highly-publicised demonstration on television of the tasting of an 85 g patty made from cultured bovine muscle fibres that had been grown *in vitro* from satellite cells • The steps in this "proof of concept" demonstration are outlined • Surveys of consumer attitudes to this approach were generally positive • It is concluded that many challenges remain, but that research in this area should continue in order to help satisfy the predicted increases in demand for meat over the next few decades
van der Weele and Tramper. 2014. *Trends in Biotechnology*, **32**, 294–296. (Wageningen University, The Netherlands)	"Cultured meat: Every village its own factory"	• The authors suggest that the production of cultured meat is likely to be technologically feasible in the future, and that it almost certainly will have certain advantages over conventional meat production systems • Some of the steps and processes are summarised • They suggest that small-scale production of cultured meat near where it will be consumed may prove effective • It is concluded that, economically, competition with 'normal' meat will be a challenge unless the price of conventional meat increases greatly

Table 2 Characteristics of several types of mammalian stem cells[1)]

Type of stem cell	Tissues and stem cell can differentiate into	Persistency in terms of number of replications *in vitro*
Embryonic stem cells	Most tissues of the animal body	Long-term persistency and may be limitless (Zeng and Rao 2007)
Totipotent stem cells	All cells of the body and the developing foetus. The newly fertilised egg is a good example	Theoretically high
Pluripotent stem cells	Most tissues of the body, but more restricted than totipotent stem cells. The embryonic stem cell is an example of this type	Variable
Induced pluripotent stem cell	Most tissues of the body. Fully differentiated cells can be induced to become pluripotent by appropriate treatments (Holde and Vogel 2008)	Variable and unknown in many cases
Adult stem cells	A broad classification across tissues, with the most being specific to the tissue they originate from	Most adult stem cells are limited to 50–60 divisions. This replicative capacity is termed the "Hayflick limit" (Roobrouck *et al.* 2008)
Multipotent stem cells	Several tissues depending on the tissue of origin. For example, the mesenchymal stem cells from the mesoderm can differentiate into fibroblasts, adipocytes, osteoblasts, chondrocytes or myocytes (muscle cells)	Variable, depending on animal age
Myosatellite stem cell	Muscle tissue. An example of a unipotent or committed stem cell that is capable of supporting one tissue type only	Decreases with age (Roobrouck *et al.* 2008), and may be less than 20 divisions *in vitro* for adults (Mouly *et al.* 2005)

[1)] Stem cells are cells that have the capacity to either replicate, to increase the number of identical cells, or to differentiate into specialised cell types depending on the type of stem cell (Roobrouck *et al.* 2008).

capacity (Telugu *et al.* 2010), but this is unlikely currently as establishment of embryonic stem cell lines from several species such as bovine, porcine, and camelids have not yet been achieved. It has yet to be determined whether embryonic stem-cell-like cells generated from those species can fully differentiate into myofibrils. Use of myosatellite cells in cultured meat production (van Eelen *et al.* 1999; Edelman *et al.* 2005), requires that they be successfully induced to differentiate from an undifferentiated state, to myoblasts (Bach *et al.* 2003). Myosatellite cells have been successfully isolated from the skeletal muscle tissue of several species used for meat production including cattle (Dodson *et al.* 1987), chicken (Yablonka-Reuveni *et al.* 1987), fish (Powell *et al.* 1989), lambs (Dodson *et al.* 1986), pigs (Blanton *et al.* 1999; Wilschut *et al.* 2008), and turkeys (McFarland *et al.* 1988). Isolation usually involves the use of proteolytic enzymes to separate the myosatellite cells from other tissue structures (Danoviz and Yablonka-Reuveni 2012). It has been suggested by Edelman *et al.* (2005) that regularly replenishing a culture with an immortal cell line would enhance cell divisions when the replicative rate of existing cells decline or cease.

Another cell type that has received attention as a possible starter for cultured meat is the induced pluripotent stem cell (iPS), such as those obtained by dedifferentiating mature skin cells to form totipotent cells by switching on just a few

genes (Holden and Vogel 2008). It should be stressed, however, that improving the proliferative capacity and developing methods to guide the differentiation, dedifferentiation and *trans*-differentiation of iPS cells to form myosatellite cells must be achieved prior to incorporating iPS cells into cultured meat protocols. A promising note arises from the fact that skeletal myocytes can be derived successfully by *trans*-differentiation from abundantly available fat cells (Kazama *et al.* 2008).

To improve the quality of cultured meat, it may be desirable to co-culture adipocytes (fat cells) with myofibrils in order to enhance the texture, flavor and tenderness of cultured meat by effectively increasing the intramuscular fat (Hocquette *et al.* 2010). Tissue engineering of adipose cultured cells has been described by Frerich *et al.* (2011), Dodson *et al.* (2012) and Verseijden *et al.* (2012).

3. Cell and tissue culture

The process of developing a cultured meat production system involves the initial collection of suitable cells with the potential to form muscle, as outlined in the previous section, and then greatly expanding the numbers in a bioreactor (Post 2012). Strips of muscle fiber can be generated (Post 2014), but the development of a full-scale bioreactor suitable for mass cultured meat production has yet to be designed and built (Datar and Betti 2010). Muscle structure requires something akin to a circulatory system to deliver nutrients and oxygen close to the growing cells or fibers and to remove the waste products of metabolism. It is feasible to generate very small pieces of muscle that acquire an adequate nutrient and oxygen supply through diffusion, but cultured muscles with built-in blood vessels for supplying the flow of oxygen and nutrients have not been developed, although advanced biomaterial technologies may make this possible and testable (Skardal *et al.* 2010). Cultured muscle tissue also needs to be physically stretched to make it resemble natural meat. According to Grinnell (2000), fibroblast stem cells can organize collagen or collagen/matrigel into tight fibers between the anchors to develop tension within the developing muscle fibers. This static tension will boost protein production by the cultured muscle significantly (Vandenburgh *et al.* 1999). Boonen *et al.* (2010) reported that imposition of the cyclic stretching protocol used in their study failed to improve protein synthesis, but Powell *et al.* (2002) observed positive effects of cyclic stretches on muscle maturation. Contractile and other types of proteins in muscle are important for texture, color and taste of cultured muscles. For example, the heme-carrying protein myoglobin is responsible for the red color of meat and is an important source of iron in meat (Suman and Joseph 2013). Contractile activity muscle will stimulate myoglobin synthesis, which may enhance the color of cultured meat.

Although many cell culture techniques are currently available, it was suggested by Datar and Betti (2010) that the most difficult step in cultured meat production is likely to be in determining the best culture medium formulation. The media should be affordable, contain only food-grade components, be readily available in large quantities, and be effective and efficient in supporting and promoting muscle cell growth, proliferation, and differentiation. An example of items included in culture media for experimental purposes is given in Table 3. In some cases the medium will be changed in order to change the emphasis from being on proliferation (a serum-rich medium) to differentiation (a serum-poor medium) (Danoviz and Yablonka-Reuveni 2012).

Tuomisto and de Mattos (2011) pointed out that designing recycling mechanisms that enable the replenishing of the culture with nutrients during the process would create substantial benefits and improved efficiency. The biochemical composition of meat could in theory be changed to make it healthier or to produce specialized products by modifying the nutrient mix supplied and/or by devising culture conditions that would enable other cell types such as adipocytes (fat cells) to be grown in the same bioreactor.

Sera from either adult animals, newborns or from fetal sources have been included as standard supplements for cell culture media (Table 3; Coecke *et al.* 2005), but the use of components from animals raises ethical and other concerns and constraints (Merten 1999), including the high costs, the possibility that disease-producing organisms or unhealthy compounds may be present, and the problem of variation between batches of the product (Table 3). Commercial serum replacements and serum-free culture media can offer alternatives for culturing cells (Froud 1999). Such products have been developed to support cell cultures from various species such as turkeys (McFarland *et al.* 1991), sheep (Dodson and Mathison 1988) and pigs (Doumit *et al.* 1993). Ultroser G is one of many commercially available serum substitutes designed to replace fetal bovine serum for growth of anchorage-dependent cells as it contains all the necessary constituents for eukaryotic cell growth (Duque *et al.* 2003). Serum-free media is usually supplemented with purified proteins of animal origin (Merten 1999). Benjaminson *et al.* (2002) found that amino acid-rich mushroom extracts were comparable to serum as a growth medium in promoting surface area expansion. Alternatively, substitution of animal proteins with those of a plant (soybean lecithin extracts) is widely used as a diluent media for sperm cell ejaculates (Khalifa *et al*. 2013). Two products are commonly used, AndroMed (Minitub, Germany) and BioXcell (IMV Technologies, France).

In general the ideal culture media should be free of animal-derived components, but if plant derived proteins are

Table 3 An example of items included in the culture medium for the growth, proliferation, and differentiation of myosatellite cells *in vitro* as used by one laboratory (Danoviz and Yablonka-Reuveni 2012)[1)]

Item in the culture medium	Notes
Dulbecco's modified medium (DMEM)	High glucose (4 500 mg L^{-1}), 4 mmol L^{-1} L-glutamine, 110 mg L^{-1} sodium pyruvate, supplemented with 100 U mL^{-1} penicillin and 100 μg mL^{-1} streptomycin
Foetal bovine serum (20%)	Not heat activated, and selected only after it has been shown that the batch supports proliferation and differentiation of myoblasts. Foetal serum contains a number of growth factors including fibroblast growth factors and insulin-like growth factors
Horse serum (10%)	Selected on the basis of the ability of a batch to support proliferation and differentiation of primary myoblasts
Chicken-embryo extract (1%)	Details of preparation are provided in the first reference given in this Table

[1)] Other groups have used similar but not identical culture media (e.g., Baquero-Perez *et al.* 2012).

used, the potential risk of allergens has to be eliminated. A limited number of culture media have been developed for medical purposes and there may be opportunities to increase the efficiency of muscle cell cultures with these (van der Valk *et al.* 2010).

For cultured meat production, the initial cells have been successfully grown on a collagen meshwork (van Eelen *et al.* 1999) or on collagen beads as the scaffold (Edelman *et al.* 2005). These culture frameworks or scaffolds can only produce a thin myocyte layer of 100–200 μm thick, however, due to diffusion limitations (Carrier *et al.* 1999; Powell *et al.* 2002; Dennis *et al.* 2009), although several cell culture layers or products might be added together to make a muscle or meat product of an acceptable size (van Eelen *et al.* 1999; Post 2014).

Jun *et al.* (2009) stated that growing myoblasts on electrically conductive fibers induced differentiation and the formation of more myotubes of greater length. Stem cells grown on porous microbeads suspended in growth media in large bioreactors are expected to offer higher cell yields and could be easily collected and further processed as a mince-meat-like product, but scaffolding components should be safe to consume andbe easily digested. The advantage of using three-dimensional (3D) scaffolds is that it enables the more effective spread of media, nutrients, and growth factors, and, more importantly, it can be used to dictate the shape of the cultured meat product. Development of biomaterials that enable contraction to stimulate proliferation and differentiation may be beneficial for cultured-muscle growth (De Deyne 2000). Porous beads are capable of varying the surface area by changes in pH and temperature, thereby fulfilling the contraction requirements of myoblast cells (Edelman *et al.* 2005).

The sheets of cultured cells or fibers can be removed enzymatically or mechanically, but both techniques will damage the cells (Canavan *et al.* 2005). Thermo responsive coatings that change from hydrophobic to hydrophilic at lowered temperatures can release the scaffold as an intact sheet upon cooling (da Silva *et al.* 2007). The thermal liftoff method results in undamaged sheets of cells that maintain the ability to adhere if transferred onto another substrate (da Silva *et al.* 2007). Lam *et al.* (2009) reported a method for detaching a culture sheet from a non-adhesive micro-patterned surface using biodegradable selective attachment proteins such as laminin (an important component of the product matrigel (Danoviz and Yablonka-Reuveni 2012)). Use of a fibrin hydrogel was found to be a suitable scaffold for skeletal muscle tissue because cells can migrate, proliferate and produce their own extracellular matrix (Lam *et al.* 2009). The development of suitable scaffolding for cultured meat is the subject of considerable ongoing research.

The development of cultured meat production procedures is constrained by the facts that the tissue will be cultured in the absence of *in vivo* homeostatic regulation, and that the process needs to be carried out on a large scale. The cultured meat production systems currently envisaged will lack the natural organ systems that maintain homeostasis in a living organism. The myocytes need to be metabolizing aerobically to prevent acidification of the culture medium with lactic acid (Datar and Betti 2010), and cell viability positively correlates with the oxygen gradient in growing cultures of myocytes (Radisic *et al.* 2008), so oxygen carriers are likely to be needed to maintain oxygen concentrations high enough to prevent hypoxia and acidification (Datar and Betti 2010). The removal of waste products including carbon dioxide and lactate will also be necessary (Datar and Betti 2010). In the conversion of conventional muscle to meat the metabolic processes include anaerobic glycolysis, lactic acid accumulation, a decrease in pH, protein denaturation and enzymatic proteolysis (Lawrie 1991). These changes influence the texture, taste and appearance of meat, so it is likely that it will be necessary to ensure that comparable processes occur in cultured meat after harvest.

Efficiency of production in a commercial sense as well with regard to use of resources and effects on the environment, along with the requirement that the product mimic conventional meat, are two keys to success and acceptance of any meat alternative (Post 2012). Appreciable advantages in efficiency, however, may mean that some shortcomings in mimicry could be tolerated. To be widely

adopted cultured meat will ideally be similar or even better than conventional meat in its palatability and appearance characteristics including visual color, aroma, flavor, texture, tenderness and overall palatability (Verbeke *et al.* 2010), as well as in its nutritive value. The flavor aspect of palatability is likely to be the most difficult parameter to get right as it is made-up of more than 1 000 water-soluble and fat-derived components in addition to the fact that differences exist amongst species (Claeys *et al.* 2004).

4. Nutritional value

In addition to having a high protein content with a full complement of essential amino acids, conventional meat is also a source of several other desirable nutrients such as vitamins and minerals, and bioactive compounds (Young *et al.* 2013). It is desirable that any cultured meat product meets or exceeds the nutritional value of conventional meat products in order to be competitive on the market. Nutrients in cultured meat that are not synthesized by muscle cells must be supplied as supplements in the culture medium. For instance, the essential vitamin B_{12} is synthesized exclusively by certain species of gut-colonizing bacteria and is therefore found solely in food products of animal origin. Supplementation of vitamin B_{12} produced commercially by biosynthetic microbial fermentation would be necessary for it to be in a cultured meat product grown in an aseptic environment. Iron in meat is present primarily as the highly bioavailable heme form within the prosthetic group found as part of the proteins myoglobin and hemoglobin (Uzel and Conrad 1998). To provide iron in a bioavailable form, for example, ferric ions bound to the plasma binding protein transferrin will probably need to be provided in the culture medium to enable iron to enter the myocyte mitochondria and be incorporated into heme synthesis and subsequent myoglobin synthesis (Aisen *et al.* 2001). Levels of transferrin will need to be closely monitored, however, in order to minimize levels of free ferric or ferrous ions in the medium, as they could potentially catalyze the production of damaging reactive oxygen species under aerobic environments (Papanikolaou and Pantopoulos 2005). Graber and Woodworth (1986) found that myoglobin concentrations in cultured myocytes were low until a stable population of myotubes was formed, which may help to determine the optimal growth time necessary before harvesting the cultured meat.

5. Large-scale operations

The development of large-scale facilities capable of producing cultured meat at a rate comparable to traditional slaughterhouses has not been widely investigated. Presently, “large” pieces of cultured tissue are mainly measured on a millimeter scale in connection with medical applications (Klumpp *et al.* 2010). Examples of mass production of cultured organisms exist in the pharmaceutical industry and microbial biotechnology where organisms in bioreactors are used to produce purified chemicals, and although the objectives are quite different, some of the technology and methodology may prove relevant.

6. Rationale for developing cultured meat production

It is known that meat consumption per capita increases with economic development (WWI 2006; Fiala 2008) and that global meat production has more than doubled since 1970, with higher rates of increase in developing countries (WWI 2006). Projections by Fiala (2008) suggested that world meat consumption in 2030 could be 72% greater than in 2000, due in part to increases in world population, which has been estimated to increase by 2 billion (~28%) from 2012 to 2050 (Springer and Duchin 2014). The availability of cultured meat may help to meet this predicted increase in demand while at the same time save animals and satisfy meat eaters (Hopkins and Dacey 2008). Many alternative techniques are being investigated to improve the efficiency of the entire supply chain for meat within conventional systems (Post 2012) in order to lower the impact on the environment. It has been estimated that world meat production contributes between 15 and 24% of global anthropogenic greenhouse gas emissions (Datar and Betti 2010) with a significant proportion of this percentage due to deforestation to create grazing land (Steineld *et al.* 2006). Tuomisto and de Mattos (2011) suggested that cultured meat production could lead to a large reduction in greenhouse gas emission. In their model using cyanobacteria-produced biomass as a nutrient source and relative to European systems of conventional meat production from cattle, sheep, pigs and chickens, they estimated considerable reductions in energy consumption (except for meat production from chickens), land use, water use and greenhouse gas emissions. Many natural resources could be spared from depletion if cultured meat made a significant contribution to the total meat supply, as illustrated in Latin America where pastures for cattle grazing have been converted to soybean fields and the cattle have been moved on to pastures that have replaced Amazon forests (Howard-Borjas 1996; Rother 2003). This threatens biodiversity and also diminishes the capacity of rain forests to absorb carbon dioxide.

Carefully controlled conditions of myocyte culturing will potentially minimise the spread of animal-borne diseases by following hygienic procedures throughout the culturing

process. Foodborne pathogens found in meats, such as *Salmonella*, *Campylobacter* and *Escherichia coli* are responsible for millions of episodes of illness each year (CDC 2012). By controlling conditions used in producing cultured meat it should also be possible to eliminate its exposure to hazardous products like pesticides, fungicides, heavy metals, aflatoxins, melamine, anabolic agents, and antibiotics (Marques *et al.* 2011), an outcome that is difficult for conventional meat production. Pathogens and emerging diseases, such as avian and swine influenza are associated with the intensification of livestock farming (Greger 2007). Moreover, by limiting the extent of close quarter human-animal interactions, the incidence of epidemic zoonoses developing will be curbed (Datar and Betti 2010).

7. Ethics, public health and animal welfare

Consumers worldwide have a growing interest in food ethics along with animal ethics and the ethics of other human activities (Williamson 2003). Food ethics have been linked to religion and lifestyle with many religions having explicit dietary rules that believers must follow. Some foods are deemed unclean and not fit for eating, and there are rules for how food should be prepared and sometimes also for when eating various kinds of food is appropriate. From a secular perspective, there is what may be called a “lifestyle” kind of food ethics, which may be summarized as “you are what you eat”. In this view, food needs to be compatible with a person’s basic values and life plans. Even people, who do not reflect very much on food, may refuse to eat some kinds of food. In the Western world, for example, many people will not eat meat from dogs, cats or other pet animals, while Muslims do not eat pork.

Consumers often look to media for information concerning food issues. Therefore, to understand how the media influence consumers’ opinions of cultured meat, it would behoove meat industry authorities to be aware of media coverage concerning alternative forms of meat (Meyers and Abrams 2010; Goodwin and Shoulders 2013). Media coverage of cultured meat has often been with reference to livestock production problems and the benefits of cultured meat (Goodwin and Shoulders 2013), but it is possible that consumer attitudes will be different when the product is actually available, at which time it is suggested that the closeness with which the product mimics conventional meat, and the efficiencies associated with its production will assume a greater importance (Post 2012, 2014; Goodwin and Shoulders 2013).

The present interest in food ethics has been exacerbated by concerns about the impacts food related hazards have on human health (Verbeke *et al.* 2000), with many negative stories about meat production having made headlines in mainstream media, including those about Bovine Spongiform Encephalopathy (BSE or Mad Cow Disease), *E. coli* and *Salmonella* outbreaks, inhuman handling of livestock, and the contribution of livestock production to global warming (Goodwin and Shoulders 2013). This publicity has led to increased public scrutiny of the conventional meat industry, and possibly to an increased interest in the potential benefits of cultured meat, particularly in relation to the growing world population and predicted growth in demand for meat (Springer and Duchin 2014).

Questions concerning cultured meat are not only about technology and science, they are also about its acceptability as a food. Will it be considered “unnatural” and run into issues similar to those faced by genetically modified organisms? The naturalness/unnaturalness issue is likely to be greater if cells used in bioreactors need to be genetically modified in some way to make them grow and develop satisfactorily, although there is no indication that this will be necessary. Many people seem to want meat to come from animals that have lived as naturally as possible, but they are concerned about the way many meat-producing animals are raised and killed (Welin *et al.* 2012). Cultured meat does have a competitive edge in this respect, but it is not known whether meat consumers will prefer meat from animals that were once alive to that produced in a bioreactor.

The welfare of animals used for meat production has been widely discussed and non-vegetarians have been reported to decrease consumption of meat with increased exposure to awareness campaigns about animal welfare in the public media (Tonsor and Olynk 2011). There is a general consensus that animal suffering should be avoided (DeGrazia 1996), and despite many improvements, slaughterhouse practices do tend to evoke negative reactions among the public. Producing cultured meat does not involve the killing of animals, as live animals can be used as a source for the initial cells in the bioreactor (Fig. 1). It can be argued that people have a moral obligation to support the development of this kind of food for ethical as well as efficiency reasons (Welin *et al.* 2012). Animal welfare groups are generally in favor of cultured meat production because the culture does not have a nervous system and therefore cannot feel pain, but some drawbacks are also recognised (Stephens 2010).

8. Conclusion and future prospects

1) Cultured muscle has been produced by taking skeletal muscle stem cells (myosatellite cells) from live animals and inducing them to grow and differentiate to form muscle fibers *in vitro*, but the development of methods to do this in a commercially viable way has yet to be achieved.

2) Cultured meat, which is also known as synthetic or *in vitro* meat, is seen as having a number of advantages relative to conventional meat in terms of efficiency of resource use (land, energy, and water), lower greenhouse gas production, better animal welfare, and in the ability to manipulate the nutrient composition of the product. Consumers, however, may be cautious about accepting such products due to perceptions of "unnaturalness" and "artificialness".

3) The culture media surrounding the growing cells and fibers in culture must contain, not only adequate levels of all necessary nutrients and oxygen, but also growth factors and bioactive compounds required for normal muscle development. Currently some of these are obtained from animal tissues, but eventually it would be desirable for the media to be free of all animal products.

4) Growth *in vitro* of a single layer of myocytes and muscle fibers on a base of collagen fibers has been achieved, but the formation of steak-like three-dimensional (3D) structures will require a 3D framework or scaffold and a means of ensuring that every cell/fiber has a continuous and adequate supply of nutrients and oxygen, as well as a means of removing waste products such as CO_2.

5) It is likely that the initial cultured meat products will simulate processed meat items such as mince with limited structural requirements in terms of a meat-like texture. The production of steak- or roast-like products, however, likely requires significant further developmental research concerning scaffolds, circulatory systems, and the creation of key quality attributes such as flavour and tenderness.

6) If successfully produced, it is possible that cultured meat products could play a useful complementary role alongside conventional meat products in meeting predicted increases in the global demand for meat. The extent to which they constitute competitors of conventional meat remains to be seen.

7) It is too soon to accurately assess the readiness with which consumers will accept cultured meat products. The real test will be when such products are on the market.

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RESEARCH ARTICLE

The environmental prospects of cultured meat in China

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Abstract

To deal with concerns in China about environmental degradation and a growth in population accompanied by increased consumption of livestock products, a meat alternative is required. This study compared the environmental impacts of producing different protein sources for nutrition, including crops, livestock products, and cultured meat. The results showed that cultured meat has the lowest land use per unit of protein and unit of human digestible energy. China's crops have the lowest energy use and greenhouse gas (GHG) emissions per unit of energy and protein. The energy use in cultured meat production is slightly higher than that of current pork production in China, whereas GHG emissions are lower. It is concluded that the overall impact of replacing livestock products with cultured meat would be beneficial for China's environment and would potentially improve food security because less land is needed to produce the same amount of protein and energy.

Keywords: cultured meat, *in vitro*, environmental degradation, livestock products, greenhouse gas (GHG)

1. Introduction

Livestock production is one of the major contributors to environmental degradation in China. Why is this? China's livestock production contributes between 18 and 34% of total current greenhouse gas (GHG) emissions, and a large proportion of this percentage is due to deforestation to create grazing land (Wang *et al.* 2005; Zhang *et al.* 2014). In China, 35% of the land surface is used for livestock production, with 38% of arable land being used to grow livestock feed crops and 31% being used for grazing (Wang *et al.* 2014). According to some studies, about 68% of the fresh water use and 21% of the energy consumption of mankind is directly or indirectly used for China's food production, of which a considerable proportion is used for the production of meat (Wu and Cheng 2014; Yan *et al.* 2014). Meanwhile, by the end of 2013, the population of China had reached 1.368 billion, accounting for 22.8% of the world's total, and the population has been forecast to grow to 1.7 billion by 2050 (UN 2014). Villegas and Xiang (2012) have estimated that 6.25% of Chinese people live primarily on a meat-based diet, and because of increasing population size and increasing per capita meat consumption in China, it is predicted that meat consumption will double between 2010 and 2050 (FAO 2011). At the same time, it appears that the capacity of conventional meat production is close to its maximum (FAO 2011). Such an increase will also meet production's impact on the environment unless meat production methods that are more effective are adopted.

Humans are taxonomically omnivorous, and meat provides a source of protein and energy unavailable in plant sources. Meat is particularly valuable as a source of omega-3 fatty acids, vitamin B12, protein, and highly bioavailable iron (Verma and Banerjee 2010). In the industrialized countries, average protein consumption is 106.4 g person^{-1} d^{-1}, of which 56.1 g comes from animal products (FAO 2006). Biologically, it is not

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necessary to circulate plant protein through animals before human consumption. All essential amino acids for human nutrition could be retrieved directly from plants by combining cereals and pulses (Steinfeld *et al.* 2006). Some legumes, such as soybeans, contain all the essential amino acids.

One proposed method for reducing the negative environmental impacts of meat production is to grow only animal muscle tissue *in vitro*, instead of growing whole animals (Datar and Betti 2010; Post 2014). This technology is called cultured (or *in vitro*) meat production, and it is currently at the research stage. The term *in vitro* culturing means growing cell types of either animal or plant origin without the organism from which it is derived (Chiles 2013). Culturing involves the extraction of cells from the organism and their transfer onto or into a suitable growth medium. Engineered *Escherichia coli* bacteria are used for the production of specific growth factors that induce the stem cells to differentiate into muscle cells (Boonen *et al.* 2010; Pluhar 2010). The muscle cells are grown in a bioreactor on a medium composed of cyanobacterial hydrolysate supplemented with growth factors and vitamins (Gilbert *et al.* 2010; Gutteridge *et al.* 2010; Wilschut *et al.* 2010). The technology is still at the research stage, and commercial cultured meat is not yet available.

Meat is an increasingly important source of high-value animal protein in China. Meat fat comprises mostly monounsaturated and saturated fatty acids, with oleic (C18:1), palmitic (C16:0), and stearic acid (C18:0) being the most ubiquitous. Meat and meat products are also sources of cholesterol in the diet (Delgado 2003). In most industrialized countries, a high meat intake contributes to a higher-than-recommended saturated fat and cholesterol intake (Bender 1992). Nutrition-related diseases associated with the overconsumption of animal fats, such as cardiovascular disease and diabetes, are responsible for one third of global mortalities (WHO 2001). Food-borne illnesses have become increasingly problematic, with a six-fold increase in gastro-enteritis and food poisoning in industrialized countries in the last 20 years (Nicholson *et al.* 2000) and the most common causes of food-borne diseases in China, the EU, the USA, and Canada are contaminated meat and animal products (European Food Safety Authority 2006; Fisher and Meakens 2006). Cultured meat is considered as potentially safer than conventional meat and, because of the non-sustainability of traditional meat production, there may be a huge market for this in the long term future. According to its promoters, *in vitro* culturing of meat would also facilitate the design and production of novel products (Boonen *et al.* 2011). Controlled conditions also offer the capacity for manipulation to create meat products with different nutritional, textural, and taste profiles (Skardal *et al.* 2010; Visconti *et al.* 2010). This can be accomplished by co-culturing with different cell types, medium supplementation, or genetic engineering.

The present paper examines the problems of environmental degradation and a growth in population accompanied by increased consumption of livestock products in China. First, why do we need meat alternatives in China? There are at least three motivations to intensify the exploration of production alternatives to livestock meat production. Second, we will describe the basic methodology which is presented: the culturing of *in vitro* meat, cell cultures, and tissue cultures. The paper will compare the land use, energy use, and GHG emissions of China's different crops, livestock products, and cultured meat by identifying impact per unit of protein and energy. Finally, it will be estimated how much land would be saved by retrieving all protein for human nutrition from crops or by replacing conventional meat with cultured meat.

2. Why do we need meat alternatives in China?

First, there is growing concern about the environmental impact of livestock breeding and management in China as in developed countries. Current livestock production accounts for a significant large share of land and water use and is the main contributor to the eutrophication of waterways and the loss of biodiversity in China (Yang 2013). In light of data from the FAO for GHG emissions from meat production and a range of published cost estimates for these emissions, we find that the global environmental costs of meat consumption are more than $140 billion per year, totaling between $4 trillion and $15 trillion from 2010 to 2050 (FAO 2011). Livestock meat production accounts for a considerable portion of GHG emissions, land usage, and water and energy consumption (Vries and Boer 2010). Currently, livestock raised for meat use 30% of global ice-free terrestrial land and 8% of global freshwater while producing 18% of GHG emissions. Globally, 34% of the GHG emissions related to livestock production are due to deforestation, 25% are methane emissions from enteric fermentation of ruminants, and 31% of the emissions are related to manure management (Datar and Betti 2010). It has been found that beef generally has the highest environmental impact, whereas poultry has the lowest impact of meat-producing species. It is clear however, that major improvements can be made in the environmental impact of meat production, either through conventional (Capper 2011; Mathews and McConnell 2011) or other technologies. In a preliminary life-cycle analysis, Tuomisto and de Mattos (2011) calculated that production of 1 000 kg of cultured meat requires 26–33 gigajoule (GJ) energy, 367–521 m^3 water, and 190–230 m^2 land while emitting 1 900–2 240 kg CO_2-eq GHG emissions. In comparison to conventionally produced European meat, cultured meat involves approximately 7–45% lower energy

use (only poultry has lower energy use), 78–96% lower GHG emissions, 99% lower land use, and 82–96% lower water use, depending on the product compared.

A second motivation for exploring livestock alternatives in China is concern about animal welfare as in developed countries. Animal welfare—related issues have been discussed intensively in recent years as a consequence of changes in public attitudes and regulatory reform that is taking place in China (Han *et al.* 2011). A combination of public opinion pressure and trade policy has driven requirements for regulation, and the World Trade Organization (WTO) has delegated the World Organization for Animal Health (OIE) to develop guidelines that could be used as international standards. Animal production is exported, and the process varies according to international demands (Nielsen and Zhao 2012). Many of the guidelines are based on rules, sociological issues, and sustainable principles that are not standardized, and there is still some concern, requiring more discussion in China. As shown by Lu *et al.* (2013), Chinese people who are the most educated, have the best salaries and conditions of life, accounted for 34.2% of the total population, are worrying about a better world, recycling trash, buying organic foods with concern regarding animal welfare. They specially worry about animal welfare issues in livestock meat production. Cultured meat has the potential to greatly reduce animal suffering and make eating animals less necessary, even while satisfying all the nutritional and hedonic requirements of meat eaters (Post 2012). Thus, public concern about animal welfare may affect consumer behavior, thereby forcing the meat industry to continuously evaluate its practices in view of that concern in China.

Lastly, there are public health problems surrounding livestock production in China. Most Chinese people focus on the environmental externalities and animal welfare, but there are also health-related externality costs, which include both individual health impacts and infectious diseases (Rizzino 2007; Cederberg *et al.* 2011), such as the serious threat posed by chicken flu, that can lead to possible new influenza epidemics or even pandemics, which can kill millions of people (Webster 2002). Furthermore, from a commercial perspective, animals are notoriously unreliable as a raw material for meat production, because of illness, stress, and uneven growth (Holmes and Dacey 2008). Cultured meat is potentially a much more reliable alternative. In comparison with animals, a product from a bioreactor could be attractive because it does not come with all the vicissitudes of animals (Roelen and Lopes 2008). For instance, stem cells from mammalian sources or blends of cell sources can be used as a basis for hitherto unimaginable meats. In addition, the biochemical composition of meat may be changed to make it a healthier or specialized diet product, for instance, by increasing the content of polyunsaturated fatty acids through changes in culture conditions.

3. Basic methodology

Meat may commonly be defined as the flesh part of farm animals that mostly contains the skeletal muscle composed of bundles of muscle fibers (Skardal *et al.* 2010). During embryological development, committed muscle tissue formation begins with mononucleated myoblasts of limited proliferation capacity (Danka *et al.* 2014). Three technologies that have emerged in recent years make it possible to generate skeletal muscle and other mesenchymal tissues such as bone, cartilage, fat, and fibrous tissue: stem cell isolation and identification, *ex vivo* cell culture, and tissue engineering (Frerich *et al.* 2011; van der Weele and Tramper 2014). The methods so far proposed have a common set of elements. Van Eelen *et al.* (1999) proposed the growth of myocytes on a collagen meshwork, while Edelman *et al.* (2005) suggest collagen beads as the scaffold. The scaffold-based method can only produce a thin myocyte layer of 100–200 μm thick on the scaffold in static culture because of diffusional limitations (Gutteridge *et al.* 2010). As a result, the products of these methods lack the structure of native muscle tissue and therefore could only be used for processed meat products (Edelman *et al.* 2005; Langelaan *et al.* 2010). An alternative method of creating a three-dimensional product is the expansion in volume of an explant of muscle tissue of animal origin. In these cases, myosatellite cells are responsible for generating new myofibers or contributing additional myonuclei to existing ones (Marcu 2014). Located between the basal lamina and sarcolemma of an associated myofiber, mononucleated myosatellite cells are normally in a quiescent, non-dividing state (Hill *et al.* 2003; Kanatous and Mammen 2010). Benjaminson *et al.* (2002) were able to expand the surface area of an explant of fish by growth in a medium containing a crude cell mixture; the resulting product was prepared and well rated by a food panel. This method also faces diffusional limitations and is unlikely to translate well into a large-scale operation, however, so it is proposed to use tissue engineering to produce *in vitro* cultured meat. With the help of tissue engineering, the attempt is made to mimic neoorganogenesis *ex vivo* for the treatment of various diseases and surgical reconstruction. It is a powerful technique that is mainly being designated for regenerative medicine in a wide variety of tissues and organs (Datar and Betti 2010). In particular, tissue engineering of skeletal muscle has many applications, ranging from *in vitro* model systems for drug-screening (Vandenburgh *et al.* 2008), pressure sores (Gawlitta *et al.* 2007), and physiology to *in vivo* transplantation to treat muscular dystrophy and muscular defects (Boldrin *et al.* 2008).

Obviously, tissue engineering could also be employed for the *in vitro* production of skeletal muscle tissue from farm animals for consumption purposes (Edelman *et al.* 2005). Danka *et al.* (2014) cultured loose myosatellite cells on a substrate and harvested mature muscle cells after differentiation. It is possible to co-culture the myoblasts with other cell types to create a more realistic muscle structure that can be organized in much the same way as real muscles (Verseijden *et al.* 2012). The technology may be feasible with existing tissue engineering techniques and may offer health and environmental advantages by reducing environmental pollution and land use associated with current meat production systems (Hocquette *et al.* 2013).

4. The environmental value of cultured meat in China

In this paper, the land use, energy use and GHG emissions were allocated per unit of protein and per unit of human digestible energy. Transformation factors were created in order to calculate the protein and energy contents of the original Functional Units used in the data. The data for the environmental impacts of the production of the foods compared are presented in Table 1. The production of crops and livestock represent the average production systems in China (Yan *et al.* 2014). The system boundaries included the processes from input production up to the farm or factory gate. The conversion factors used for converting a ton of carcass dead weight to a ton of edible meat was 0.3847, 0.4555 and 0.4455 for beef, lamb and pork, respectively (Tuomisto and Roy 2012). The energy and protein contents of the products are presented in Table 2 (FSA 2002).

The global impacts of replacing livestock products by *in vitro* animal protein technology were estimated by using the FAO data for global livestock protein consumption (FAO 2011) and the global GHG emissions and land use related to livestock production (FAO 2006). The data for the annual demand of meat in China was also based on the FAO database (FAO 2011). The global average land requirements for production of wheat were compared with the highest yielding countries by using the global average crop yields and the average crop yields in the top five highest yielding countries as an average in 2007–2011.

The results show that plant protein production requires significantly less land, energy and has lower GHG emissions compared to production of animal protein (Figs. 1 and 2). However, cultured meat has the lowest land use requirements per unit of protein (Fig. 3). When impacts were allocated per unit of energy, potatoes had the lowest land requirements followed by cultured meat. The energy input for cultured meat production is substantially lower compared to conventional produced beef, sheep, but requires more energy use both energy and per unit of protein compared to conventionally produced pork.

Table 1 The environmental impacts of crop and livestock products (Yan *et al*. 2014) and cultured meat (Tuomisto and de Mattos 2011)

Project	FU[1)]	Energy use (MJ)	GWP (kg CO_2-eq)[2)]	Land use (ha)
Potatoes	t DM	1 232	217	0.03
Rice	t DM	1 170	203	0.15
Wheat	t DM	2 460	804	0.15
Beef	t carcass DW	27 410	15 920	2.35
Pork	t carcass DW	16 300	6 350	0.73
Sheep	t carcass DW	23 100	17 200	1.33
Cultured meat	t WW	32 710	1 794	0.02

[1)] FU, functional unit; DM, dry matter; DW, dead weight; WW, wash weight.
[2)] GWP, global warming potential.

Table 2 Nutritional values of the products (FSA 2002)

Project	Energy (kcal 100 g^{-1})	Protein (g 100 g^{-1})
Potatoes	74	3.5
Rice	338	7.1
Wheat	319	12.3
Beef	123	21.4
Pork	119	17.3
Sheep	151	20.1
Cultured meat	105	18.2

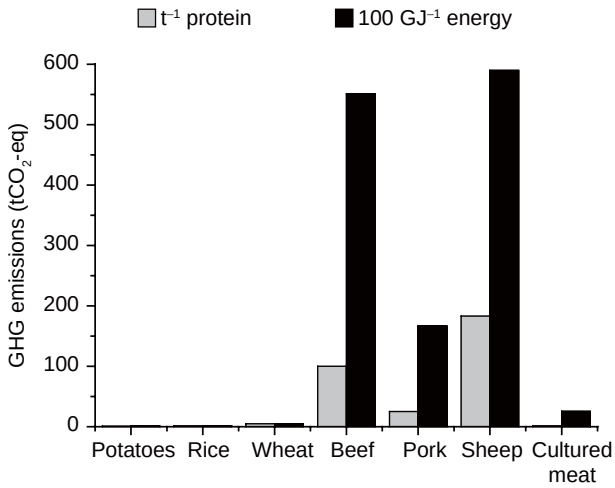

Fig. 1 Comparison of greenhouse gas (GHG) emissions of producing different food products allocated per ton of protein and 100 gigajoule (GJ) of food energy.

Currently the global livestock protein consumption is about 58.9 million tons $year^{-1}$. The production of that amount of wheat protein requires between 2.7 to 3.2 million km^2 of land area ranging from the highest yielding countries to the world average wheat yields. This equates to 12.0 or 6.9% of the total land area that is currently used for livestock produc-

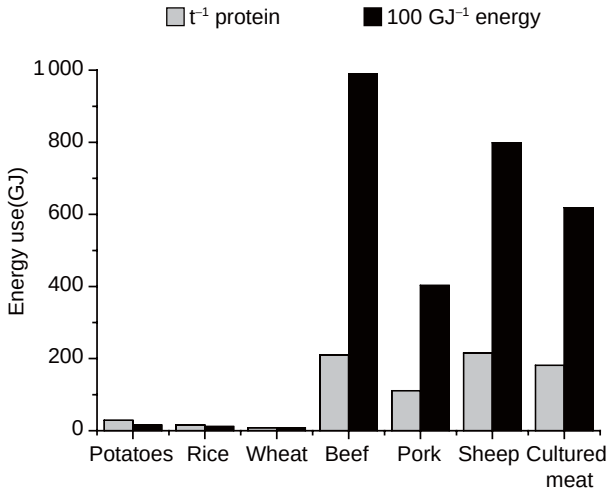

Fig. 2 Comparison of energy use of producing different food products allocated per ton of protein and 100 GJ of food energy.

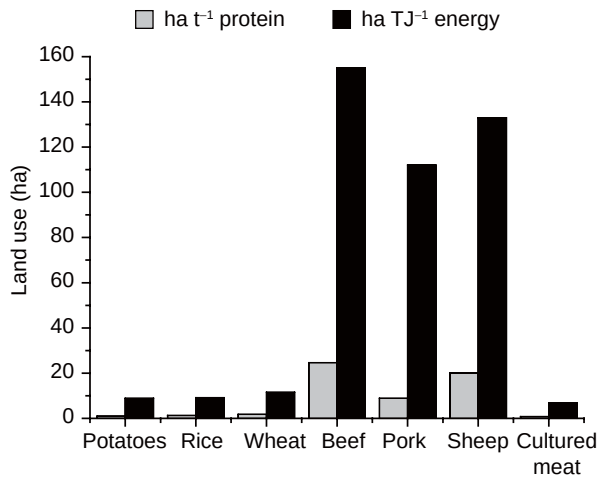

Fig. 3 Comparison of land use requirements (ha) for producing different food products allocated per ton of protein and terajoule (TJ) of food energy.

tion and 61 or 43.5% of the arable land that is currently used for livestock feed production. Replacing livestock protein with *in vitro* technology would require only 0.07 million km^2 land which is about 0.2% of the current land area that is used for livestock production.

In China, the replacement of conventionally produced meat by cultured meat would require only 1.1% of the land area that is currently used for production of meat. Energy requirement would be about 7% higher and GHG emissions 85% lower compared to the current GHG emissions related to the meat production in China. So the cultured meat in China could potentially contribute toward mitigating GHG emissions because, instead of clearing more land for agriculture, large land areas could be reforested or used for other carbon sequestration purposes.

5. Conclusion and prospects

In light of concerns about environmental degradation in China and the country's growth in population, accompanied by increased consumption of livestock products, replacing meat with cultured meat would substantially reduce GHG emissions and the demand for agricultural land. Even though the energy requirements for cultured meat are slightly higher than that of current pork production in China, the overall energy balance would be more beneficial if the opportunity costs of land use are taken into account (Tuomisto *et al.* 2009). However, large-scale replacement of conventional meat production by cultured meat production may have some negative impacts on rural biodiversity because of the reduction in need for grasslands and pastures (Weiss and Leip 2012). The overall value of the biodiversity impact would depend on the indicators used. The conversion of grasslands into forest may benefit some species, whereas others may suffer. This study did not take into account the additional impacts that may occur if the by-products of meat production, such as leather and wool, need to be produced separately.

A change in food consumption habits toward vegetarian diets and replacement of livestock products with alternatives would also provide health benefits because the consumption of saturated fat would be potentially reduced (Marcu *et al.* 2014). In cultured meat technology, the quality of fatty acids has the potential to be controlled and only beneficial fatty acids could be used (Hopkins and Dacey 2008). More research efforts are needed to develop cultured meat technologies and other alternatives for meat. Alongside the research and development of large-scale production of cultured meat in China, efforts to increase public acceptance of cultured meat are required. If the structure and taste can be developed to resemble conventionally produced meat, the main obstacle may be an intuitive aversion to unnatural foods. However, cultured meat consists of similar muscle tissue to conventionally produced meat, and only the production technique differs. It can also be argued that many current meat production systems are far from natural systems.

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REVIEW

In vitro meat production: Challenges and benefits over conventional meat production

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Abstract

In vitro meat production system is the production of meat outside the food animals by culturing the stem cells derived from farm animals inside the bioreactor by using advanced tissue engineering techniques. Besides winning the favour of animal rights activists for its humane production of meat, *in vitro* meat production system also circumvents many of the issues associated with conventional meat production systems, like excessively brutal slaughter of food animals, nutrition-related diseases, foodborne illnesses, resource use, antibiotic-resistant pathogen strains, and massive emissions of methane that contribute to global warming. As the conditions in an *in vitro* meat production system are controlled and manipulatable, it will be feasible to produce designer, chemically safe and disease-free meat on sustainable basis. However, many challenges are to be faced before cultured meat becomes commercially feasible. Although, the production cost and the public acceptance are of paramount importance, huge funds are desperately required for further research in the field.

Keywords: *in vitro* meat, history, advantages, techniques, problems

1. Introduction

In vitro meat production involves culturing of stem cells outside the food animal from which it is derived. Culturing involves the extraction of cells from the farm animal and transferring them into a suitable medium that contains nutrients, energy sources, growth factors, etc., required for the growth and differentiation of the stem cells into mature muscle cells within a bioreactor. Cell (or tissue) culturing may be performed for the production of edible animal muscle, better known as meat, that requires the proliferation of a small amount of muscle cells to a large muscle cell mass or tissue.

The techniques required to produce *in vitro* meat are not beyond imagination and the basic methodology of an *in vitro* meat production system involves culturing muscle tissue in a liquid medium on a large scale. By culturing loose myosatellite cells on a substrate, it is probably possible to produce cultured meat by harvesting mature muscle cells after differentiation and processing them into various meat products (Bhat and Bhat 2011b). Thus, a radically new way of obtaining meat, namely animal-free meat, is probably feasible with the newly proposed *in vitro* meat production.

Due to the costs involved in the research and experimentation, cultured meat is having a slow start. At its current stage, *in vitro* meat may cost up to $50 000 per pound to produce and must be grown in such miniscule samples that one sausage could require tissues from 3 000 separate Petri

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dishes (Bartholet 2011). Even with the difficulties of progress so far, many scientists have great hopes and determination in regards to *in vitro* meat production and hypothesize that *in vitro* meat may soon have the ability to become a universal medium and envision a world where, instead of mega farms across the country, there is a local meat laboratory on each block (Kaplan 2012). Thus, *in vitro* meat production is the inescapable future of humanity; however, the extremely high prohibitive cost of the biofabricated meat is the main potential obstacle, although large-scale production and market penetration are usually associated with a dramatic price reduction (Bhat and Bhat 2011a).

2. History of *in vitro* meat

The idea of *in vitro* meat for human consumption was written long back by Winston Churchill in essay 'Fifty Years Hence' later published in book *Thoughts and Adventures* in 1932. He declared that "Fifty years hence we shall escape the absurdity of growing a whole chicken in order to eat the breast or wing by growing these parts separately under a suitable medium". Although, the idea of *in vitro* meat was predicted two years earlier by a writer and conservative politician Frederick Edwin Smith, 1st Earl of Birkenhead, who predicted that "It will no longer be necessary to go to the extravagant length of rearing a bullock in order to eat its steak. From one 'parent' steak of choice tenderness, it will be possible to grow as large and as juicy a steak as can be desired" (Ford 2010).

In 1943, a French science fiction author Rene Barjavel described *in vitro* production of meat in restaurants in his novel '*Ravage*' in 1943 later translated as '*Ashes, Ashes'* in 1967.

Alexis Carrel managed to keep a piece of embryonic chick heart muscle alive and beating in a Petri dish in 1912. The muscle tissue grew considerably.

Willem Van Eelen of the Netherlands independently had the idea of using tissue culture for the generation of *in vitro* meat in the early 1950s. It took until 1999 before van Eelen's theoretical idea was patented as the concept of stem cells and *in vitro* culture of cells was yet to emerge.

SymbioticA harvested muscle biopsies from frogs and kept these tissues alive and growing in culture dishes (Catts and Zurr 2002). Anticipating on the infection risk associated with serum-based media, other research initiatives have also achieved keeping muscle tissue alive in a fungal medium.

Benjaminson *et al.* (2002) cultured muscle tissue from the common goldfish (*Carassius auratus*) in Petri dishes aiming to explore the possibilities of culturing animal muscle protein for long term space flights or habituation of space stations. The cultured muscle explants, or biopsied muscle tissue, obtained in the study were washed, dipped in olive oil with spices, covered in breadcrumbs and fried. A test-panel judged these processed explants and agreed that the product was acceptable as food (Benjaminson *et al.* 2002).

In 2013, the world's first *in vitro* meat based burger was cooked and tasted by a sensory panel in Riverside Studios in London. The burger contained five-ounce burger patty produced by using laboratory grown beef worth more than $330 000. It took only three months to grow the beef in the laboratory, using stem cells harvested from a cow's shoulder. The cultured meat produced was reported to be colourless and more like chicken. So a bit of red beet juice and saffron was added to colour the meat. The sensory panel comprised of Mark Post, the scientist who created the cultured meat in his laboratory at Maastricht University in the Netherlands, Josh Schonwald, the American author of "The Taste of Tomorrow", and Hanni Rützler, an Austrian nutritional scientist. The panellists said that the burger tasted, "almost" like a conventional one. No one spat the meat out; no one cringed. The professor Mark Post said that he would expect to see cultured meats in supermarkets in 10 to 20 years. At first, according to experts, it might be a luxury item, maybe in the form of such exotic treats as snow leopard burgers or rhino sausages (Zaraska 2013).

3. Merits of *in vitro* meat production

Nutrition-related diseases, foodborne illnesses, antibiotic-resistant pathogen strains, use of resources and farm animals, environmental repercussions of raising livestock, including pollution from their excrement and massive emissions of methane contributing to global warming are some of the serious consequences associated with conventional meat production systems and consumers have expressed growing concern over them (Bhat and Bhat 2011a, b, c; Bhat *et al.* 2013).

In the light of the sizable negative effects of current meat production on environment and human health, a viable solution lies with *in vitro* meat production, a process that poses to revolutionize human existence. *In vitro* meat production is one of the ideas that are being proposed to mitigate these ill effects associated with current meat production systems. The production of *in vitro* meat may offer health and environmental advantages by reducing environmental pollution and water and land use associated with current meat production systems (Bhat and Bhat 2011a, b, c). Thus *in vitro* meat production systems hold great environmental promise. Besides reducing the environmental hazards, it will also reduce animal suffering significantly and will ensure sustainable production of designer, chemically safe and disease-free meat as the conditions in an *in vitro* meat production system are controlled and manipulatable (Bhat and Bhat 2011a, b).

Besides satisfying all the nutritional and hedonic requirements of meat eaters, *in vitro* meat has the potential to greatly reduce animal suffering and make eating animals unnecessary (Hopkins and Dacey 2008). It is potentially a much more reliable alternative as a product from a bioreactor does not come with all the vicissitudes of animals and is not bound to soil or place and opens up possibilities for new places of production or for alternative land use. Furthermore, due to illness, stress and uneven growth, animals are notoriously unreliable as a raw material for meat production from a commercial perspective (Bhat and Bhat 2011a, b).

3.1. Functional and designer meat

In comparison to the conventional meat, *in vitro* meat can be engineered to be healthier and functional by manipulating the composition of the culture medium, the fat content and fatty acid composition of the cultured meat. Fat content can also be controlled by supplementation of fats after production and the ratio of saturated to poly-unsaturated fatty acids could be better controlled. Harmful saturated fats could be replaced by healthy fats, like omega-3. Moreover, health aspects of the meat can be enhanced by adding factors to the culture medium which might have an advantageous effect on the health, like certain types of vitamins (Van Eelen *et al.* 1999).

3.2. Animal welfare

Hailed by animal activists and meat experts alike as "victimless meat", *in vitro* meat bypasses the moral ramifications of standard meat production, avoiding animal death entirely by typically removing cells from the donor animal *via* biopsy and cultivating cells in medium containing mushroom extract rather than animal blood serum (Hopkins and Dacey 2008; Alexander 2011). Thus *in vitro* meat production system will reduce the use of animals and theoretically, a single farm animal may be used to produce the world's meat supply (Bhat and Bhat 2011a, b). If ten stem cells divide and differentiate continually for two months, they could yield 50 000 metric tons of meat (Bartholet 2011). Culturing embryonic stem cells would be ideal for this purpose since these cells have an almost infinite self-renewal capacity. In theory, one such cell line would be sufficient to literally feed the world (Bartholet 2011).

3.3. Reduction in zoonotic and foodborne diseases

Due to strict quality control rules, such as Good Manufacturing Practices, the incidence of foodborne diseases could be significantly reduced as the chance of meat contamination would be lower in absence of a potentially compromised organism. In addition, the risks of exposure to other hazards associated with conventional meat production systems like pesticides, arsenic, dioxins, and hormones could be significantly reduced.

3.4. Quick production

The current meat production systems are inefficient in terms of nutrient and energy utilization and also take long conversion time with months for chickens, and years for pigs and cows before the meat can be harvested and commercially available. *In vitro* system takes significantly lower time to culture the meat and takes several weeks instead of months (for chickens) or years (for pigs and cows) before the meat can be harvested. As the time for which the tissue has to be maintained is much less, the amount of energy and labour required per kg of *in vitro* cultured meat is much lower.

3.5. Reduction in resource use and ecological foot print

The *in vitro* meat production system is more environmental friendly and energy efficient than conventional factory farming. It will reduce the carbon footprint of meat products and further energy requirements will also be reduced as unlike traditional meat where 75–95% of the feed given to an animal is lost because of metabolism and inedible structures like skeleton or neurological tissue, all the energy and nutrients will be utilized in the production of lean meat only (Madrigal 2008; Alexander 2011; Bhat and Bhat 2011a, b).

Bioreactors for *in vitro* meat production do not need extra space and could be stacked up in a fabric hall. Thus in comparison to the conventional cattle farming; *in vitro* meat production system would reduce the amount of land used to produce meat because *in vitro* meat facilities could be built vertically, taking up less ground space and thus producers could place production centres in or near cities close to city-dwelling consumers which will additionally reduce the transportation costs involved (Kuang 2008; Datar and Betti 2010).

According to some researchers, *in vitro* meat production systems could reduce greenhouse gas emissions from raising livestock by as much as 90% and reduce use of land and water resources for raising meat by up to 80% (Fox 2009; Schneider 2013). Tuomisto and de Mattos (2011) estimated that *in vitro* meat involves 7–45% less energy than conventionally produced meat, 78–96% lower emissions of greenhouse gases, 99% lower land use, and 82–96% lower water use assuming that cyanobacteria can be used as the source of nutrients and energy. According to a study carried out at the University of Oxford regarding the environmental impacts of cultured meat, if scientists grew

the muscle cells in a culture of cyanobacteria hydrolysate, it would involve approximately 35–60% lower energy use, 80–95% lower greenhouse gas emissions and 98% lower land use compared to conventionally produced meat products in Europe (Bartholet 2011).

3.6. Efficient nutrient and energy conversion

In vitro meat production system will utilize the nutrients and energy required for growth and maintenance of muscle tissue only unlike conventional meat production where nutrients and energy is required for biological structures required for successful living, locomotion and reproduction. These include bones, respiratory system, digestive system, skin, and the nervous system. Thus the nutritional costs for *in vitro* cultured meat will be significantly lower than for traditionally cultured meat, however, the financial advantages are yet unclear and it might very well be that the decrease in costs of resources, labor, and land is compensated by the extra costs of a stricter hygiene regime, stricter control, computer management, etc. As projected by the first *In vitro* Meat Symposium in 2008 held in Aas, Norway, the first commercial *in vitro* meat products will be available in the next 5 to 10 years at prices competitive with European beef (~$5 200–$5 500 per ton or 3 300–3 500 euros) (Alexander 2011).

3.7. Public support

As *in vitro* meat production system would not involve the killing of the animals and has potentially profound environmental benefits; it will have a strong basis of support in the scientific, animal rights, and environmental communities (Hopkins and Dacey 2008; Schneider 2013).

3.8. Reforestation and wild life

The dramatic reduction in land use opens the prospect that much of this land may be used for other purposes or just returned to wilderness which may help in restoration of many endangered species.

3.9. Availability of exotic meat

As *in vitro* meat production system uses stem cells for the production of meat, in theory, cells from captive rare or endangered animals or even cells from samples of extinct animals could be used to produce exotic meats in bioreactors. Thus exotic meats could be produced commercially without any threat to the existence of the species. Conventional global trade of meats from rare and endangered animals has reduced wild populations of many species in many countries.

3.10. Vegan meat

In vitro meat being free from all the vicissitudes of animals may be suitable for people who are vegetarians due to the ethical reasons.

3.11. Space missions and settlements

For current space missions, supply and physiochemical regeneration (of water and oxygen) are the most cost-effective, but for longer periods and permanent bases, bioregeneration becomes more attractive (Drysdale *et al.* 2003). A controlled ecological life support system (celss) would not only provide fresh food to the astronauts, but also deal with waste, and provide oxygen and water (Saha and Trumbo 1996; Benjaminson *et al.* 1998; Drysdale *et al.* 2003). There are other situations also, like stations in Polar Regions, troop encampments in isolated theaters of war and bunkers designed for long-term survival of personnel following a nuclear or biological attack, in which it is more economical to produce food *in situ*.

3.12. Alternate protein source

Increasing demand for other protein sources also support the production of *in vitro* meat which is, unlike the other products, animal-derived and with respect to composition most like meat. Other reasons to produce *in vitro* meat would be consumer demand as more and more people are interested in newly proposed meat. Further, due to the non-sustainability of traditional meat production, there is a huge market for the *in vitro* meat. Other factors like prevention of food scarcity that can be expected with an increasing world population also favour the *in vitro* meat.

4. Techniques of production

Using a variety of techniques, varying from that which use scaffolds to those which rely on self-organization, meat is already cultured on small and early scales (Edelman *et al.* 2005). However, the production of highly-structured, unprocessed meat faces considerably greater technical challenges and a great deal of research is still needed to establish a sustainable *in vitro* meat culturing system on an industrial scale (Bhat and Bhat 2011a). The different design approaches for an *in vitro* meat production system, all of which are designed to overcome the diffusion barrier, range from those currently in use (scaffold/cell culture based and self-organizing/tissue culture based) to the more speculative possibilities (organ printing, biophotonics, nanotechnology) (Bhat and Bhat 2011a, b).

4.1. Scaffolding techniques

A scaffold based *in vitro* meat production system would involve isolation of embryonic myoblasts or adult skeletal muscle satellite cells from the farm animals like cattle, sheep, pig, etc., which would be allowed to grow inside a stationary or rotating bioreactor using a plant origin growth medium. These cells would divide and redivide for weeks and months together and would be finally differentiated into the muscle fibers onto a scaffold inside the bioreactor. Attached to a scaffold or carrier such as a collagen meshwork or microcarrier beads, stem cells fuse into myotubes, which can then differentiate into myofibers by introducing a variety of environmental cues (Kosnik *et al.* 2003). The resulting myofibers may then be harvested, processed, cooked, and consumed as emulsion or ground meat products (Fig. 1).

These scaffold-based techniques cannot produce highly structured meats like steaks but can be used to produce ground and boneless meats with soft consistency. However, cells can also be grown in substrates that allow for the development of "self-organizing constructs" that produce more rigid structures.

Currently there are two detailed proposals which use cell culture for production of meat (Boland *et al.* 2003; Zandonella 2003) and both these proposals are similar in nature and neither of the two has been tested (Bhat and Bhat 2011a). These proposals are written by Willem Van Eelen who also holds a worldwide patent for this system (Van Eelen *et al.* 1999) and Vladimir Mironov who has written the proposal for the NASA (National Aeronautics and Space Administration) (Wolfson 2002). Vladimir Mironov's proposal uses a bioreactor in which cells are grown together with collagen spheres to provide a substrate onto which the myoblasts can attach and differentiate whereas Van Eelen's proposal uses a collagen meshwork and the culture medium is refreshed from time to time or percolated through the meshwork (Bhat and Bhat 2011a, b).

4.2. Self-organizing techniques

Another potential method of creating *in vitro* meat utilizes explanted animal muscle tissue, a more ambitious approach to produce highly structured meats creating structured muscle tissue as self-organizing constructs (Dennis and Kosnik 2000) or proliferating existing muscle tissue *in vitro*, like Benjaminson *et al.* (2002) who cultured goldfish (*Carassius auratus*) muscle explants. Benjaminson *et al.* sought to test if cocultures of cells derived from similar "adult muscle tissue" can adhere, attach and grow onto a muscle tissue explants "substrate". They took slices of goldfish tissue, minced and centrifuged them to form pellets, placed them in Petri dishes in a nutrient medium and grew them for 7 days. They utilized mature skeletal muscle explants because they contain muscle fibers as well as "all the cell types generally associated with muscle *in vivo*" (Benjaminson *et al.* 2002). Benjaminson tested a variety of growth media, such as fetal bovine serum, fish meal extract, and various mushroom extracts, to see how each enhanced the growth of the explant muscle tissue and to seek alternatives to fetal bovine serum. Out of 48 cultures grown, 81% showed tissue adherence to the culture vessel after 2 weeks in culture, 63% demonstrated the self-healing phenomenon, and 74% of the cultures showed cell proliferation. The explanted tissue grew nearly 14% when using fetal bovine serum as the nutrient medium and over 13% when using Maitake mushroom extract. When the explants were placed in a culture containing dissociated *Carassius* skeletal muscle cells, explant surface area grew a surprising 79% in a week's time. The explants and their newly grown tissue looked like fresh fish filets which were marinated in olive oil and garlic and deep-fat fried and presented to a sensory panel for observation who reported that the it looked and smelled good enough to eat (Benjaminson *et al.* 2002; Britt 2002; Sample 2002; Hukill 2006).

Self-organizing *in vitro* meat production may hold the promise to produce the highly structured meats as the explants contain all the tissues which make up meat in the right proportions and closely mimics *in vivo* situation, however, lack of blood circulation in these explants makes substantial growth impossible, as cells become necrotic if separated for long periods by more than 0.5 mm from a nutrient supply (Dennis and Kosnik 2000). Vladimir Mironov suggested a branching network of edible porous polymer through which nutrients could be perfused and myoblasts and other cell types can attach (Wolfson 2002). Such a design using the artificial capillaries for the purpose of tissue-engineering has already been proposed (Zandonella 2003).

4.3. Contamination risks

Although, *in vitro* meat production systems are considered to be sustainable and safer in comparison to the conventional meat production systems but it may have a completely different risk profile and much attention would require to be paid to the safety of added substrates and other compounds of the culture medium. As it will be easier to keep control of pathogenic contamination in cultured meat production (Welin 2013), *in vitro* meat is associated with more risks of contamination of substrates and fewer risks with respect to microbial contamination.

5. Drawbacks and dangers

Although, *in vitro* meat is highly advocated by many people for its potential environmental and climatic benefits and also

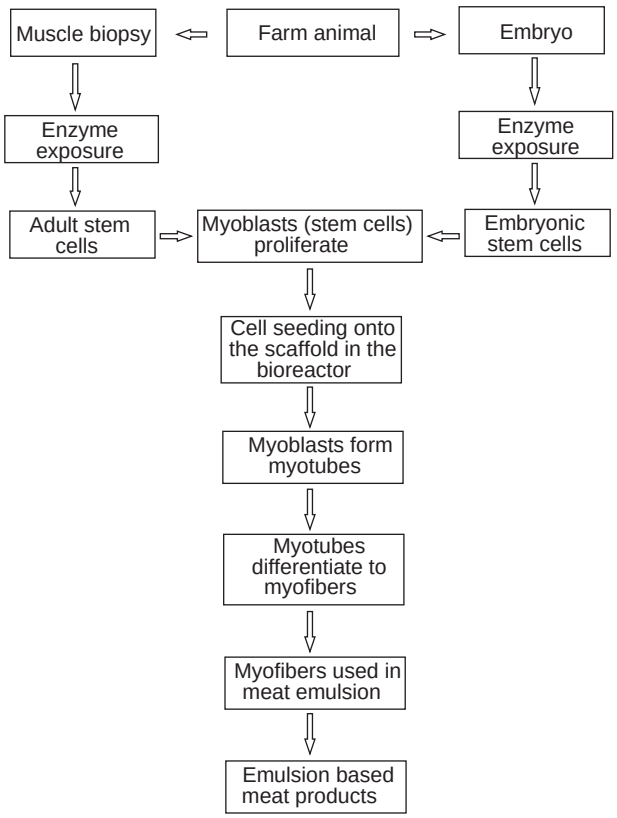

Fig. 1 Scaffold-based *in vitro* meat production.

favoured by animal ethics activists but simultaneously it has also generated doubts and criticism (Welin 2013).

5.1. Sensorial characteristics

The colour and appearance of the *in vitro* meat may have some difficulties in competing with the conventional meat. The cultured meat produced and tasted by a sensory panel in Riverside Studios in London in 2013 was reported to be colourless. The colour of the meat was improved by adding a bit of red beet juice and saffron (Zaraska 2013). Thus new meat processing technologies have to be developed to enhance the appearance and flavour of the developed *in vitro* meat products. *In vitro* meat produced initially included yolk-like blobs of self-assembling muscle fibers and tissue monolayers harvested from scaffolds for preparation of communited meat products. However, many innovations are being attempted by using tissue engineering techniques to produce more appealing meat products by using scaffolds seeded with muscle cells that can firm up the resulting meat. Scaffolds developed by using natural and edible biomaterials like collagen that allow for 3-D tissue culture and complex structuring of meat have also been proposed and attempted (Hopkins and Dacey 2008).

5.2. Alienation to nature

Another problem with the *in vitro* meat production system is that it may alienate us from nature and animals and can be a step in our retreat from nature to live in cities. Cultured meat fits in with an increasing dependence on technology, and the worry is that this comes with an ever greater estrangement from nature (Welin 2013). In the absence of livestock based farming, fewer areas of land will be affected by human activities which is good for nature but it may at the same time alienate us from nature.

5.3. Cost of production and economic disturbances

The extremely high prohibitive cost of the cultured meat is the main potential obstacle, although large-scale production and market penetration are usually associated with a dramatic price reduction (Bhat and Bhat 2011b). *In vitro* meat production on an industrial scale is feasible only when a relatively cost effective process creating a product qualitatively competitive with existing meat products is established and provided with governmental subsidization like that provided to other agribusinesses (Bhat and Bhat 2011b).

The *in vitro* meat production will certainly affect the economies of those nations which are involved in the conventional meat production on a large scale and are dependent on the meat export to other countries. This technology will also affect the employment in the agricultural sector in countries with a large scale introduction of cultured meat production. Being close to the cities to curtail the transport cost, these production centres will reduce the environmental pollution but perhaps it will not be so good for countryside.

5.4. Social acceptance

Unnaturalness of cultured meat is being perceived as one of the strongest barriers for public acceptance (Welin 2013). Potential consumers worry about the unnatural character of *in vitro* meat, however, as Hopkins and Dacey state, “Just because something is natural, does not mean it is good for you” (Hopkins and Dacey 2008; Schneider 2013). Ideas of unnaturalness seem, however, to play a large part in much resistance at least in Europe to new food technologies. Whether or not a good argument can be made for the unnaturalness of cultured meat one has to take such perceptions seriously (Schneider 2013).

Further, people may feel *in vitro* meat as artificial meat and not the real thing and as such they depreciate the value of the meat in the same way they would look down on artificial flowers or synthetic diamonds (Hopkins and Dacey 2008).

Many people who are against the concept of *in vitro* meat

production worry that this technology could result in victimless cannibalism by its ability to culture human muscle tissue (Mcilroy 2006; Peterson 2006; Hopkins and Dacey 2008).

People pay attention to the reaction of disgust in trying to judge whether a new, and especially biotechnological, process is morally permissible and whether it should be legally permissible (Kass 1997; Hopkins and Dacey 2008).

Another objection that is already familiar from critiques of ethical vegetarianism is that animals' lives will go better, paradoxically, in a world with something like the present meat industry, than in a world with universal or widespread vegetarianism. Further argument is that *in vitro* meat shall use original cells gathered from some animal in a morally suspect way and that the use of such cells will morally taint all future generations of tissue (Hawthorne 2005; Hopkins and Dacey 2008).

6. Conclusion

Conventional meat production systems require a relatively high proportion of land, energy, and water besides contributing to the emission of greenhouse gases significantly and in many countries to the pollution of water and soil. Nutrition-related diseases, foodborne illnesses, development of antibiotic-resistant pathogen strains, and animal welfare issues are the other factors that are associated with the current meat production. Global meat consumption is expected to double with 50% increase in the global population during the next 40 years and if no actions are taken, it will be accompanied with an almost doubling of the greenhouse gas emissions and aggravating the environmental repercussions of raising livestock. Production of *in vitro* meat by culturing muscle cells of farm animal species seems to be one of the prospective solutions. Besides reducing the use of animals, it may combine a favourable ecological footprint with similar nutritional values and sensory qualities as that of the conventional meat. Thus *in vitro* meat production system holds great promises as an alternative to conventional meat production systems, provided consumer resistance can be overcome. However, more developments need to be made in this area and a great body of research has to be performed with respect to the cost effectiveness of the technology, and ethical and societal issues before effective large-scale production can be achieved.

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REVIEW

A case for systemic environmental analysis of cultured meat

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Abstract

The environmental implications of cultured meat are profound. An anticipatory life cycle assessment of cultured meat published in 2011 suggested it could have a smaller impact than agricultural meat in all categories except energy consumption. As with most technologies, cultured meat will almost certainly be accompanied by unintended consequences as well as unforeseen costs and benefits that accrue disproportionately to different stakeholders. Uncertainty associated with new engineered products cannot be completely eliminated prior to introduction, but ongoing environmental assessments of the technologies as they advance can serve to reduce unforeseen risks. Given the pace at which tissue engineering is advancing, systemic assessments of the technology will be pivotal in mitigating unintended environmental consequences.

Keywords: cultured meat, *in vitro* meat, factory-grown food, anticipatory life cycle assessment, systemic environmental implications of emerging technologies

1. Introduction

On August 5, 2013, a hamburger made from cultured, or *in vitro*, meat was tasted at a well-publicized event in London (Maastricht University 2013b). This hamburger was not grown in an animal, but rather from bovine skeletal muscle stem cells in Dr. Mark Post's laboratory at Maastricht University, the Netherlands. The event may foreshadow a day when traditional livestock production has given way to large-scale growth of meat in factories, or carneries. Dr. Post has suggested that commercialization of cultured meat could be ten to twenty years away (Maastricht University 2013a), and engineering of edible muscle and fat tissue is the subject of perhaps thirty research programs around the world (Flynn 2012), two issued US patents (Vein 2004; Van Eelen 2007), and at least two additional patent applications (Challakere 2009; Forgacs *et al.* 2013). Thus large-scale production may be on the horizon.

As with most technologies, cultured meat will almost certainly be accompanied by unintended consequences as well as unforeseen costs and benefits that accrue disproportionately to different stakeholders. Uncertainty associated with new engineered products cannot be completely eliminated prior to introduction, but ongoing environmental assessments of the technologies as they advance can serve to reduce unforeseen risks. Further, in some cases, optimistic assumptions about a technology could exacerbate undesirable trends. For example, a perception that cultured meat is healthier than agricultural meat could lead individuals to over-consume fat and protein at the expense of a healthy and balanced diet. Given the pace at which tissue engineering is advancing, ongoing cautious and systemic assessments of the technology will be pivotal in mitigating unintended environmental consequences.

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2. Cultured meat

Meat consists primarily of skeletal muscle and fat tissue in varying proportions. Emerging engineering techniques have enabled the growth of these tissues *in vitro*, as opposed to the traditional *in vivo* process which requires the raising and slaughtering of a whole animal. A number of *in vitro* cultivation methods have been proposed, but perhaps the most promising (Bhat and Bhat 2011) begins by extracting adult stem cells from a donor animal tissue sample (the animal remains otherwise unharmed). These stem cells are then submerged in a culture medium that enables the cells to divide and increase in biomass. Once a growth cycle is complete, the cells may be separated from the broth for further processing and packaging.

Cultured meat is expected to have a number of advantages over traditional meat. In addition to a potential reduction in the environmental impact of meat production (Siegelbaum 2008; Tuomisto and de Mattos 2011), the culturing process could enhance human health *via* management of harmful contents such as saturated fats and pathogens (Siegelbaum 2008). It has also been suggested that cultured meat could alleviate ethical concerns associated with industrial livestock operations (Bartholet 2011) and address global hunger issues (Tuomisto and Roy 2012). However, large-scale production and widespread replacement of agricultural meat with *in vitro* meat (IVM) still depends on a number of factors. Even though Dr. Post believes that the process could be scaled up for commercial meat production in perhaps 10–20 years (Maastricht University 2013a), he has also stated that challenges still exist in terms of ensuring quality and safety of the final products (Post 2012). One of these is the need to develop and optimize synthetic (animal-free) nutrient growth media. Another is the need to design production facilities that ensure all cells receive sufficient nutrients and oxygen (cells will die if they are more than 0.5 mm from a nutrient supply for a significant period of time (Bhat and Bhat 2011)). Carneries must also promote cell exercise in order to impart a familiar and acceptable texture. Absent exercise, meat grown *in vitro* could be perceived by consumers as “weak and textureless” (Jones 2010). Consumer acceptance constitutes an additional hurdle as cultured meat sometimes elicits a “yuck” response from individuals first introduced to the concept (van der Weele and Driessen 2013).

Despite its uncertain future, cultured meat has profound environmental, economic, cultural, and institutional implications for the planet as a whole. It is because of these implications that critical assessments and conversations about the technology should proceed. It is in this spirit that we continue the discussion surrounding cultured meat and its potential environmental implications.

3. Anticipatory life cycle analysis

In July, 2011, a life cycle analysis (LCA) was published comparing cultured meat to conventionally-produced meat (Tuomisto and de Mattos 2011). It acknowledged significant uncertainty, but found that, “In comparison to conventionally produced European meat, cultured meat involves approximately 7–45% lower energy use (only poultry has lower energy use), 78–96% lower greenhouse gas (GHG) emissions, 99% lower land use, and 82–96% lower water use depending on the product compared” (Tuomisto and de Mattos 2011). These results have been cited extensively, and it is now commonly believed that cultured meat will be an environmentally-friendly alternative to livestock rearing. While there is nothing wrong with the results and subsequent acceptance, for a number of reasons discussed below, it would premature to consider the environmental discussion closed.

The Tuomisto and de Mattos (2011) life cycle analysis was a significant contribution to both the cultured meat and life cycle literature; however, it was anticipatory in nature: One of the most common challenges facing LCAs of emerging technologies is the availability of a working commercial-scale process on which to base the life cycle inventory (the “recipe” for production). As a result, it is less accurate to think of anticipatory LCA results as predictions than as scenarios that could be realized as the technology advances. In this way, anticipatory LCAs can provide insight into the environmental implications of new products, but they should not be interpreted as conclusive or definitive. In addition, whereas this LCA was based on a hypothetical model of cultured meat production that might be reasonable given existing knowledge, the techniques that ultimately enable the large-scale production of cultured meat are likely to deviate significantly and perhaps fundamentally from those in use today. For example, genetic modification could result in cells that grow rapidly but require active cooling of the bioreactor, and thus additional energy. Moreover, the model will become less realistic the further into the future one looks. As depicted in Fig. 1, while path dependencies constrain evolution in the short-term, complex interactions between natural, human, and technological systems become compounded over time, rendering the far future much less predictable than the near future. This points to the need to revisit the environmental analysis on an ongoing basis as the technology advances and commercial plants are designed.

4. The need for a systemic environmental analysis

In addition to the ambiguities associated with new tech-

nologies, assumptions inherent in the LCA process may introduce further uncertainty into the reported results. For example, in the case of the Tuomisto and de Mattos (2011) study, the environmental impacts of cultured meat were compared to the edible meat as obtained from livestock. Specifically, that study assumed that all environmental impacts were associated with the relatively small portion of the animal considered to be edible by humans (see Table 1, row 1). However, other sources report larger edible portions of beef, pork, and poultry (see Table 1, rows 2–3) and varying this percentage has a significant influence on the computed environmental impacts of the products being compared. As shown in Fig. 2, assuming a larger edible livestock percentage serves to decrease the reported impacts of livestock production and suggests that cultured meat is less advantageous on a relative basis.

To complicate matters further, much of the inedible byproducts of animal slaughter are not thrown away, but rather sold for productive purposes, implying that at least some environmental impacts should be allocated to them. Marti *et al.* (2011) report that only about 14.1% of cows and 11% of hogs is lost through shrinkage or waste. The remaining byproducts are used in leather production, pet food, cosmetics, and pharmaceuticals among many other household and industrial products (Marti *et al.* 2011). For poultry, waste products from slaughter include offal (heads, feet, and intestines totaling about 17.5% of live weight), feathers (7% of live weight), and blood (3.5% of live weight) (Ockerman and Hansen 1999). All but the feathers can be dried and processed into byproduct meal suitable for animal feed (Ockerman and Hansen 1999). Feathers and down may be utilized for clothing, insulation, bedding, decorations, sporting equipment, feather meal, and fertilizer (Ockerman and Hansen 1999).

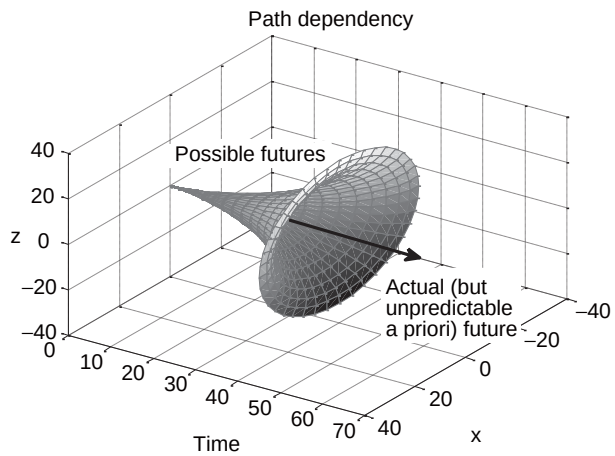

Fig. 1 Path dependency and unpredictability inherent in the evolution of complex systems over time. Source: Allenby B R (2012).

Were production of the primary source of meat byproducts to diminish, a number of scenarios might play out. One of these might be the continued raising of livestock specifically for commercial and industrial purposes—possibly inflating the cost of the final products in the process. Another scenario might be the use of synthetic substitutes for the byproducts. Such substitutes would have unforeseen but possibly significant environmental impacts or other unintended consequences of their own. For this reason, there is value in considering the holistic context in which the technology is emerging—not only to more accurately assess the potential environmental impacts, but the economic and practical downstream effects as well.

This suggests that a more extensive LCA framework is needed in order to better understand technological transitions at a system level, including the secondary effects associated with co-products. Approaches such as consequential LCA or attributional LCA using a displacement method for co-product allocation would constitute steps toward such a systemic analysis. These methods entail identification and quantification of products and primary byproducts, followed by a qualitative survey of their main uses and potential substitutes. LCAs or streamlined LCAs must then be performed to obtain environmental impacts of all products and substitutes to facilitate comparisons. In the case of leather, for example, the analysis would begin with LCAs of cattle rearing and slaughter. A portion of these impacts would be allocated to the hide which would in turn be added to the impacts determined by an LCA of tanning. In parallel, LCAs of fabric or plastic substitutes would be performed and, finally, the impacts associated with leather and its substitute products could be compared on a relatively equivalent basis. In aggregate, life cycle analyses of all products emanating from livestock and their substitutes would yield a more comprehensive environmental assessment of the potential technology transition from livestock production to cultured meat.

Even at first glance, this appears to be a significant undertaking. Moreover, simply compiling the preliminary

Table 1 Estimates of human-edible portions of livestock from various sources

Row	Description	Beef (%)	Pork (%)	Poultry (%)	Source
1	Edible wt as % of live weight	20	33	35	Tuomisto and de Mattos (2011)
2	Edible wt as % of live weight	40	53	60	Smil (2013)
3	Edible wt as % of live weight	43	56	56	(Pelletier 2008; Pelletier *et al.* 2010a, b)

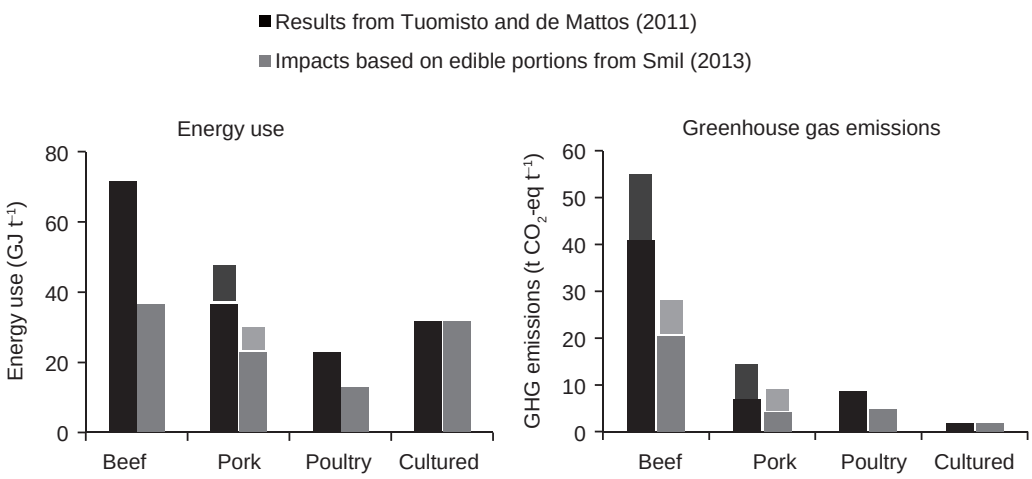

Fig. 2 Selected results reported by Tuomisto and de Mattos (2011) compared with the same results assuming larger edible livestock portions given by Smil (2013). Column extensions indicate a range of values given by the source.

inventory of livestock byproducts and substitutes may not be as straightforward as it seems: Designer Christien Meindertsma tracked a single pig from an industrial slaughterhouse in the Netherlands through sales of all of its component parts (Meindertsma 2010). She discovered that byproducts of pig slaughter find their way into a wide variety of everyday products including bread, concrete, human medical devices and therapies, renewable energy sources, and even bullets. Moreover, a preliminary compilation of cattle byproducts shown in Table 2 suggests a similarly diverse range of uses. Hence a reduction or elimination of livestock production could have surprising downstream effects including raising prices for vaccines and other therapeutic substances: According to Marti *et al.* (2011), “In many of these treatment uses, no other synthetic products function or perform equally well”. Hence, despite the required investment, a more comprehensive technology innovation network analysis could produce a more precise environmental comparison while highlighting areas for targeted innovation.

Thus far, proposed applications of tissue engineering have not been extended to animal commodities other than meat and hide. For this reason, still more complication arises when one considers that beef and milk production may be intricately linked. The above proposed analysis makes sense in the United States where the beef and dairy industries are largely separate (USDA 2012) and the dairy herd is only about 16% of the total cattle population (NASS 2014). In countries such as the Netherlands, however, the majority of beef originates in the dairy industry (PVE 2013) and may therefore be considered a byproduct of milk production. Such a situation underscores the need to take a systemic approach to environmental analysis and tailor the LCA approach to local or regional conditions.

5. Extension to global impacts

Even though ongoing analyses and dialogs will serve to better anticipate the relative impacts of producing 1 kg of meat by different methods, they nonetheless provide little assurance that the anticipated environmental shifts will be realized in aggregate at the global scale. On the one hand, even though cultured meat might produce 78–96% lower GHG emissions and require 82–96% lower water use (Tuomisto and de Mattos 2011), such significant gains would be limited in total because livestock account for only a small portion of global human activities. Steinfeld *et al.* (2006) estimate that livestock produce about 18% of global anthropogenic GHG emissions (measured in CO_2 equivalent) and demand roughly 8% of human water use (predominantly for irrigation of feed crops). Therefore even the most environmentally-friendly cultured meat production process could not reduce GHG emissions or water use more than 18 and 8%, respectively. However, given a scenario where global meat consumption rises, a transition away from livestock in favor of bioengineered meat could serve to limit net increases in these areas.

A similar situation exists for land use. Steinfeld *et al.* (2006) suggest that grazing and feed production for livestock require an estimated 70% of all agricultural land and 30% of total emerged land area (land not covered by water or ice). Even though a 99% reduction in land use would be relatively significant, a number of factors could prevent these areas from being converted to lower-carbon uses such as forest. The potential shift being described here is reminiscent of the United States in the early 20th century when horses and mules were replaced by tractors and automobiles. In 1913, 28% of all harvested land (37 million hectares) was devoted

Table 2 Preliminary inventory for beef production, byproducts of slaughter, and known substitutes

Product	Cattle yield (kg)[1)]	Primary uses	Known substitutes
Live weight	455		
Dressed carcass	273		
Retail cuts			
Byproducts	190	Human consumption	Cultured meat
Hide or pelt	36	Leather	Cultured leather, fabric, or plastic
Edible fats	50	Shortening and biodiesel	Cultured fat, fossil fuels
Variety meats	17	Pet food, animal feed, some is exported for human consumption[2)]	Cultured meat, fish byproducts, vegetables and grains
Blood	18		
Thrombin		Blood coagulation, skin graft procedures[2)]	To be investigated
Fibrin		Surgical repair of internal organs[2)]	To be investigated
Fibrinolysin		Wound-cleaning agent, minor burn treatment[2)]	To be investigated
Other	80		
Inedible fats		Soap	Vegetable sources
Bone		Therapeutic hormones, enzymes[2)]	Some substances may be produced by recombinant cells; others may not have ready substitutes[2)]
Glands & other tissues		Serums, vaccines, antigens, antitoxins, xenotransplants[2)]	
Unaccounted items (stomach contents, shrinkage, etc.)	64	N/A[3)]	N/A

[1)] Source: Ockerman and Hansen (1999).
[2)] Source: Marti *et al.* (2011).
[3)] N/A, not applicable.

to growing feed for horses and mules (USCB *et al.* 1997b). This area slowly diminished in the decades that followed, but total cropland did not begin to decline as a general trend until 1950 (USCB *et al.* 1997a). Thus, even though a transition to cultured meat could exceed the land use changes seen as tractors and automobiles replaced animals for work and transportation, afforestation or reforestation is not guaranteed. Other factors including gains in productivity, economic cycles, changes in agricultural trade, and increasing biofuel production would all play important roles in land use.

6. Conclusion

Cultured meat presents opportunities to enhance human well-being, reduce animal suffering, and mitigate at least some of the environmental impacts associated with food production. Moreover, for nations expected to increase per capita meat consumption, it represents a potential for increased food security and adequacy. However, those benefits will almost certainly be accompanied by numerous unintended and unanticipated consequences. To assume that a transition away from livestock production in favor of *in vitro* meat is already fully understood is to oversimplify the interdependent nature of technology, society, and the environment. Many of the implications are unforeseeable, but ongoing research could serve to better prepare stakeholders to anticipate and respond rapidly to its unintended consequences.

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REVIEW

What is artificial meat and what does it mean for the future of the meat industry?

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Abstract

The meat industry cannot respond to increases in demand by ever increasing resource use. The industry must find solutions to issues regarding animal welfare, health and sustainability and will have to do so in the face of competition from emerging non-traditional meat and protein products in an increasingly complex regulatory environment. These novel meat and protein products, otherwise known as 'artificial meat' are utilising ground breaking technologies designed to meet the issues facing the conventional meat industry. These artificial meats, *in vitro* or cultured meat and meat from genetically modified organisms have no real capacity to compete with conventional meat production in the present environment. However, meat replacements manufactured from plant proteins and mycoproteins are currently the biggest competitors and are gaining a small percentage of the market. Manufactured meats may push conventional meat into the premium end of the market, and supply the bulk, cheap end of the market if conventional meat products become more expensive and the palatability and versatility of manufactured meats improve. In time the technology for other artificial meats such as meat from genetic modified organisms or cultured meat may become sufficiently developed for these products to enter the market with no complexity of the competition between meat products. Conventional meat producers can assimilate agroecology ecology concepts in order to develop sustainable animal production systems. The conventional meat industry can also benefit from assimilating biotechnologies such as cloning and genetic modification technologies, using the technology to adapt to the changing environment and respond to the increasing competition from artificial meats. Although it will depend at least partly on the evolution of conventional meat production, the future of artificial meat produced from stem cells appears uncertain at this time.

Keywords: artificial meat, *in vitro* meat, meat industry, consumer satisfaction, sustainable production

1. Introduction

Since the appearance of agriculture meat production has gone through many different revolutions, the most recent being the industrial revolution of the 1800's. A population explosion and the sudden influx of new technologies changed the face of agriculture into what we see today (McCurry-Schmidt 2012). The increasing demands of the

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growing population were met with the industrialisation and intensification of farming, along with increasing amount of land farmed (McCurry-Schmidt 2012). Today, agriculture is once again facing a similar challenge of increasing population coupled with the advent of new technologies. However, the challenge presented before us now is arguably far more complex. With estimates of the global population reaching a plateau at 9 billion in the year 2050 (Anon 2004), the meat industry would need to increase production by approximately 50–73% to maintain per capita demand of the growing populations (FAO 2009; NIAA 2012).

Consumer demands are complex and multifactorial. Grunert *et al.* (2004) found that cost and a number of intrinsic quality and extrinsic quality factors influence the decision to purchase the product. Intrinsic factors relate directly to the product features including meat colour, fat content, marbling scores and sensory qualities. Extrinsic factors, in contrast, are much more subjective and include cost, brand, origin, production methods, healthiness, animal welfare, safety and sustainability (Grunert *et al.* 2004). Though concerns about extrinsic qualities may not result in an increase in demand for artificial meat products, Hocquette *et al*. (2015) found no relationship betwen concern about welfare and sustainability in the meat industry and acceptance of *in vitro* meat. Finally, once a consumer has made the decision to purchase a product, variable eating quality is the most important factor influencing repeat purchase (Polkinghorne *et al.* 2008).

Controversies surrounding meat production in regard to health, safety, welfare and sustainability highlights that the industry is struggling to meet changed demands of consumers (Vinnari *et al.* 2009). At the same time, it appears the current capacity of conventional meat production is reaching its limits. Projected meat production for the year 2050 would suffice for almost 8 billion people, falling short of projected population estimates by 1 billion (Gilland 2002). In response to the projected shortfall the meat industry, and the agricultural industry as a whole, must endeavour to utilise resources in the most effective manner in order to both fully supply the marketplace and to satisfy consumer's demands. One response by the conventional meat industry to these challenges is the development and implementation of agroecology, meaning to stimulate natural processes to reduce inputs, to reduce waste and to maximise efficiency (Dumont *et al.* 2013). Technologies, such as genetic modification and cloning are also being researched (Maga *et al.* 2010). Other products being researched and developed focussed on producing food external to the traditional meat industry, such as using mycoproteins and plant and insect based proteins as meat replacements and *in vitro* meat culturing techniques.

For the purposes of this review article, we will be considering artificial meat defined within three broad categories encompassing both real and hypothetical products (Table 1). The first, are meat substitutes manufactured from alternative protein sources, known as 'meat alternatives'. Commonly used alternative protein sources are plants and fungi (mycoproteins) (van der Spiegel 2013). The second is cultured meat, or *in vitro* meat, derived from tissue and cells grown in a laboratory setting rather than in a living organism (Post 2012). Genetically modified organisms can be considered as a third category of artificial meat. Despite the similarities with traditional meat production, animals that have had their genome artificially altered in the laboratory may be considered as artificial or man-made and are worthy in a discussion of artificial meats. Cloned animals are the fourth category of artificial meat. Meat from cloned animals could be considered a natural as it is simply a 'scientist assisted' form of producing identical offspring. However the cloning process is 'man made' and the clone is a copy of the 'parent' animal and thus the meat could be considered artificial.

This review will investigate how each of these broad categories of artificial meat have different advantages and limitations, and have a varied approach to 4 major issues facing the meat industry: sustainability, health and safety, welfare and market acceptability, both today and in the future.

Table 1 The different product categories of artificial meat

Types of artificial meat	Definition
Meat substitutes	Plant and myco-proteins used as meat alternatives, e.g., quorn, tofu
Cultured meat	Produced though the *in vitro* culture of tissues or cells (stem cells, myocytes)
Modified meat	Meat derived from genetically modified organisms

2. Sustainability

About 70% of all agricultural land is used for some aspect of livestock production. However, the exact environmental impact is controversial. Some authors estimate that livestock produce approximately 18% of all greenhouse gas emissions including 37% of all methane emissions mainly associated with ruminants (FAO 2009). However, other authors have delivered dramatically lower numbers (Pitesky *et al.* 2009) and there is yet to be general agreement. However as ruminant animals are the major sources of greenhouse gas emissions associated with meat production, any decrease in the total number of ruminant animals farmed for meat would better satisfy requirements for environmental sustainability. Artificial meat products may help to reduce the greenhouse gas emissions compared to conventional meat production; however a full lifecycle analysis will be

needed to confirm this.

In vitro meat recently received a large amount of publicity in August 2013 following the production and tasting of the world's first 'burger' made from stem cells grown in tissue culture medium (Goodwin and Shoulders 2013). In a superficial life cycle analysis, Tuomisto *et al.* (2011) calculated that, under specific production conditions, *in vitro* meat may reduce energy consumption and land usage by 99%, water usage by 90% and energy consumption by 40% when compared with conventional meat production. If realised, these reductions may lead to a large reduction in greenhouse gas emissions. However, it should be noted that the technology to produce *in vitro* meat on an industrial scale remains a theoretical evaluation at this stage to make any predicted reductions of greenhouse gas emissions. Furthermore, the development of such technology will be time-consuming and costly. If the goals of research and development programs are rapid and guaranteed reductions in greenhouse gas emissions then resources might be better invested in technologies which are closer to be ready for commercial application.

The majority of meat replacement products on the market today are made from alternative protein sources such as soy, wheat proteins or mycoprotein. Depending on the animal species and various other conditions, between 2 to 15 kg of plant material is needed to produce 1 kg of meat. In 2008, 40–50% of the global grain harvest was used for animal feed (Grigg 1995). Accordingly many studies suggest that the direct consumption of plant proteins would have lower total carbon emissions than one including meat. However livestock, particularly ruminants can consume waste products from cropping have the ability to thrive on land unsuitable for cropping, and thus be ideal for agroecological techniques.

Genetic modification is another tool that can be utilised to reduce the environmental impact associated with meat production. This tool appears best suited to the management of specific problems, for example, phosphorous digestion in pigs. The addition of a single enzyme, phytase, which is secreted in the saliva, can markedly reduce phosphorous concentrations in effluent, eliminating this particular environmental hazard. Enviropigs are awaiting approval by the Food and Drug Administration in the USA (Bruce *et al.* 2013). However attempts to progress efficiency in sheep by adding growth hormone genes with genetic modification technologies led to the development of sheep that were metabolically unstable and more prone to cardiac hypertrophy and metabolic diseases (Adams *et al.* 2006). At present, there are no genetically modified livestock approved for human consumption.

Animal cloning allows the industry to further disseminate valuable, naturally occurring genetics by increasing the number of individuals in a population with a particular genotype, increasing efficiency, therefore reducing carbon emissions (Petetin 2012). This amplification of favourable genetics can be utilised to enhance other techniques such as genetic modification or agroecology.

3. Health and safety

Foodborne pathogens such as *Salmonella*, *Campylobacter* and *Escherichia coli* are responsible for millions of episodes of illness each year in the USA. Though the most common source of food borne pathogens is fresh produce, 22% originate from meat products (http://www.cdc.gov). From an epidemiological point of view, it is evident that these pathogens and emerging diseases, such as avian and swine influenza, are associated with the intensity of livestock farming and other developments in the agricultural industry.

Avian and swine influenza are important public health considerations. Vaccinating animals against these diseases is costly and time-consuming, and difficult to achieve in some circumstances. Furthermore the scorched earth approach of slaughtering all exposed individuals is also becoming more and more unacceptable to the public. Poultry that have been genetically engineered to eliminate their susceptibility to avian influenza offer an alternative humane method of risk minimisation (McColl *et al.* 2013). These genetically modified birds are unlikely to become the dominant production animal, however they could provide valuable exclusion zones and create disease free boundaries slowing and restricting the transmission of avian influenza. They could also improve the safety and viability of combined pig/chicken production systems. Strains of pigs and poultry that are resistant to salmonella are also currently being developed (McColl *et al.* 2013). Livestock which provide significant public health benefits are more likely to be encouraged and subsidised by governments and regulating authorities than by consumer demand.

By contrast, cloning may heighten the risk of disease in intensive industries through a reduction in genetic diversity, and therefore a loss of the variation in susceptibility to pathogens that exists in genetically diverse groups. While there may be a slight increase in both communicable and individual disease risk, testing has yet to reveal any health problems related to food products from cloned animals (Petetin 2012).

The techniques for industrial *in vitro* meat production are yet to be developed and as such have the potential for both positive and negative consequences for public health and food safety. The highly controlled environment of the cell culture process may allow for improvements in health and safety, reducing the risk of food borne pathogens or contaminants. *In vitro* meat would also allow for a reduction

in close quarter human—animal interactions, reducing the risks of epidemic zoonosis' and emerging diseases (Datar *et al.* 2010). Sterile environments and antimicrobials could remove pathogens such as salmonella and *E. coli* from the production process (Datar *et al.* 2010). However, sterile environments are expensive, if not impossible to achieve on an industrial scale therefore the cultures would require chronic long term use of antimicrobials generating their own health and safety issues. Furthermore, some authors argue that the process of cell culture is never perfectly controlled and that some unexpected biological mechanisms could occur. For instance, epigenetic modifications could occur during the culture process with unknown potential effects on the muscle structure and possibly on human metabolism and health when it is consumed (Hocquette *et al.* 2014) .

4. Market acceptability

The different forms of artificial meat all inherently contain both barriers and advantages to commercial implementation that will affect the uptake of the technology (Table 2). Manufacturers and producers will only adopt new technologies and products if there is a potential of increasing turnover and profit. Products must have a capacity for mass production and be capable of supplying a significant proportion of the marketplace. Ideally products would be able to be produced with limited change to existing infrastructure, which acts to reduce set up costs and the initial risk for the industry. Consumers are also more likely to purchase a product that is similar to an existing product that they are familiar with. Therefore for a product to compete with conventional meat it should closely mimic or recreate the position conventional meat has in the minds of the consumers in terms of appearance nutrition, convenience and meal solutions (Verbeke *et al.* 2010).

Regulatory systems are among the most important influences in determining the course of technological innovation (Bruce *et al.* 2013). None-the-less they are still actively supporting conventional agriculture at a local level, including meat production. This support is tightly controlled and may be in the form of a quota system, or restricted to specific geographical regions with a low production capacity (Anon 2003). Meat substitutes based on plant proteins may be able to access this existing agriculture support

Table 2 The relative abilities of traditional meat production, types of artificial meats and alternative protein sources to meet the demands of the market place

		Traditional meat	Cultured meat	Manufactured meat (plant and mycoproteins)	Insect proteins	Modified meat (genetically modified and cloned organisms)
Sustainability	Resources used	High	Significantly reduced	Significantly reduced	Moderate reduction	Reduced, depending on the product
	Waste	High	Potentially reduced	Reduced	Reduced	High
	Greenhouse gas emissions	High	Potentially reduced	Reduced	Reduced	Reduced
Health		Unchanged	Potential improved fatty acid profile and reduced iron content Untested product	High in protein	High in protein and minerals	Improved fatty acid profile, improved vitamin and mineral content
Safety		Unchanged	Untested product	Reduction of food borne diseases Reduced cholesterol content	Safe with small scale production, untested with large scale production	Reduction or elimination of zoonotic disease
Market acceptability	Capacity for mass production	Yes, but reaching limitations	Marked technological barriers at present	Yes	Yes	Moderate technological barriers at present
	Need for further research	Moderate	High	Low	Moderate	Moderate
	Cost	Increasing	Very expensive	Cheap	Moderate	Expensive premium product
	Government regulation	Subsidies, but increasing regulation	Untested	Subsidies, standard regulation	Standard regulation	Severe restrictive regulation
Addresses welfare concerns		No	Yes	Yes	Yes	Moderate
Acceptability to consumers		Demand increasing	Neophobia and technophobia	Palatability problems	Neophobia	Technophobia

structure, but other artificial meats will have to compete with a subsidised product. Specific artificial meat products or producers may also receive encouragement and subsidies from government and regulating bodies if they can prove definitive reductions in greenhouse gas emission and other environmental benefits (Dagevos and Voordouw 2013). The support of government funds would greatly increase the likelihood of commercialisation of artificial meat technologies.

The largest challenge with the commercial uptake of genetically modified meat technology is licensing requirements. The European Union has reacted to genetically modified organisms with a de-facto ban (Carlarne 2007). The USA has not banned genetically modified animals from entering the food chain, but is yet to approve any such products for human consumption (Carlarne 2007; Bruce *et al.* 2013). The regulatory hurdles for genetically modified livestock are, at present, negatively affecting the likelihood of investment return. If the regulatory hurdles are overcome genetic modification techniques are arguably quite suited to conventional production techniques and infrastructure. While no major infrastructure investment is necessary for the farming of most of the currently feasible genetically modified livestock, once the new organism is developed, the major cost involved in this form of artificial meat production is the dissemination of the new desired genetic material within the population. Artificially produced sires and dams are an expensive initial cost and the transfer rate of the new genetics and, more importantly, phenotypes to future generations is still low (McColl *et al.* 2013).

Several artificial meats made from plant based proteins and mycoproteins are currently available in the marketplace. These meat substitutes hold a small market share, which is estimated at only 1–2% (Hoek *et al.* 2004). The most important barrier for these products is consumer acceptability. Consumers are familiar with these types of products and classify the products in similar categories as processed meat (Hoek *et al.* 2011b). This gives these products an advantage over completely novel products. However, there are several negative stigmas attached to plant based meat substitutes associated with taste and texture (Hoek *et al.* 2011a). As such these meat substitutes are not currently considered a real alternative for non-vegetarian consumers (Hoek *et al.* 2004, 2011b).

The cell culture approach for *in vitro* meat is in preliminary stages of development and the technology is at least 10–20 years away from being commercially available (Mattick *et al.* 2013). The realisation of this technology will require significant commitment and investments from both governments and industry. As an example, the first *in vitro* burger made for human consumption cost $335 000 USD to produce (Mattick *et al.* 2013). Furthermore, any *in vitro* meat enterprise would require the construction of an entirely new type of manufacturing facility with a number of untested technologies. This presents a significant risk for commercial organisations, however the vast majority of media coverage for *in vitro* meat has been positive, and consumers have expressed hypothetical interest in the product, were it to become available (Goodwin and Shoulders 2013).

Food products derived from cloned animals are considered safe for human consumption in the USA, while they are still banned in the European Union. The cloning process has been commercialised and is available through a number of different companies (Brooks *et al.* 2011), however, the process is still relatively expensive and has a lower success rate than other assisted reproductive technologies (Verzijden 2012). Agroecological techniques generally require minimal to no change to existing legislature and strive to decrease inputs through using waste products, and lowering costs for producers (Soussana *et al.* 2012). Certain types of agroecological methods will be difficult to implement as they may require a paradigm shift in the thought processes of producers and/or legislative change. These aspects are unlikely to see rapid uptake in the industry, particularly if a producer has to accept a decrease in efficiency and production with the promised decrease in costs.

5. Animal welfare

Consumers, particularly from developed countries, are concerned about the treatment of livestock (Latvala *et al.* 2012). Some are questioning not just the treatment of livestock but the ethical justification for the use of any animals in human food production (Croney *et al.* 2012). The different forms of artificial meat addresses this issue in different ways and thus may be preferred by consumers when they are presented with the opportunity to buy products that closely resemble traditional meat (Richardson *et al.* 1994), but without an association with animal welfare problems.

Plant- and fungal-based meat alternatives and *in vitro* meat both have the capacity to vastly reduce the numbers of animals required to meet global demands for meat/protein, thereby improving animal welfare by reducing the numbers of animals farmed (Croney *et al.* 2012). However, traditional meat production, especially from ruminants, functions best in an integrated agricultural system (Hou *et al.* 2008), which includes animals as an essential element in broader agricultural system. Moreover at present, all cultured meat techniques still require animal products such as the use of fetal calf serum as an essential component, and as such are unable to eliminate the use of animals entirely (Datar *et al.* 2010; Post 2012).

Eliminating livestock from food production is not the

only way to address animal welfare problems. Other options involve redesigning husbandry systems and employing conventional breeding technologies. The now commercialised 'polled gene marker' test for beef cattle, for example, has the potential to eliminate the need for dehorning (Mariasegaram *et al.* 2012; Francis 2013), a significant animal welfare issue, through the application of targeted breeding programs. Cloning is another technology that is used to increase the genetic improvement of agricultural animal species. However this particular technique may have some negative impacts on animal welfare. There are higher juvenile mortality rates and the cloning process itself is not perfect, with some progeny acquiring defects, such as large offspring syndrome as a direct result of the cloning procedure (Verzijden 2012).

The European Union focus however is to develop agroecology and industrial ecology concepts for animal production in the 21st century (Dumont *et al.* 2013). This entails the utilisation of species and breeds that have already been selected, over hundreds of years, to better suited their particular environment and production systems enabling the welfare of the animals to be improved through decreased stress and disease (Anon 2003).

6. The future of the meat industry

Conventional meat production is reaching the limits of its production capacity and any further increases in output will require new technologies and techniques (FAO 2009). Currently only conventional meat and certain types of meat replacement products are present in the market place (Fig. 1). In the future agroecology, cloning, and artificial meat may provide technologies and techniques which would allow the meat industry to meet the increasing consumer demands. However, it would be unrealistic to expect artificial meat to completely replace conventional meat (Hou *et al.* 2008) due to the complexity of the market place and the vast array of different consumer groups.

As climate change begins to have more and more influences on government policy (NIAA 2012), it is likely that the push for sustainable production methods may not come directly from the consumer, but through increasing government regulations. More and more regulatory bodies, including the European Union and the Food and Drug Administration in the USA, are passing legislation requiring companies to act in a more environmentally sustainable fashion (Anon 2003; Carlarne 2007). In the year 2012, the world's largest coal exporter, Australia, implemented a carbon tax (Head *et al.* 2014) and the Swiss government has even discussed a possible 'meat tax' as a result of concerns regarding the greenhouse gas emissions of livestock (Lerner *et al.* 2013). These types of legislations will make greenhouse gas emissions, resource usage and waste disposal more difficult and costly in the future. Regulatory systems are among the most important influences in determining the course of technological innovation (Bruce *et al.* 2013), but they can also be unpredictable, for example the carbon tax in Australia has been rescinded with the change in government in 2014. The changing regulatory environment will likely favour meat, artificial or not, and meat alternatives produced with lower greenhouse gas emissions and environmental impacts.

As the demand for meat increases, the resources available decrease and the regulatory environment becomes more complex conventional meat production is likely to incur greater costs, making meat more expensive (NIAA 2012). As the price of conventional meat increases the demand for cheap alternatives will also increase. The first products which are likely to generate strong competition for conventional meat are meat substitutes manufactured from plant or insect proteins. These products are the most attractive to manufactures and have the lowest barriers to commercialisation. They are likely to enter the market in the lower quality 'burger/sausage' sector where the division between 'real' and 'artificial' is already blurred for the consumer (Hoek *et al.* 2011b). This may push meat, particularly red meat, into the premium end of the market.

Cloning technology, genetically modified livestock and cultured *in vitro* meats, still have significant technological and/or regulatory barriers to commercialisation. Genetic modification has to overcome some minor and some major technological issues and significant regulatory issues before it is a viable option. *In vitro* meat has significant technological barriers to overcome before it can enter the market. Some scientists argue that the product will never see commercialisation, while others argue that it will revolutionise the meat industry (Chiles 2013). Furthermore it remains to be seen if the majority of consumers will accept such a new technology.

Keeping the meat industry consumer focused, and delivering a consistent, quality product will be essential when faced with competition from artificial meat (Grunert *et al.* 2004; Polkinghorne *et al.* 2008). The conventional meat industry has the capacity to adopt and harness accelerated genetic selection, cloning and genetic modification technologies in order to not only increase production capacity but also to improve its ability to satisfy consumer demands for quality animal welfare, sustainability and healthiness (Novoselova *et al.* 2007). It would also give the industry greater flexibility and a greater capacity to improve the quality of the product offered to the consumer and increase efficiency and production. However the strict regulatory barriers and the passionate activism of certain consumer groups would have to be addressed before this

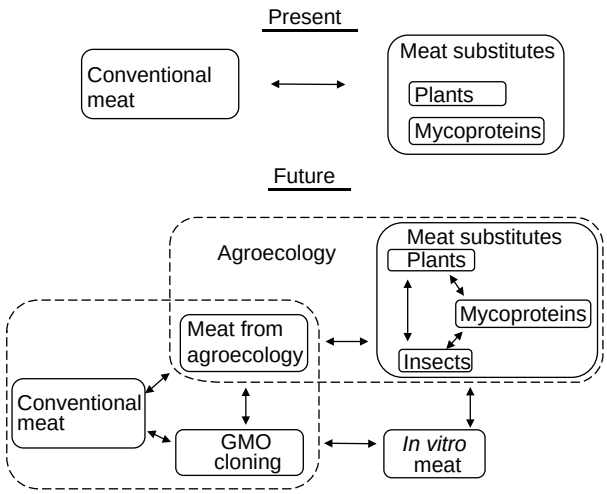

Fig. 1 Competition between conventional meat products and alternatives in the present and in the future. Box, solid and dashed, represent groups of products; arrows represent competition between groups; GMO means genetically modified organism. In the present, conventional meat products compete with meat substitutes which are plants- and mycoproteins-based products. In the future, new products may become available to consumers such as cloned and genetically modified meat, meat produced through agroecological systems, proteins from insects and possibly artificial meat produced from stem cells. Some of these new products will be assimilated with conventional meat production or with meat substitutes. Therefore, in the long term future, the market will become more complex market with many interconnected groups competing with each other.

is successful (Bruce *et al.* 2013).

Alternatively or additionally, conventional meat production can embrace agroecological techniques to increase production while simultaneously meeting consumer demands for quality, animal welfare and sustainability. Consumers which are attracted to agroecological produce are also likely to reduce their meat consumption and increase their intake of alternative protein sources, more closely matching the outputs of agroecological systems. This emergence of these products and techniques will lead to a complex marketplace with different products and groups of products all competing and appealing to different sectors of the consumer base (Fig. 1).

Feedback from the customer to the farmer in the conventional meat industry is poor and reactivity is slow at best. This is particularly evident in sectors of the industry which are comprised of many small to medium size enterprises, such as the beef and sheep industries. In contrast the large industrial enterprises that form vegetable and fungal based meat replacement products, and potentially *in vitro* meat products in the future, have the ability to respond much faster to consumer demands. However it cannot be taken for granted that consumer concern about the sustainability or welfare of the meat industry will inevitably lead to greater acceptance of artificial meat technologies (Hocquette *et al*. 2015). Currently the major form of feedback to meat producers in Europe is carcass price, as determined by the European carcass classification score. These scores are at best an approximate assessment of lean meat yield and provide very little information to the producer. For all meat producers to have better connectivity to consumers there will need to be better investment in systems for efficiency and quality, overlaid with welfare, environmental and health standards.

A quality based grading system such as the USDA system in USA or the MSA (Meat Standards Australia) system in Australia provides the framework for increasing the connectivity between producers and consumers. These systems provide producers with direct feedback on eating quality and monetary incentives for improvements in both lean meat yield and eating quality. This type of system empowers farmers to choose to target their production system to either high yield, or high quality, or a combination of the two. Changing the focus of conventional meat producers from yield or arbitrary scales to consumer assessed quality will allow for consumers to have a greater influence over meat production and increase the adaptability of the industry.

7. Conclusion

The traditional meat industry is facing a changing market place. Different groups of consumers are demanding a variety of modifications to current meat producing practices and it would be detrimental to the industry to ignore any of these pressures. Regulating authorities are also introducing new, environmental legislation changing the economics of production. Artificial meat technologies are utilising ground breaking techniques and technologies to meet the evolving demands of consumers which include environmental sustainability, health concerns and animal welfare. However many barriers are in place before these products can enter the market on a large scale. Many products rely on untested technology, not ready for commercial application or are struggling with government regulations and thus have yet to find a place in the industry. The market place is large and varied with many different consumer groups demanding different products. The products that best fit these markets will out-compete other products and determine the future of the meat industry. Currently the only products that are widely available to consumers are meat replacement products manufactured from plant proteins and mycoproteins. While the conventional production of meat utilising animals is unlikely to ever be completely eliminated, not least due to ruminants' unique ability to digest cellulose, the industry will

face a challenging market place and regulatory environment, leading to changes in the industry as a whole. The traditional more extensive livestock systems (pasture based beef and lamb) will need to develop improved systems for transparent monetary transaction and feedback so as to have 'market pull' improvements in efficiency and quality.

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REVIEW

Cultured meat in western media: The disproportionate coverage of vegetarian reactions, demographic realities, and implications for cultured meat marketing

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Abstract

This paper examines the media coverage of the 2013 London cultured meat tasting event, particularly in the United States, Canada, and the United Kingdom. Using major news outlets, prominent magazines covering food and science issues, and advocacy websites concerning meat consumption, the paper characterizes the overall emphases of the coverage, the tenor of the coverage, and compares the media portrayal of the important issues to the demographic and psychological realities of the actual consumer market into which cultured meat will compete. In particular, the paper argues that Western media gives a distorted picture of what obstacles are in the path of cultured meat acceptance, especially by overemphasizing and overrepresenting the importance of the reception of cultured meat among vegetarians. Promoters of cultured meat should recognize the skewed impression that this media coverage provides and pay attention to the demographic data that suggests strict vegetarians are a demographically negligible group. Resources for promoting cultured meat should focus on the empirical demographics of the consumer market and the empirical psychology of mainstream consumers.

Keywords: cultured meat, vegetarianism, vegans, Mark Post, *in vitro* meat, moral psychology, consumer market, disgust

1. Introduction

The highly publicized tasting of a cultured beef hamburger on August 5, 2013 in London accomplished what it was supposed to do. It served as a proof-of-concept that meat could be grown in a laboratory. It garnered a lot of media attention. It avoided any public relations disaster because the tasters described it fairly positively. It may have attracted investors. It may end up being an important step in diminishing the novelty of cultured meat and its attendant consumer hesitance.

However, the publicity also provides another benefit. Examining the public reaction and the priorities of those who staged the event can generate potentially useful insights into how cultured meat can be successfully promoted, what strategies promoters should take and avoid, where best to put marketing resources, and where the greatest resistance and support for cultured meat is likely to lay.

This paper examines the online coverage of the cultured meat tasting, particularly in the United States, Canada, and the United Kingdom. Though not a scientific survey of coverage but rather an initial assessment, it draws material

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from major news outlets, prominent magazines covering food and science issues, op-ed pieces, and advocacy websites concerning meat consumption. The paper has three goals. First, to characterize the overall emphases of the coverage—what issues were most prominently displayed? Second, to characterize the tenor of the coverage—was cultured meat presented as exciting, dangerous, weird, promising, controversial, or odd? Third, to compare the media coverage and portrayal of the issues to the demographic and psychological realities of the actual consumer market into which cultured meat will compete—were proponents, opponents, potential consumers and market issues accurately and proportionately addressed? It concludes with recommendations for how best to understand the consumer market for cultured meat and how best to spend promotional resources. The upshot is that the online coverage gives an inaccurate sense of what obstacles are really in the path of cultured meat acceptance, particularly by overemphasizing and overrepresenting the importance of the reception of cultured meat among vegetarians. Promoters of cultured meat should recognize the skewed impression that this media coverage creates and avoid getting distracted by issues that can be flashy and conspicuous but are demographically negligible. They should instead pay close attention to empirical demographics of the consumer market and the empirical psychology of mainstream consumers.

2. The issues of cultured meat in popular online media

The cultured meat tasting received fairly widespread coverage in the UK and North America in a variety of online outlets. Most mainstream news organizations had short reports, invited commentary, and blog or forum threads dedicated to the London event. Most of the news stories began with the novelty of the hamburger—phrases such as “burger built in a lab”, “lab-made burger”, “lab-grown meat”, “lab-grown beef”, and “test-tube burger” peppered the titles or first sentences of many of the stories. This is not surprising since most people had not heard of cultured meat. The novelty of cultured meat, however, quickly turned in most of these stories to be related to its taste rather than to its politics or its technological nature. It was somewhat surprising that few of the news stories referred to cultured meat as “brave new meat”, given that the tropes of technological dystopias are often invoked in popular media (Marcu *et al.* 2014). It may indicate the wisdom or cleverness of the London event itself being staged around taste-testing with prominent food writers and researchers. If the event had simply been an announcement and visual presentation of the burger, it is likely that speculation about its “brave new” dangers would have been more common. As it was, the salient feature of cultured meat was immediately its taste and its ingestion by human beings, which smartly curtailed journalistic excesses.

The taste of the beef itself was characterized in different ways by different writers and news organizations. Some opened with how judges were “pleasantly surprised at the texture and juiciness” (Jamieson and Boyle 2013). Some emphasized its relative lack of flavor, saying judges “gave it good marks for texture but agreed there was something missing” (Associated Press/Fox 2013). Some focused on how the cultured meat was “close to meat” but lacked some texture or quality (CBS Interactive 2013). Some highlighted more or less negatively or positively that the tasters were surprised at the acceptability of the taste and “No one spat the meat out; no one cringed” (Zaraska 2013a).

After taste, most stories also remarked on the high cost of the project (over $300 000), in neutral or humorous ways, but most acknowledging that this was an early technological process that would get cheaper. They also pointed out the private funding behind the project and typically then went into a discussion of the process of making the beef, from biopsy to cell growth techniques to creating the strands of tissue needed for making the beef patty. Most of the descriptions of the technology of producing the beef were neutral, using dispassionate language that underscoring the labor intensiveness of the process.

Many of the reports prominently included the rationale behind the development of cultured meat, focusing on the potential benefits of a fully developed cultured meat system. The benefits described included—in different proportions—reduced environmental impact and land use, reduced harm to livestock animals, and human health advantages. Surprisingly, the most common and prominent benefit described was about environmental impact and land use and how cultured meat could address a future world food crisis as meat consumption grows in developing countries. Stories regularly included statements about the huge and unsustainable percentage of land currently used to grow livestock (Associated Press/Fox 2013; CBC News 2013; CBS Interactive 2013; Duhaime-Ross 2013; Hanlon 2013; Jha 2013; Woollaston *et al.* 2013; Zaraska 2013a). They also regularly remarked on the superior efficiency and lowered greenhouse gas emissions of a cultured meat system over the energy intensive and wasteful livestock system (Coghlan 2013; Duhaime-Ross 2013; Fox 2013; Hanlon 2013; Jha 2013; Telegraph Media Group Limited 2013; The Economist 2013; Zaraska 2013a). While the space allotted to concerns about environmental impact and agricultural advantages was greatest, numerous stories and advocacy pieces described the value of reducing the pain that livestock animals experience (CBC News 2013; Datar 2013; Hines 2013; Levine 2013; Singer 2013) and the potential health

benefits of cultured meat from eliminating saturated fats and growth hormones, circumventing livestock pathogens, and including essential nutrients (Associated Press/Fox 2013; Datar 2013; CBC News 2013; Zaraska 2013b).

Many of the stories included the reactions, enthusiasms, and concerns of vegetarians. The focus was usually whether or not cultured meat would be eaten by vegetarians and whether it was considered acceptable on moral or health grounds. Regular references were made to PETA's (People for the Ethical Treatment of Animals) support of cultured meat, including the organization's offer of $1 million for successfully making cultured chicken and quotes from PETA's president and other officials: "As long as there's anybody who's willing to kill a chicken, a cow or a pig to make their meal, we are all for this … Instead of the millions and billions (of animals) being slaughtered now, we could just clone a few cells to make burgers or chops" (Associated Press/Fox 2013; CBS Interactive 2013); "Americans, for example, eat a million chickens an hour in this country … And then you think, if you can grow the chicken flesh from a few cells, that's a lot of birds won't be suffering" (Fox 2013); "*In vitro* meat provides a way for people to be able to eat ethically, while still kind of getting that meat fix" (CBC News 2013).

Numerous quotes from individual vegetarians were also included, including both enthusiastic and hesitant: "I'm a vegetarian, but I would be first in line to try this" (Associated Press/Fox 2013); "I'd buy it … I'd pay extra money for meat I could eat without feeling guilty about it" (Fox 2013); "Meat is objectively delicious. I don't understand vegetarians who say they don't like the taste … I can't wait to try test-tube meat" (Hines 2013); "Why grow it in a Petri dish or eat the meat from a slaughtered animal when plant sources of protein and meat replacements are ever more commonly available and are better for our health?" (Izundu 2012); "Vegetarians should remain vegetarian. That's even better for the environment" (by cultured meat pioneer Mark Post himself) (Hines 2013).

While the responses or potential responses from vegetarians were often referred to, several news outlets posted or reported focused stories on vegetarians with titular references to a significant controversy: "It's (not) alive! Lab-grown meat is here—but will vegetarians eat it? No animal died to make this burger. No bleating calf was separated from its mother; no manure polluted the waterways; no blood was shed on the slaughterhouse floor. But vegetarians and vegans aren't lining up to get a mouthful just yet" (Fox 2013); "Can vegetarians eat in-vitro meat? The debate rages. So … if a piece of beef is grown in a lab, without killing the cow, can vegetarians eat it? Some say no. Others say they must … The debate is raging on vegetarian forums" (Hines 2013); "Some are waiting with bated breath, keen to experience the taste and texture of meat without actually harming an animal, while others find the whole idea utterly repulsive" (Izundu 2012).

Finally, and to a lesser extent, news stories brought up four other elements of the cultural reception of cultured meat that are worth noting. A couple of stories and commentaries brought up the issue of whether cultured meat would pass a religious ritual test. Questions about whether cultured meat could be considered halal (ritually sanctified meat in Islam) or kosher (ritually sanctified meat in Orthodox Judaism) were seen as significant. In some cases, the issue was about the letter of the law—were source cells from a ritually appropriately slaughtered animal? (Fox 2013). In some cases, the issue was more about the spirit of the law—did cultured meat still symbolize a violation of religious codes? (Zorn 2013).

Some stories brought up the psychological issue of disgust, noting that many people (both vegetarians and meat eaters) initially react with disgust toward cultured meat: "Yet there remains the problem of the 'yuck factor' of what many already call 'frankenmeat'" (Zaraska 2013b); "Another challenge is what many call the 'yuck' factor. Cultured meat has already been dubbed 'franken-meat' or even 'schmeat'" (Zaraska 2013a). Some stories quoted people who supported cultured meat in general as a way to reduce animal pain, but nonetheless characterized the desire for meat as repulsive and weak-willed: "Lab-grown meat will provide people who were addicted from childhood to the saturated fat in flesh with the 'methadone' for their habit" (Woollaston *et al.* 2013).

A few stories also reported reactions that are similar to disgust but are more about a general anti-technology attitude than psychological disgust. These reactions can be termed "romantic" reactions, seeing as how they are part of a general ideology that values a romanticized "nature" and views technology as inferior. For example, a biologist is described as believing "that all our food should be grown lightly on the land, using the riches of the Earth and the power of the sun—not in a factory." (Levine 2013). A chef is quoted as saying "There's absolutely no way that you can recreate the flavour of what Mother Nature and the universe creates for us in the lab … There's no way." (CBC News). A restaurant owner is quoted as saying: "Personally, I don't like synthetic food, and avoid all that soy-based fake meat stuff aimed at vegetarians. So, no, I wouldn't be interested in using it, either as a restaurant product or on my plate at home." (Izundu 2012).

Though very few reports dealt with this issue directly, language also indicated a concern that cultured meat was somehow not real meat—that it was fake or somehow chemically differed in nature from livestock-derived beef. Some stories simply assumed that cultured meat was somehow fake: "As for how to make the fake meat, there are two diametrically opposed philosophies. One, as espoused by

Dr. Post, involves taking real animal tissue and using it to grow meat in a vat" (Hanlon 2013). Some stories pointedly referred to cultured meat with derogatory names: "Meet 'schmeat': Lab-grown meat hits the grill this month" (CBC News 2013); "But the debate among vegetarians and vegans about the freaky frankenburgers was kicked off in earnest this week as the first proto-type "*in vitro*" hamburger was eaten in London on Monday" (CBC News 2013). Some stories quoted people who seemed to be responding to the unstated assumption that cultured meat's authenticity was questioned: "It is a real burger made of real meat. It's as real as real can be" (CBC News 2013); "So, to recap the opinions on the state of shmeat…at least one carnivore thinks it's real meat … " 'if it [looks] like muscle, if it [smells] like muscle, if it tastes like muscle, that's muscle', Mironov says" (CBC News 2013).

To summarize: The most common aspects of cultured meat that this sampling of online western media outlets brought up had to do with taste, benefits, cost, process, and vegetarian reactions. While almost all the stories brought up these issues, a few dealt with religion, disgust, and fakery (typically assuming cultured meat was fake rather than explicitly examining that claim).

3. Comparing media issues to real issues

What was covered in the cultured meat reporting is important, but of equal interest is what was not covered. There was no mention at all of the reaction of meat producers. Though there are numerous lobbying and professional organizations dedicated to promoting the meat business, and many farmers who raise animals for consumption, not a single one was quoted nor did any statements about cultured meat appear from meat producer organizations. Instead, vegetarian reactions (from the animal rights movement, from vegetarian cooks, and general vegetarian responses) were featured prominently, as if the vegetarian reaction to cultured meat was critical to its success and as if the debate "raging" among vegetarians was somehow a major social factor in the cultured meat narrative. Sometimes, disgust reactions were reported, but most of these were in conjunction with vegetarian reactions and very few dealt with the reactions of meat eaters. Even concerns about religious slaughtering rituals received more attention than the ordinary reactions of ordinary meat eaters.

The overall sense one gets from reading these mainstream news and other media reports is that cultured meat is strange but interesting, is expensive but promising, is mainly being developed to improve environmental impact and food production problems, and that the primary social issue to be explored is the position taken by vegetarians. While media reports can obviously be a force all of their own, irrespective of their accuracy, it is still useful to ask whether the media have it right. When comparing media emphasis to the demographic and psychological facts of the market into which cultured meat will actually compete, the coverage appears to be a poor guide to what actual market forces are in play. In particular, the emphasis on vegetarian responses to cultured meat is interesting. Are vegetarians that important to the success of cultured meat? Should promoters of cultured meat work to appeal to vegetarians? Contrary to the impression one gets from media reports, the numbers suggest no.

4. The importance of vegetarians to the cultured meat movement

There are two questions one can ask about the importance of vegetarians for the cultured meat market. One is about how many vegetarians there actually are. The other is about what motivates a person to become a vegetarian in the first place and whether cultured meat can address those motivations.

4.1. Vegetarian market size

Counting the number of vegetarians is not easy and there is no definitive assessment of the world vegetarian population. Individual countries have some data, however, and they suggest that the vegetarian population is very small.

Polling in the US indicates somewhere between 5% and 3% vegetarians. Vegans are usually recorded at the 2% level. While vegetarian organizations typically emphasize that the number could be larger given sampling error (Stahler 2012) and some make claims such as "A vast number of people are seeking to reduce their meat intake, creating a rapidly growing market for all things vegetarian" (Vegetarian Times), a 2012 Gallup poll states "Vegetarianism in the U.S. remains quite uncommon and a lifestyle that is neither growing nor waning in popularity. The 5% of the adult population who consider themselves to be vegetarians is no larger than it was in previous Gallup surveys conducted in 1999 and 2001. The incidence of veganism is even smaller, at a scant 2% of the adult population." (Newport 2012).

Although data from other countries are not easy to find, the European Vegetarian Union and the European Vegetarian and Animal News Alliance, drawing on various, but not definitive sources, estimate the percentages of vegetarians in European countries between 1 and 9%. Various other sources (all of which are usually admitted to be less than certainly accurate) rate a few South American countries and Asian countries similarly. The only outlier is India, which one poll estimates has about 31% vegetarians (Yadav and Kumar 2006).

With the exception of India, then, the percentage of vegetarians is small. What's more, there are other factors that suggest the percentage of vegetarians might even be smaller than what surveys show. First of all, surveys and polls are notorious for asking how a person identifies themself rather than how they behave. This often leads to a response bias in which the person claims to have a particular trait because they want to have it, or think they should have it, or hope to have it. For example, in a 2002 TIME/CNN poll, 6% of respondents said they were vegetarians—but when asked what they had eaten in the previous day, 60% of the self-identified vegetarians said they had eaten meat. Other studies have shown similar results (Herzog 2011). Respondents in surveys may also be related a temporary state. One study found that after reading a book on vegetarianism, students often dedicated themselves to being vegetarian—but after one year, most had reverted to eating meat (Hormes *et al.* 2013).

The problem then is that news and other online media exaggerate the importance of vegetarians to the success of cultured meat simply by putting a disproportionate emphasis on what is in fact a very small group of consumers. The developers of cultured meat also tend to have a skewed sense of the importance of vegetarians, perhaps because they themselves became involved in the cultured meat movement in order to reduce animal harm and the environmental impact of animal farming (Hines 2013). As a result, they may be more likely to be attentive to vegetarian culture and the internal debates of that culture.

In practical terms of promoting cultured meat, however, attending to the reactions of vegetarians is largely a waste of time. The number of vegetarians is very small (more than 95% of the human population eats meat). The number of vegetarians who are vegans is even smaller. With more prominent animal rights organizations such as PETA already in support of cultured meat, there is little value and great opportunity for losing resources in marketing to the tiniest element of a society. It would be far more useful to focus almost entirely on meat eaters and ignore the media overrepresentation of vegetarians.

4.2. Vegetarian culture and meat emotions

Even if it were important demographically to appeal to vegetarians to support cultured meat, understanding the motivations behind vegetarian diets would suggest diminishing returns in promoting cultured meat's benefits. There are several reasons given for why people adopt a vegetarian or vegan diet. The most common reported motivations are health-related and morality-related (Beardsworth and Keil 1992; Santos and Booth 1996; Jabs *et al.* 1998; Kenyon and Barker 1998; Lea and Worsley 2003). Religious and gustatory motivations have also been recognized, though religious reasons are often strongly connected to moral concerns and gustatory preferences are both relatively small and often related to other motivations (Beardsworth and Keil 1992; Fessler and Navarrete 2003).

Health vegetarians are primarily in support of eating only plant material and avoiding meat because they believe meat is less healthy. Moral vegetarians are primarily opposed to eating meat because of the pain, harm, and injustice they see in farming practices that produce meat. These types of vegetarians are familiar. There is a third group, however, that is not as familiar but is worth noting. This group can be called emotional vegetarians or purist vegans. They may have originally been opposed to eating meat for health or moral reasons but have since developed a visceral resistance to meat itself—experienced not simply as a fear of health problems or disapproval of farming practices but more as a moral emotion of disgust and revulsion.

Those who are strictly health vegetarians could probably be convinced that cultured meat could be healthy. There are technologically possible ways to produce real meat that has no saturated fats, no cholesterol, is heme-iron free, and has all sorts of added vitamins and other nutrients (Zarask 2013b). Those who are moral vegetarians could probably be satisfied as well. Utilitarian moral vegetarians such as Peter Singer would have no problem with cultured meat as long as the harm and pain to animals was eliminated (which is part of the goal) (Singer 2013). Deontological moral vegetarians, who believe in animals' natural rights, could also probably be convinced provided no animals were used at all in the production of cultured meat or were used in ways that did not violate their natural rights.

Emotional vegetarians, however (who typically use deontological rhetoric to justify their positions) for the most part cannot be convinced. Even when cruelty, pain, and even formal rights are taken out of the equation, emotional vegetarians reject cultured meat. Consider these examples:

(1) "By honoring the false proposition that it is important for people to be able to eat cows ("beef"), we implicitly encourage everyone to think that it is also important for people to be able to eat chickens ("chicken"), ducks ("duck"), fishes ("fish"), birds' ovulatory secretions ("eggs"), cows' and other mammals' mammary secretions ("milk"), or whatever their favorite animal corpse or secretion might be … As a vegan, I acknowledge that I find the idea of a cultured animal product unappetizing … I no longer regard nonhuman animals as food (or clothing or beauty product) sources … My disgust response, in this case, is thus very closely connected to my moral development in coming to realize that animals are beings whose lives matter to them … Gary Francione, commenting on the In Vitro meat debate, said it very well when he asked rhetorically whether we would want to eat

a human arm if we could do so without hurting any human? Of course we would not, because we do not view humans as food … If you learned that a handbag or briefcase was made out of human skin—even the skin of a human who had died naturally—you would probably prefer to avoid using that handbag or briefcase." (Colb 2013).

(2) "The creation of In Vitro meat is not productive in changing the public's attitudes toward nonhuman animals. Contrary to what Singer said … the animal liberation movement is not restricted to the one goal of ending animal suffering and pain; rather, it is about liberating animals from the category of "objects" … When we support the production of In Vitro meat, we perpetuate the idea that nonhuman animals are mere resources to be used for our benefit. As Francione writes, this sort of activity … is "problematic as a symbolic matter" … Furthermore, we must come to understand that oppression and exploitation is inherently linked to the need to control the bodies and freedom of others. In Vitro meat is yet another way of controlling nonhuman animals—the process requires that we force them into a lab and extract their muscle cells against their will just so we can greedily indulge in animal flesh while feeling morally at ease. This, I'm sorry, does not describe animal liberation. Liberation requires the removal of human dominance and control over the nonhuman animal world—something which In Vitro meat production does not allow". (Abbate 2013).

(3) "Even if it were possible to create meat without the use of non-human…getting to that stage would still require the exploitation of non-human animals and the research and development needed would involve lethal and painful vivisection. For this reason alone, the exploration and development of *in vitro* meat production is fundamentally immoral. Consider that the reason why it is agreed that the Nazi hypothermia experiments…were immoral is that the human victims of this vivisection had basic rights … Decades after the holocaust, the Nazi research has been used to develop life-saving treatments for hypothermia … The original research, however, was fundamentally immoral and should not have been conducted, even though this would have entailed that modern day hypothermia victims would of had a greater likelihood of dying. In short, the good end of saving lives is not justified by the immoral means of human vivisection because humans have basic rights. Similarly, even if *in vitro* meat production that did not involve any non-human animals or their exploitation were developed in the future and the consumption of this meat resulted in the lives of non-human animals being saved, this good end would not be justified by the immoral means of vivisection … Therefore, for the sole reason that vivisection must be an integral part of the research and development of *in vitro* meat, pursuing it is inherently immoral and must be rejected outright … " (Perz 2011).

In these comments and others like them, there are frequent references linking not only meat eating but cultured meat eating to corpses, cannibalism, human skin accessories, oppression, Nazis, and holocaust defenders. These terms are not accidental—and that does not simply mean they were chosen deliberately for rhetorical impact. The reason they have rhetorical impact (particularly "corpses", "secretions", and "cannibalism") is that those concepts trigger primal evolved disgust responses in most humans that are evolutionarily related to pathogen avoidance (Rozin *et al.* 1985; Rozin and Fallon 1987; Curtis *et al.* 2004). Obviously, part of the rhetoric is geared toward trying to elicit a disgust or horror response in readers, but the use of such rhetoric also indicates a phenomenon described by psychologists as "moralization".

In the research on disgust and moral psychology, researchers have found that it is common for people to have certain automatic disgust and moral disapproval responses (likely evolved) to situations historically and biologically associated with pathogens and reproductive dangers, such as incest or eating a cooked animal that has been used for sex. While most people have strong disgust reactions to these situations, when asked why they also judge them to be immoral, they typically give explanations associated with consequences, e.g., in the case of incest, that it is nonconsensual, that it is psychologically harmful, that it could result in birth defects. However, when researchers control for consequences, building into the hypothetical that the incest is consensual, not harmful, and cannot result in pregnancy, people still maintain their moral disapproval. This research suggests that an evolved moral judgment and disgust response comes first and then reasons are devised to justify that response (Haidt 2001).

In the phenomenon called "moralization", the reverse causal relationship can develop for moral reactions that are not evolved but are learned. When a person comes to believe that a particular behavior is immoral (for various reasons but typically including strong consequentialist reasons), they can begin to develop emotional associations toward that behavior and in particular begin to recruit the emotion of disgust. Studies have shown that moral vegetarians (in contrast to health vegetarians) "find meat more disgusting, offer more reasons in support of their meat avoidance, and avoid a wider range of animal foods" (Rozin *et al.* 1997). This does not appear to be their initial reaction, however. Studies show that moral vegetarians have no higher level of disgust sensitivity than health vegetarians though they evince moral disgust for meat. This suggests they develop the higher level of disgust after their moral judgments (Fessler *et al.* 2003). In addition, experimental studies have shown that the emotion of disgust strongly moralizes concerns about purity, adherence to behaviors seen as pure,

and moral condemnation of behaviors seen as violating the purity of a moral commitment. Disgust is not correlated with judgments about justice or harm, however, only purity. Other emotions studied, including anger and fear, do not increase purity violation concerns (Horberg *et al.* 2009).

Taken together, this research suggests that strict moral vegetarians are more likely to develop a set of strong disgust emotions that attach to meat itself, rather than merely the initial farming practices that elicited moral condemnation. Given this moralization of meat itself and the increased concern with purity violations that disgust generates, it is not surprising that strict moral vegetarians react to cultured meat in the ways exemplified above. Using justification strategies and language reminiscent of subjects in disgust studies of incest and pathogens, these moral vegetarians usually begin with objections that cultured meat still has not developed to the point where animals are not harmed, but they soon move on to claim that even if cultured meat met the utilitarian conditions of avoiding harm and pain, they would still be opposed for "symbolic", "inherent", "intrinsic", and "fundamental" reasons involving deontological and attitudinal concerns, independent of harm. This leads to a classic purity violation concern in which the thing being judged is stripped of harm but is nonetheless judged as evil because it sends the wrong message, indicates the wrong motivation, or violates some valued symbolic order.

For people who feel this way about meat, cultured meat will likely never be acceptable because they have transferred their moral emotions to meat itself rather than simply the practices that produce meat. As such, no amount of evidence about harm and consequences is likely to make a difference. Promoters of cultured meat would be wasting their time in trying to convince such emotional vegetarians or vegan purists. This is not to say that all vegetarians who are at first disgusted by cultured meat are vegan purists or that all moral vegetarians become purists. On the contrary, those moral vegetarians who are still focused on consequentialist concerns can recognize their own disgust and yet still come to support cultured meat because they see the consequentialist benefit. Peter Singer, for example, explicitly argues an anti-purist point: "My own view is that being a vegetarian or vegan is not an end in itself, but a means towards reducing both human and animal suffering, and leaving a habitable planet to future generations. I haven't eaten meat for 40 years, but if *in vitro* meat becomes commercially available, I will be pleased to try it." (Singer 2013). Other commenters on cultured meat explicitly confront their own disgust, for consequentialist reasons:

(1) "The subsequent wave of disgust that washed over me terminated that fantasy fairly quickly … Whether or not cultured meat makes someone like me uncomfortable is ultimately not that important. What is important is the fact that it is a potential solution to a global problem … Until some other elegant solution presents itself, pursuing the goal of artificially grown, biologically real meat is an idea that just makes sense … Why wouldn't we want something that could help save our planet, and feed everyone to boot? How can that be disgusting? (Jiang 2014).

(2) "About 6 years ago, when I first learned of the concept of *in-vitro* meat … my initial reaction was revulsion. As a registered nurse/health advocate and vegetarian for many years, I could not imagine myself promoting a product I associated with pain, disease, and pollution. In my frustration at the slow progress of the materialization of my pipe dream to turn the entire world vegetarian, I decided to learn more about the process. After much thought I have come to the conclusion that it's not about (the turning of) my stomach that's important. It's about the potential to spare the suffering of tens of billions of animals per year and, at the same time, improve human health, and reduce insult to the environment." (Deych 2014).

All of this shows that vegetarians are a group with multiple motivations, attitudes, and moral psychological profiles. Looking at the differences in these groups can help with understanding reactions to cultured meat and to determine how to promote cultured meat. Some vegetarians are primarily motivated by consequentialist animal welfare concerns—they can support cultured meat in principle. Some vegetarians are primarily motivated by environmental impact concerns—they can support cultured meat. Some vegetarians are primarily motivated by health concerns—they can support cultured meat. Some vegetarians, however they started, have developed moralizing disgust and purity attitudes toward meat itself—they will not support cultured meat.

5. Conclusion

Given that more than 95% of the human population eats meat, it would be wise for promoters of cultured meat to focus on that population. Though it is beyond the scope of this paper, meat eaters can be divided into sub groups and the moral emotions related to their diets examined in the same way vegetarians are examined above. It is important to recognize the market size of meat eater subcategories (for example, though media reports sometimes asked whether cultured meat could be kosher, the number of people who eat kosher diets for religious purposes is also tiny). The key issues for the meat eating market are about the psychology of disgust (which has developed more about meat than other foods throughout our evolutionary history) and the issue of the realness or artificiality of cultured meat (Fessler and Navarrete 2003).

For the purpose of this paper, it is simply useful to highlight a conspicuous and potentially distracting element of

the Western media coverage on the cultured meat tasting. The vegetarian reaction to meat is portrayed as an important element of the reception of cultured meat. That reaction is described as controversial and elicits all kinds of moralizing responses. While the moral responses and arguments are interesting to look at on their own (Hopkins and Dacey 2008), examining the demographics of vegetarianism shows that the vegetarian portion of the consumer market is small and the portion of emotional vegetarians who are deeply resistant to cultured meat based on their moral psychology is tiny. Interestingly, few studies that have been done on consumer reactions to cultured meat have not mentioned vegetarianism at all as a factor, demonstrating instead a concern among consumers about novelty, naturalness, disgust, and fear of technology (Goodwin and Shoulders 2013; Marcu *et al.* 2014). Promoters of cultured meat should not let themselves be led astray by the media misrepresentation of the importance of vegetarian reactions nor by the disproportionately salient volume and passion of vegan responses. To work toward their stated goals of improved environmental impact, improved food safety, and reduced animal pain, they should focus on meat eaters.

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RESEARCH ARTICLE

Educated consumers don't believe artificial meat is the solution to the problems with the meat industry

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Abstract

The production of *in vitro* meat by cell culture has been suggested by some scientists as one solution to address the major challenges facing our society. Firstly, consumers would like the meat industry to reduce potential discomfort of animals on modern farms, or even to avoid killing animals to eat them. Secondly, citizens would like meat producers to reduce potential environmental deterioration by livestock and finally, there is a need to reduce world hunger by increasing protein resources while the global population is predicted to grow rapidly. According to its promoters, artificial meat has a potential to make eating animals unnecessary, to reduce carbon footprint of meat production and to satisfy all the nutritional needs and desires of consumers and citizens. To check these assumptions, a total of 817 educated people (mainly scientists and students) were interviewed worldwide by internet in addition to 865 French educated people. We also interviewed 208 persons (mainly scientists) after an oral presentation regarding artificial meat. Results of the three surveys were similar, but differed between males and females. More than half of the respondents believed that "artificial meat" was feasible and realistic. However, there was no majority to think that artificial meat will be healthy and tasty, except respondents who were in favour of artificial meat. A large majority of the respondents believed that the meat industry is facing important problems related to the protection of the environment, animal welfare or inefficient meat production to feed humanity. However, respondents did not believe that artificial meat will be the solution to solve the mentioned problems with the meat industry, especially respondents who were against artificial meat. The vast majority of consumers wished to continue to eat meat even they would accept to consume less meat in a context of increasing food needs. Only a minority of respondents (from 5 to 11%) would recommend or accept to eat *in vitro* meat instead of meat produced from farm animals. Despite these limitations, 38 to 47% of the respondents would continue to support research on artificial meat, but a majority of them believed that artificial meat will not be accepted by consumers in the future, except for respondents who were in favour of artificial meat. We speculated that the apparent contradictory answers to this survey expressed the fact that people trust scientists who

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are supposed to continuously discover new technologies potentially useful in a long term future for the human beings, but people also expressed concern for their health and were not convinced that artificial meat will be tasty, safe and healthy enough to be accepted by consumers.

Keywords: meat production, artificial meat, consumers' responses

1. Introduction

Our society is facing three major new challenges which are summarized below.

Firstly, consumers would like the meat industry to improve the welfare of the animals raised on modern farms and a small subset of consumers are taking this one step further and encouraging modern agriculture to eliminate the need for animals entirely. This shift in the demands of consumers has created two new areas for debate within the meat industry. The first concerns the ability of modern, large scale, agriculture to provide adequate animal welfare standards with the conditions of traditional small family farms considered to be the benchmark. At a deeper theological level, the entire industry of raising and killing animals for human needs has been called into question and is another important moral issue to be solved in our society (Hopkins and Dacey 2008; Tonsor and Olynk 2011; Hocquette *et al.* 2013).

Secondly, coinciding with concerns regarding animal welfare are concerns regarding the environment as a whole. Livestock, particularly ruminants are considered major contributors to global greenhouse gas emissions. The Food and Agriculture Organization of the United Nations claimed that livestock contribute to 18% of greenhouse gas emissions on average (Steinfeld *et al.* 2006). As a result of the recognition of climate change, many agri-businesses have prioritized altering their farming practices and choosing farming systems with the lower carbon footprints. Many scientists agree that research has to focus on how to decrease carbon footprint by livestock while increasing efficiency of production to ensure enough food for the increasing human population. The selection for efficient animals in different systems that reduce environmental impacts is key issue (Scollan *et al.* 2011).

Thirdly, growing global demands for protein necessitate an increase in production. The global population is predicted to grow to 9 billion people in the year 2050 (US Census Bureau 2008), with a huge increase in meat requirements. The Food and Agriculture Organization of the United Nations (FAO 2009) suggests that food production will have to increase by 70% to fulfill the caloric and nutritional needs associated with this population increase. Failing to meet these increases in demand is not an option as it is clear that malnutrition and under nutrition are socially unacceptable. The additional demands being placed on the current agricultural system is serving to increase the already existing competition for energy, land and water supplies between livestock, crops and human beings. Food producers, therefore, face the challenge of producing ever increasing quantities of safe, affordable animal proteins, using a finite resource base and while increasing animal welfare and using less and less animals to avoid killing them and less and less lands or biological resources to protect the environment in order to meet consumer demand.

However, according to some experts, the capacity of meat production by conventional means is close to its maximum (FAO 2011) and further production, even if possible, would come at high costs of greenhouse gas emission, land usage, energy use and water use (Post 2014). Given the appropriate technology is developed, meat alternatives have the potential for three major advantages over traditional meat production which make them attractive in this climate of increasing demand coupled with diminishing resources. These advantages are: (i) less and less usage of animals (Dawkins and Bonney 2008), even need of almost no animals which may solve welfare and moral issues; (ii) less environmental impact of meat alternatives than production of meat from alive livestock (Tuomisto *et al.* 2011); and (iii) the ability for mass production to take advantage of economies of scale (Post 2012). Among meat alternatives, *in vitro* meat produced from stem cells is presented as an interesting process because it mimics natural meat, not only in shape and aspect, but also in biological composition because *in vitro* producers are supposed to artificially synthesize real muscle cells.

Some researchers are convinced that it is the logical progression of the meat industry, while others criticize either the technical possibility to produce artificial meat or the potential advantages of such a process. The debate has been quite extensive and thus far failed to reach a consensus between experts in the field. Therefore, we believe that the continuation of this debate and the decision to continue research into *in vitro* meat or devote those resources to other avenues is now best placed neither in the scientific nor the technical arenas, but should be debated with consumers and citizens. However societal debate is often biased by media coverage of the issues, particularly with the presentation of partial arguments. We thus hypothesized that as a result of positive media coverage (Goodwin and Shoulders 2013),

consumers opinion would be largely positive. Therefore we developed a questionnaire evaluating opinions on artificial meat and distributed it to different groups of educated people around the world.

2. Methods

2.1. Principles of the survey

A survey with the same questions was asked either orally or over the internet to different groups of people. For all but two questions there were three possible responses: (i) yes, I agree; (ii) no, I disagree and (iii) I do not know. At the end of the questionnaire, some demographic information was gathered about gender, country, occupation and age.

The questionnaire was supplied to respondents in one of two different ways. Before answering the questionnaire, the first method involved respondents viewing a short power point presentation covering (i) the principles of artificial meat production; and (ii) its ability to solve the potential problems faced by the meat industry in terms of welfare, environmental and food security issues. This method was time consuming but ensured a better understanding of the issues by the respondents. People were invited to answer the questions on a sheet of paper. Therefore, this method is referred as the paper survey in this manuscript.

The second method was based on a questionnaire freely available on internet and sent to different mailing lists or groups of people known by researchers. The survey was preceded by a small text to explain the problem, followed by the internet questionnaire with the same questions as in the first method. The small text has been built from abstracts from scientific papers which explained the challenges facing the meat industry (FAO 2006; Scollan *et al.* 2011) and the principles of artificial meat production with its potential ability to solve the mentioned challenges (Post 2012). The internet survey was mainly distributed in English, except in France where it was distributed in French.

2.2. Details of the questions

The questionnaire was built with 10 questions always asked in the same order (Table 1).

The questionnaire began with a question asking the respondent to indicate if they thought *in vitro* meat was a feasible and realistic technology. Both the presentation and the written information provided to respondents gave the indication that *in vitro* meat was indeed a feasible and realistic technology. Respondents who answered 'yes' to this question were better able to give more balanced opinions to the questions in the remainder of the questionnaire.

The next two questions asked "Do you think meat produced *in vitro* will be healthy?" and "Do you think meat produced *in vitro* will be tasty?". These questions aimed to evaluate the respondents trust in *in vitro* technology and the likelihood of their acceptance of the product.

The responses to the following question, "Do you think the meat industry is really facing important problems (environment degradation, animal welfare, inefficient production to feed humanity)?" were also likely to be influenced in a positive manner by either the presentation or the written information provided to respondents prior to the questionnaire.

From this question, it was logical to then ask the respondents if they thought that *in vitro* meat could help resolve some of these problems. Different possibilities exist to potentially reduce animal welfare and carbon footprint of livestock while sparing meat to feed the whole human population. One of the most commonly presented solutions is a reduction in the overall consumption of meat or even to eat no meat (Vinnari and Tapio 2009). Therefore we decided to compare the potential ability of artificial meat to solve the problems by comparison to these solutions only (eating less meat, or eating no meat). To provide a more comprehensive response, we designed two questions, one asking what respondents would recommend to others, and the other asking what they would do themselves.

The next questions concerned the ability of artificial meat to environment degradation and animal welfare problems. This issue has been assessed by the two following questions: "Do you think that *in vitro* meat will significantly contribute to reduce the environmental impact of livestock?" and "Do you think that *in vitro* meat will significantly contribute to reduce the animal welfare problem?"

Assuming that respondents had been convinced by artificial meat so far through the different questions, the last challenges are on one hand to convince public authorities to financial support research on this technology, and on the other hand to convince consumers to buy and to eat it. The two last questions were to assess the point of view of respondents about the feasibility of these two points.

2.3. Statistical analysis

Distributions of respondents according to their age and sex as well as standardized residuals (which are standardized differences between observed and theoretical effectives) were calculated using the R Software version 3.1.0 (R Core Team 2014) and two packages specialized in data analysis: the ade4 package (Dray *et al.* 2007) and the FactoMineR package (Husson *et al.* 2014). Multiple correspondence analyses (MCA) were performed with questions 1 to 10 except questions 5 and 6. In this type of analysis, associations between variables are uncovered by calculating the chi-square distance between different categories of the

Table 1 Questions of the survey

Nowadays, the livestock and meat sectors are facing new and important challenges: their environmental impact and role in global climate change; balancing the need for increased production of animal products (to satisfy the increasing human population) coupled with a lower footprint, and addressing societal needs in terms of animal welfare and product quality for the consumer (Scollan *et al.*, *Animal Production Science*, 2011, 51, 1–5).

In recent years the notion has been growing that alternatives may be needed for conventional meat production through livestock. This is generally based on concerns about sustainability, environmental burden and animal welfare. These concerns have grown due to further intensification of livestock herding and slaughtering, and on the other hand a predicted rapid increase in global meat consumption (Steinfeld *et al.* FAO, 2006).

As one of the alternatives for livestock meat production, *in vitro* culturing of meat is currently studied. The generation of bio-artificial muscles from satellite cells has been ongoing for about 15 years, but has never been used for generation of meat, while it already is a great source of animal protein. In order to serve as a credible alternative to livestock meat, lab or factory grown meat should be efficiently produced and should mimic meat in all of its physical sensations, such as visual appearance, smell, texture and of course, taste. This is a formidable challenge even though all the technologies to create skeletal muscle and fat tissue have been developed and tested. The efficient culture of meat will primarily depend on culture conditions such as the source of medium and its composition. Protein synthesis by cultured skeletal muscle cells should further be maximized by finding the optimal combination of biochemical and physical conditions for the cells. Many of these variables are known, but their interactions are numerous and need to be mapped. This involves a systematic, if not systems, approach. Given the urgency of the problems that the meat industry is facing, this endeavour is worth undertaking. As an additional benefit, culturing meat may provide opportunities for production of novel and healthier products (Post, *Meat Science*, 2012, 92, 297-301).

	Yes (code 1)	No (code 2)	I don't know (code 0)	
Q1. Do you think this *in vitro* meat technology is feasible and realistic?				
Q2. Do you think meat produced *in vitro* will be healthy?				
Q3. Do you think meat produced *in vitro* will be tasty?				
Q4. Do you think the meat industry is really facing important problems (environment degradation, animal welfare, inefficient production to feed humanity)?				
	Change nothing in consumption (code a)	Eat less meat (code b)	Eat no meat (code c)	Eat *in vitro* meat (code d)
Q5. To solve the potential problems that the meat industry is facing, do you think that human beings should				
Q6. Would you prefer yourself as an individual:				
	Yes (code 1)	No (code 2)	I don't know (code 0)	
Q7. Do you think that *in vitro* meat will significantly contribute to reduce the environmental impact of livestock?				
Q8. Do you think that *in vitro* meat will significantly contribute to reduce the animal welfare problem?				
Q9. As prime minister or chief of your government, will you support financially research on *in vitro* meat?				
Q10. According to your perception, will *in vitro* meat be well accepted by consumers? Will consumers buy it?				
Are you?	A male		A female	
With an age	<30 years (young group)	30–50 years old (medium group)	Older than 50 (old group)	
Someone who does not know the meat sector	Scientist working on meat	Other scientist	Not scientist but working in the meat sector	

variables and between the individuals (or respondents). Data are represented as points in a Euclidean space to visualize associations between variables.

3. Results

3.1. Characteristics of the respondents

A total of 817 people responded to the internet based survey in English (a subset of 604 answers including 103 from North America, 146 from China, 168 from other Asian countries, and 83 from Africa was analyzed in details). A further 865 responded to the internet survey in France, and another 208 people responded with a paper based French and English survey (Table 2).

A majority of the respondents of the paper survey were female scientists, but not aware of the difficulties of the meat sector (Table 2).

3.2. Answers to the perceived characteristics of artificial meat

More than half of the respondents (at least 53%) claimed that the "artificial meat" technology was feasible and realistic

(Table 3). A non-negligible proportion of the respondents (between 10 and 20%) had no opinion. However, within the paper survey, the proportion of people saying that the "artificial meat" technology was feasible and realistic was higher (75.4%) and the proportion of hesitating people lower (10.6%) (Table 3). A high proportion of young females and of old males answered that the "artificial meat" technology was feasible and realistic whereas medium and old females answered the opposite (Fig. 1-A).

Regarding the two questions related to the healthiness and taste of artificial meat, all surveys showed that many respondents had no strong opinion (from 29.6 to 37.7%, Fig. 2). However, while the rest of respondents answered in majority No to the these two questions in the internet surveys, respondents answered in majority Yes to these two questions in the paper survey (Table 3).

A large majority of the respondents claimed that the meat industry is facing important problems related to the protection of the environment, animal welfare or inefficient meat production to feed humanity. This proportion was however the lowest in the case of the paper survey (47.4%), than by internet (66.2% for the international survey and 81.6%

Table 2 Social characteristics of the different groups of respondents[1)]

	International survey (%)	French survey (%)	Paper survey (%)
<30 years	48.8	65.2	31.3
30<years<50	40.2	23.3	53.7
>50 years	10.9	11.6	15.0
Male	54.1	36.8	41.4
Female	45.9	63.2	58.6
Someone who doesn't know the meat sector	21.5	59.5	22.2
Not scientist but working in the meat sector	8.3	11.2	5.1
Scientist	53.1	26.9	47.0
Scientist working on meat	17.1	2.3	25.8

[1)] The international and French surveys were based on a questionnaire-freely available on internet and sent to different mailing lists or groups of people known by researchers, either people from different countries (international survey) or French people (in the case of the French survey). The surveys were preceded by a small text to explain the problem, followed by the internet questionnaire (Table 1). The paper survey involved respondents viewing a short power point presentation covering (i) the principles of artificial meat production; and (ii) its ability to solve the potential problems faced by the meat industry in terms of welfare, environmental and food security issues. This method was time-consuming but ensured a better understanding of the issues by the respondents. People were invited to answer the questions on a sheet of paper.

Table 3 Answers to questions related to the perceived characteristics of artificial meat[1)]

	International survey			French survey			Paper survey		
	Yes (%)	No (%)	I don't know (%)	Yes (%)	No (%)	I don't know (%)	Yes (%)	No (%)	I don't know (%)
Q1. Do you think this *in vitro* meat technology is feasible and realistic?	53.6	28.7	17.7	53.6	26.5	19.9	75.40	14.00	10.60
Q2. Do you think meat produced *in vitro* will be healthy?	32.4	37.5	30.1	21.8	41.2	37.00	42.00	26.1	31.9
Q3. Do you think meat produced *in vitro* will be tasty?	24.3	38.00	37.7	19.6	41.3	39.2	37.40	33.00	29.60
Q4. Do you think the meat industry is really facing important problems (environment degradation, animal welfare, inefficient production to feed humanity)?	66.2	25.2	8.6	81.6	12.6	5.8	47.40	38.60	14.00
Q7. Do you think that *in vitro* meat will significantly contribute to reduce the environmental impact of livestock	39.9	37.1	23.00	32.9	42.00	25.1	33.00	41.70	25.30
Q8. Do you think that *in vitro* meat will significantly contribute to reduce the animal welfare problem?	45.00	37.8	17.2	35.6	46.7	17.7	30.60	47.60	21.80
Q9. As prime minister or chief of your government, will you support financially research on *in vitro* meat?	46.7	37.2	16.1	37.9	42.8	19.3	40.5	35.1	24.4
Q10. According to your perception, will *in vitro* meat be well accepted by consumers? Will consume buy it?	19.2	48.7	32.1	9.2	64.5	26.2	15.5	51	33.5

[1)] Respondents had an oral presentation (paper survey) or a written summary regarding artificial meat (international and French internet surveys) before they answered the questionnaire.

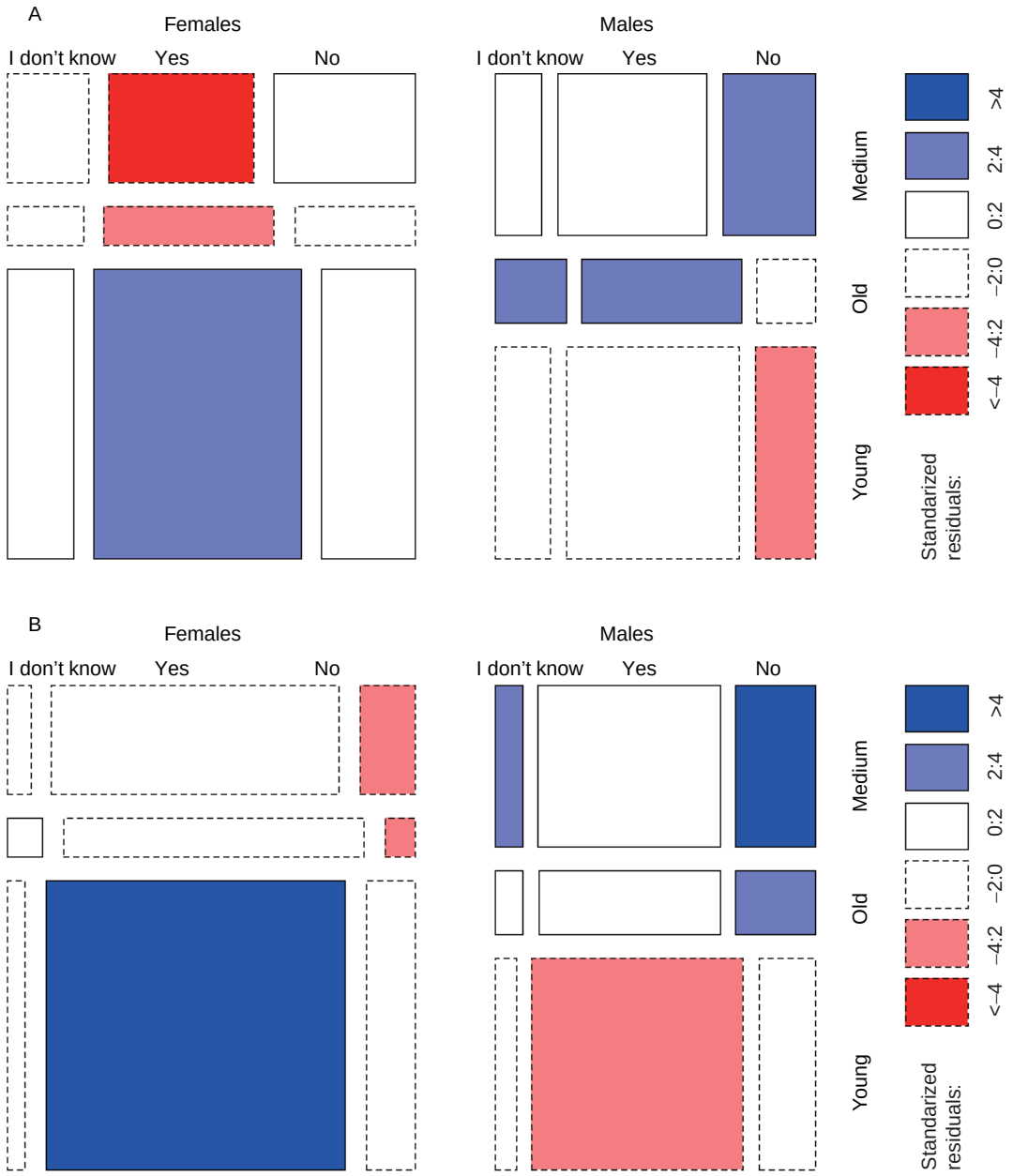

Fig. 1 Distribution of responses by gender and age for: A, survey question 1 "Do you think *in vitro* meat technology is feasible and realistic?" and B, survey question 4 "Do you think the meat industry is really facing important problems such as environment degradation, animal welfare, inefficient production to feed humanity?" Age ranges were classed as follows: Young<30, Medium≥30 and ≤50, Old>50 years. Standardized residuals are standardized differences between observed and theoretical effectives. Over-representations and under-representations of the numbers of respondents in each cell are indicated in blue and in red respectively.

for the French survey) (Table 3). Among respondents, a high proportion of young females, in contrast to the young males, claimed that the meat industry is facing important problems (Fig. 1-B).

Regarding the two questions related to the potential advantages of artificial meat concerning environmental and welfare issues, all surveys showed that some respondents had no strong opinion (from 17.2 to 25.3%). However, while the rest of respondents answered that artificial meat could have some advantages in the international survey, the majority of French respondents and scientific respondents answered the opposite (Table 3).

When compared to other options such as changing nothing in meat consumption, eating no meat or eating less meat, a majority of respondents (59.4% for French people to 64.5% for the other surveys) would recommend eating less meat. However, less were keen to follow this recommendation themselves (41.3% for French people to 58.7% for the

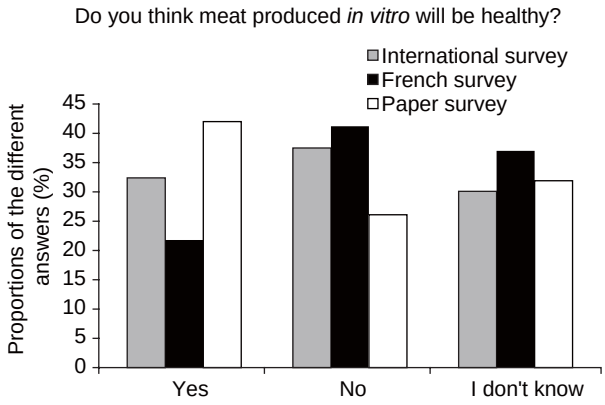

Fig. 2 Answers to question Q2 "Do you think meat produced *in vitro* will be healthy?" Respondents had an oral presentation (paper survey) or a written summary regarding artificial meat (international and French internet surveys) before they answered the questionnaire. The proportions of the different answers.

other surveys). A non-negligible proportion of respondents would recommend changing nothing in meat consumption (from 6.8 to 25.9%), especially for themselves (from 19.3 to 35.8%). The proportion of respondents who would prefer eating no meat or artificial meat was low and did not vary much between groups except for French nationals (Table 4, Fig. 3). This may be due to the fact that a large proportion of the French Nationals were vegetarians.

Regarding the question related to any public financial support to "*in vitro* meat" research, all surveys showed that some respondents had no strong opinion (from 16.1 to 24.4%). However, while the majority of international scientists responding with the internet and paper surveys answered that this type of research could be useful, the majority of French young respondents answered the opposite, and thus do not support any public research on artificial meat (Table 3, Fig. 4).

Regarding the question related to public acceptance of "*in vitro* meat", all surveys showed that some respondents had no strong opinion (from 26.2 to 33.5%), but a majority of respondents (especially young French people) answered that artificial meat will not be accepted by consumers (Table 3, Fig. 5).

3.3. Relationships between answers

Multiple correspondence analyses (MCA) allowed discriminating three groups of respondents based on their answers "Yes" [:1], "No" [:2] or "I don't know" [:0] to questions 1 to 4 and 7 to 10 (Fig. 6): (i) respondents with no strong opinion who responded "I don't know" to most of the questions; (ii) respondents who mainly answered "No" to most of the questions suggesting they are against artificial meat and (iii) respondents who mainly answered "Yes" to most of the questions suggesting they are in favour of artificial meat.

The sole answer which was not associated with any of these groups (Fig. 5) was answer "Yes" to question 4 [Q4:1]: "Do you think the meat industry is really facing important problems (environment degradation, animal welfare, inefficient production to feed humanity)?"

Respondents with no strong opinion were characterised by answers "I don't know" to question 1 [Q1:0] (is artificial meat feasible?), questions 7 and 8 [Q7:0 and Q8:0] (ability of artificial meat to reduce the environmental and the animal welfare problems) and question 9 [Q9:0] (public support in favour of research on artificial meat) (Fig. 6).

Respondents against artificial meat mostly answered "No" to question 1 [Q1:2] (is artificial meat feasible?), question 7 [Q7:2] (ability of artificial meat to reduce the environmental problem) and question 9 [Q9:2] (public support in favour of research on artificial meat) (Fig. 6).

Respondents in favour of artificial meat mostly answered

Table 4 Answers to questions Q5 and Q6 related to the solutions to reduce the potential problems raised by the meat industry[1)]

	Eat no meat (%)	Eat less meat (%)	Eat *in vitro* meat (%)	Change nothing in meat consumption (%)
			International survey	
Q5. To solve the potential problems that the meat industry is facing, do you think that human beings should:	3.1	64.5	11.1	21.3
Q6. Would you prefer yourselves as an individual:	8.9	58.7	7.8	24.7
			French survey	
Q5. To solve the potential problems that the meat industry is facing, do you think that human beings should:	25.4	59.4	8.3	6.8
Q6. Would you prefer yourselves as an individual:	34.0	41.3	5.3	19.3
			Paper survey	
Q5. To solve the potential problems that the meat industry is facing, do you think that human beings should:	0	62.9	10.7	25.9
Q6. Would you prefer yourselves as an individual:	1.4	53.6	9.2	35.8

[1)] Respondents had an oral presentation (paper survey) or a written summary regarding artificial meat (international and French internet surveys) before they answered the questionnaire.

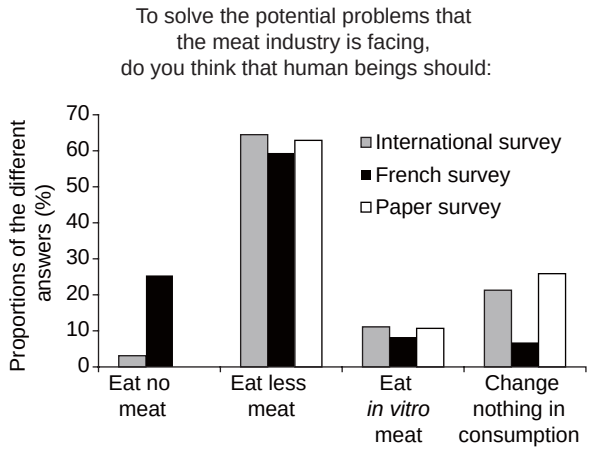

Fig. 3 Answers to question Q5 related to the recommendations to reduce the potential problems raised by the meat industry. Respondents had an oral presentation (paper survey) or a written summary regarding artificial meat (international and French internet surveys) before they answered the questionnaire.

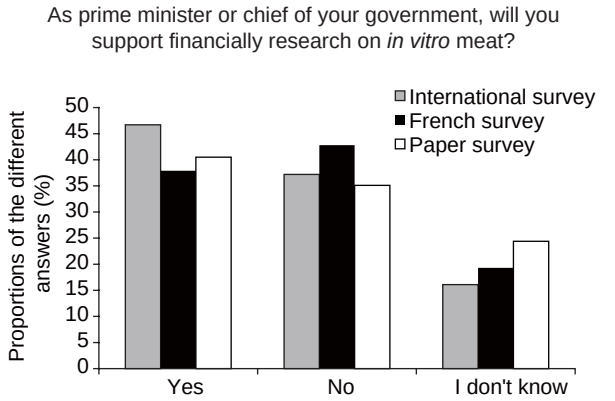

Fig. 4 Answers to question Q9 related to any public financial support to *in vitro* meat research. Respondents had an oral presentation (paper survey) or a written summary regarding artificial meat (international and French internet surveys) before they answered the questionnaire.

"Yes" to question 10 [Q10:1] (acceptance by consumers), and also questions 2 and 3 [Q2:1 and Q3:1] (taste and healthiness of artificial meat) (Fig. 6). Projections of answers to questions 5 and 6 indicated that the answers d (a preference to eat artificial meat) to both questions [Q5:d and Q6:d] were associated to this group of respondents (Fig. 6). Projections of gender, sex, main background and professional activity showed no association of these factors with any of the three groups of respondents (data not shown).

4. Discussion

A majority of the respondents of the international survey

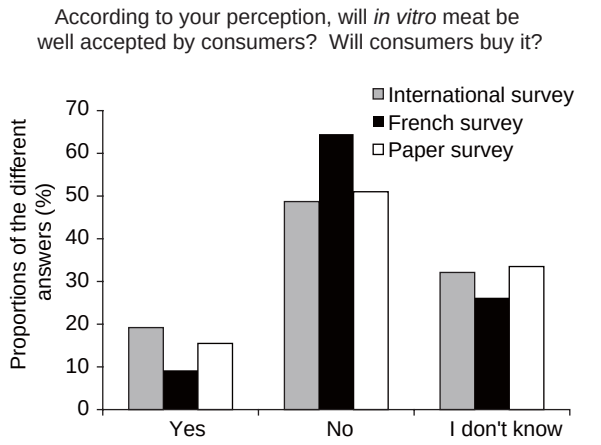

Fig. 5 Answers to question Q10 related to consumer acceptance of *in vitro* meat. Respondents had an oral presentation (paper survey) or a written summary regarding artificial meat (international and French internet surveys) before they answered the questionnaire.

made by internet were scientists. This can be explained by the fact that the French scientists in charge of the survey contacted their colleagues working in different countries. However, most of these scientists did not work in the meat sector. A majority of the respondents of the French survey made by internet were young female who were not scientists. This can be explained by the fact that the French students in charge of the survey contacted their friends who were of a similar demographic, young, not scientists and unaware of the difficulties of the meat sector. In the case of the French survey, a subset of the respondents identified as vegetarians.

Since results were similar between the two surveys made either orally or on internet, results were interpreted for both approaches together. In fact, the surveys were not built so as to give the most faithful possible image of all the meat consumers or the human beings of a gender, a country or a continent. In other words, the investigated population was not representative of all the sectors of society. It was more representative of a fairly uniform population rather than of different social types, since the people belonged mainly to educated environment (scientists and students). Because of this potential bias of the study, we focused our analysis and interpretation on relationships between answers to the different questions for the same respondents.

The fact that, most of the respondents thought that the "*in vitro* meat" technology was feasible and realistic, confirmed our hypothesis. This can be interpreted as people having trust scientists in terms of technology, resulting in cost efficient cultured beef (Moritz *et al*. 2015). Answer to this question was also a main factor discriminating respondents against artificial meat or with no strong opinion. The

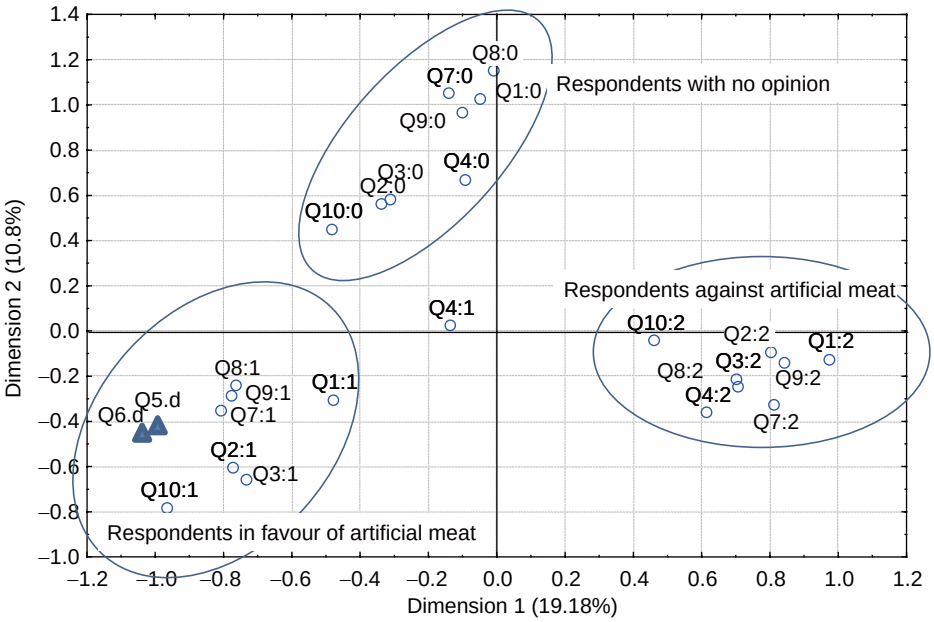

Fig. 6 Multiple correspondence analysis (MCA) performed with questions 1 to 10 (Q1, Q2, Q3, Q4, Q7, Q8, Q9, Q10) except questions 5 and 6 (Q5, Q6) which were projected. Details of the questions are indicated Table 1. Each data point is labeled with the question number e.g., Q1 and the numerical code of the response. The three responses possible "I don't know", "Yes" and "No" are indicated by 0, 1 and 2, respectively. Associations between variables are uncovered by calculating the chi-square distance between different categories of the variables and between the individuals (or respondents). Data are represented as points in a Euclidean space to visualize associations between variables. Variables near each other at the periphery of the graph are positively associated, orthogonal variables are independent and variables separated by 180° are negatively associated. The closer to the periphery, the higher is the association between variables. The analysis was performed with answers to questions 1 to 10 (Q1, Q2, Q3, Q4, Q7, Q8, Q9, Q10), excluding questions 5 and 6 (Q5, Q6) which had a different answer format. For these questions answers d, which indicated a preference for eating artificial meat were projected on to the graph.

oral explanations given during the paper survey may have even increased the proportion of convinced people and decreased the proportion of hesitating people. Even people who are not scientists trust researchers to invent new powerful technologies as the one which concerns artificial meat production. Indeed, *in vitro* meat may be a potential method to reduce animal suffering and environmental issues problems, even if artificial meat is commercialized only as ground, processed foods such as hamburgers or hotdogs as a main component or as an additive (Datar and Betti 2010). Interestingly, older females tended to be less accepting of the technology than young females. One can hypothesized that the young females may have a higher scientific culture than older one and may be more opened to new technologies. In addition, females, especially young ones, were more convinced that the meat industry is really facing important problems (environment degradation, animal welfare, inefficient production to feed humanity), which has a positive relationship with the first question regarding the feasibility of artificial meat.

Interestingly, even if the technology is judged feasible and realistic, only a minority of respondents in the two internet surveys thought that artificial meat will be healthy and tasty. The "Yes" answer to this question was also a main factor characterising respondents in favour of artificial meat, who were in addition less discriminated by the next questions. The high proportion of "I don't know" answers confirmed that respondents were hesitating. In contrast, more respondents believed that artificial meat could be healthy and tasty in the paper survey. This may be explained by the fact that scientists can be progressively convinced by oral explanations in contrast to internet surveys where respondents had some efforts to do by themselves to read the provided abstracts and understand the technology. To summarize, respondents trust scientists to rebuild the muscle tissue, but cultured myocytes is different to meat and the true muscle architecture would be more of a challenge to replicate. It can also be argued that "natural" food was always better than "artificial" one (Hopkins and Dacey 2008; Frewer *et al.* 2011) and that other means will be available to better predict meat quality which is a complex concept aggregating intrinsic quality traits (which are the characteristics of the product itself) and extrinsic quality traits (which are more or less associated to the product for instance how it is produced) (for a review, see Hocquette *et al.* 2012). However, a statement from the University of Maastricht indicated that

technological processes will be employed to create flavor and texture in *in vitro* meat that is similar to standard meat. Similarly, other authors claimed that the implementation of an *in vitro* meat production system creates the opportunity for meat products of controlled and various characteristics to be put onto the market (Datar and Betti 2010).

The next question related to the previously discussed challenges facing the meat industry also had clear trends. Most of the respondents agreed that the meat industry is facing serious problems. This is likely to be due to respondents having been convinced by the circulating ideas in the media (Goodwin and Shoulders 2013) concerning animal welfare or environmental issues regarding livestock and the difficulty to feed the increasing human population. However, there were some concerns that the phrasing of the question led to a higher amount of positive responses. Respondents that were not aware of any issues in the meat industry may have been more likely to answer yes, creating a positive bias in the survey. On the contrary, during the oral presentation and discussions in the paper survey, some respondents were influenced by those working on meat or knowing the meat sector making the proportion of respondents agreeing that the meat industry is facing serious problems lower. On the other way, young people as in the French survey, or more generally young females, were more convinced that we had an important problem to solve regarding meat production. Supporting this interpretation is the high (79.5%) proportion of respondents under 30 thought that the meat industry is facing important problems.

However, one of the major key arguments of Prof. Post (2012, 2014) and by vegetarians (Hopkins and Dacey 2008) that eating artificial meat or eating no meat will solve the lead to increased animal welfare and reduced environmental impact was not confirmed by the respondents' answers. Those respondents who recognized issues within the meat industry, but were unwilling to eat artificial meat may seem a little contradictory. The preferred solution by these respondents was to simply consume less meat than to eat artificial meat or to eat no meat. Some people think that eating less meat could be even more efficient. Curiously, among the people who were ready to recommend artificial meat, not all of them were willing to eat it themselves. In addition, "Yes" answers to questions 7 and 8 were also a main factor discriminating respondents against artificial meat or with no strong opinion, indicating that these questions are key questions to potentially convince people about artificial meat.

Eating less meat is a possible solution that would require the least amount of change to normal consumer habits, and so will generally be the most attractive. The preferences by some consumers to eat less meat in response to the issues within the meat industry are not supported by current consumer behavior at the World level. In fact demand for meat is increasing and is expected to increase for at least the next 40 years (Godfray *et al.* 2010). This indicates that despite the respondents' answers that they would prefer to eat less meat than eat artificial meat, consumer demand will continue to grow creating a gap between demand and supply that artificial meat has the opportunity to fill.

One possible hypothesis is that respondents needed to be sure that artificial meat will be completely safe, tasty enough and healthy enough, and at present the results of our questionnaire indicate that they are not convinced. For them, human healthiness and safety are also key priorities in addition to animal welfare and environmental issues. In general, respondents indicated that we must first satisfy nutritional and hedonic requirements of consumers, the vast majority of which are regular meat eaters. However even if these requirements are met, there may be competition from other products such as insect (FAO 2013) or plant based proteins (Pimentel and Pimentel 2003), which also have the benefit of reduced environmental impacts and enhanced animal welfare. In any case, the apparent contradiction between the importance of the problems to solve and the relative inefficiency of the solution chosen by respondents (eating less meat) is an important matter for debate.

Saying that artificial meat will solve welfare and environmental issues is a major argument from Prof. Post (2012, 2013). The argument is simply to be understood: we need less and almost no animals to produce artificial meat and its production which will not produce any methane unlike herbivores. However, most of the respondents were not convinced because it can be argued that huge incubators used to produce meat will consume electricity, fossil energy and that the net environmental footprint will not be simple to calculate (Hocquette *et al.* 2013). It can be also argued that the elimination of animals required to produce food will result in different problems. Animals will still be required for dairy and fiber production. If artificial meat production is a sudden success there may be millions of meat animals that no longer have a purpose and are therefore wasted. There will be a large reduction in diversity if all the domesticated meat producing breeds are no longer cultivated, though if these species remain and develop wild populations, there could be devastating ecological consequences for both the natural environment and agricultural land with over population and crop damage.

At the end of the survey, on average, several negative points regarding the production of artificial meat have been pointed out (respondents were not sure it will be tasty, healthy, environmental friendly and better for farm animals). However, some respondents (especially those in favour of artificial meat) would like to support research on artificial meat if they would have the power to decide so as prime ministry or research ministry. Most of the people argued

artificial meat has a great potential, but it must be proven first, before consumers will accept it. In addition, almost all authors agree that more research is required because a major hindrance for a potential success of artificial meat is the difficulty to develop viable mass production techniques (Datar and Betti 2010; Hocquette *et al* 2013). For many other reasons, the future of artificial meat produced from stem cells was judged uncertain at this time (Bonny *et al*. 2015).

Despite respondents positively responding to public financial support of research into artificial meat, most of them confessed they believed that consumers will neither buy nor consume artificial meat. This is in line with the fact that most authors agree that consumer acceptance, in addition to cost-effectiveness, will determine if artificial meat will become a significant meat alternative on the market (Datar and Betti 2010; Hocquette *et al.* 2013; Verbeke *et al*. 2015). Consumers may be afraid by the word "artificial" and that today, most of them do not like any type of artificial food. Consumer fear regarding artificial meat might be similar to consumer fear relating to GMO's. Artificial meat is a new product, not yet known by consumers, who may be afraid of it because new, not surely healthy, neither tasty and that the process to make it is unclear or unknown so far (Frewer *et al.* 2011; Verbeke 2011). It can also be argued that eating will always be a pleasure, or must be a pleasure and that pleasure will not be provided by artificial meat. However, other sources of pleasure are now available in our society such as travelling, practicing sports, watching movies or reading books giving less and less space to the pleasure of eating. In fact, there are huge variations in consumers' perspectives regarding the need for change in meat consumer practices. Understanding more about the diversity of consumer views is probably a main issue in the long term future (Vinnari and Tapio 2009).

5. Conclusion

According to its promoters, artificial meat has the potential to make eating animals unnecessary. It has also the potential to reduce carbon footprint of meat production. In addition, it has the potential to satisfy all the nutritional requirements and hedonic wishes of normal consumers. However, the vast majority of consumers regularly consumes meat, and would continue to do even in the context of an increased human population and therefore in a context of increasing food needs. This survey demonstrates that this apparent illogical way of thinking is common for most respondents. Indeed, while a majority of people trust the artificial meat technology and believe that the meat industry is facing major problems, they do not believe that artificial meat is an evident solution which could be efficient to solve the afore mentioned problems with the meat industry. Indeed, according to these respondents, artificial meat will not necessarily reduce animal requirements, or will not dramatically reduce carbon footprint for meat production. These arguments are the main ones discriminating hesitating respondents or respondents against artificial meat. In addition, for most respondents, consumers will not buy or consume it in majority. Despite these limitations, respondents would continue to support research on artificial meat. We speculated that the apparent contradictory answers to this survey express the dual feeling of people towards science. On one hand, people trust scientists because researchers continuously discover new technologies potentially useful in a long term future for the society. But, on the other hand, a majority of people express concern for their health. Except respondents already convinced by artificial meat, most respondents are not sure that artificial food will be tasty, safe and healthy enough to be consumed without any doubts.

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REVIEW

Challenges and prospects for consumer acceptance of cultured meat

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Abstract

Consumer acceptance of cultured meat is expected to depend on a wide diversity of determinants ranging from technology-related perceptions to product-specific expectations, and including wider contextual factors like media coverage, public involvement, and trust in science, policy and society. This paper discusses the case of cultured meat against this multitude of possible determinants shaping future consumer acceptance or rejection. The paper also presents insights from a primary exploratory study performed in April 2013 with consumers from Flanders (Belgium) (*n*=180). The concept of cultured meat was only known (unaided) by 13% of the study participants. After receiving basic information about what cultured meat is, participants expressed favorable expectations about the concept. Only 9% rejected the idea of trying cultured meat, while two thirds hesitated and about quarter indicated to be willing to try it. The provision of additional information about the environmental benefits of cultured meat compared to traditional meat resulted in 43% of the participants indicating to be willing to try this novel food, while another 51% indicated to be 'maybe' willing to do so. Price and sensory expectations emerged as major obstacles. Consumers eating mostly vegetarian meals were less convinced that cultured meat might be healthy, suggesting that vegetarians may not be the ideal primary target group for this novel meat substitute. Although exploratory rather than conclusive, the findings generally underscore doubts among consumers about trying this product when it would become available, and therefore also the challenge for cultured meat to mimic traditional meat in terms of sensory quality at an affordable price in order to become acceptable for future consumers.

Keywords: acceptance, artificial, attitude, consumer, cultured, *in vitro*, meat, synthetic

1. Introduction

Until recently, new product development in the meat sector has typically focused on secondary processing activities during the post-slaughtering phase that aimed at differentiation from the rest of the products in the commodity meat market. Consumer insight has always been crucial to ensure that the new developments were in line with consumer preferences and to enhance the likelihood of commercial success (Grunert *et al.* 2011). The idea of growing meat from animal cells (Post 2012) presents itself as a radically new way of obtaining meat through substituting livestock production at the very beginning of the meat production chain. This evolution has been referred to as "the third stage in meat production", after hunting and herding (Welin 2013). The technology may

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provide a possible solution to several problems facing current livestock production such as reducing the environmental impact of livestock farming, eliminating issues about animal welfare and slaughter, and improving meat safety and healthiness, although some of this potential is debated as well at least in the short term (reviewed by Hocquette *et al.* 2013). Commonly used names for the resulting product are cultured, *in vitro*, synthetic, artificial, and laboratory-grown or factory-grown meat. The term 'cultured meat' will be used in the present paper.

Cultured meat represents indeed a totally new development with possible benefits but also some issues of debate. Several published studies thus far are situated in the natural sciences domain and have focused on technological aspects, advancements and challenges facing the culturing of meat, most of which are believed to be solvable at some point in time (Datar and Betti 2010; Post 2012, 2014). Meanwhile, a growing number of social sciences studies have focused on sociological, philosophical, moral and ethics arguments around the issue (Pluhar 2010; Chiles 2013; van der Weele and Driessen 2013; Welin 2013; Marcu *et al.* 2015). Up to the present day, it remains largely unknown though how consumers will react to this new technology and, whether and under which conditions they would be willing to accept and adopt this novel food.

While consumers may be likely to place less importance on the issue as long as the product is not available and the time of availability is uncertain (Goodwin and Shoulders 2013), consumer insight will be indispensable for future marketplace acceptance. Several recent examples, such as biotechnology and nanotechnology illustrate that consumers may not embrace novel agro-food technologies as enthusiastically as hoped for at the times when the technologies were developed and adopted (Verbeke 2011). de Barcellos *et al.* (2010), for example, indicated that while consumers may support the development of non-invasive (processing) technologies that improve the healthiness and eating quality of meat, they are very reluctant to manipulations and interventions that are perceived as excessive, invasive and non-natural in meat production chains.

The aim of the present paper is to provide a brief review of first, the criteria or determinants that can be expected to shape consumer acceptance of cultured meat and its production technology and second, the possible reactions, concerns and questions that consumers might raise when facing this new technology and novel food product. Furthermore, this paper presents exploratory findings from a primary quantitative study with consumers in Flanders (Belgium) probing about their initial reactions when facing the idea of cultured meat as a future substitute for traditionally produced meat.

2. Criteria shaping consumer acceptance

Apart from the potential of cultured meat to meet and cope with some of the challenges associated with current livestock production, the question about its acceptability by the general public and consumers must be addressed. Numerous criteria shaping consumer acceptance of novel agro-food technologies and their resulting end-products have been discussed in previous studies. It is an interesting exercise to review and check the case of cultured meat production technology against each of these criteria, and to critically reflect on the complex picture of possible advantages and disadvantages from the perspective of future end users.

Two recent reviews identified about 15 different issues impacting on consumer acceptance of novel agro-food technologies in general (Frewer *et al.* 2011; Rollin *et al.* 2011), while Hopkins and Dacey (2008) proposed about a dozen possible objections that might be provoked if a product like cultured meat would be put on the market. A first set of determinants of acceptance or rejection included the perceived personal and societal benefits and risks of the technology, as well as perceived differences in who eventually benefits and who bears the risks associated with the technology and its end products. Hence, a major challenge lies in identifying the real and perceived benefits and risks of cultured meat (and its production technology), as well as in providing transparency about who (e.g., primary producers, industry, individual consumers or, society as a whole) is bearing them.

A second set of determinants of consumer acceptance or rejection is related to the technology itself. Technology-related perceptions pertain to perceived scientific knowledge or uncertainty (which is still substantial in the case of cultured meat, e.g., scalability of the production process or the replacement of serum-based culture media), perceived controllability of the technological processes (e.g., quality control and safety monitoring of cell and tissue cultures), and perceived naturalness of the technology and product. The perceived naturalness of food and food production technologies, for example has been shown to strongly influence the acceptance of innovative food technologies (Siegrist 2008).

Furthermore, the perceived efficacy of the regulatory framework and general trust in science and regulation in the food domain were identified as trust-related issues that determine public and consumer acceptance of novel agro-food technologies. Other issues pertain to the level of public or consumer involvement in the technology development process, as well as public awareness or familiarity with the technology, each of which is almost non-existent at the present time for the case of cultured meat. Also possible cognitive associations or attitude activation play a role,

such as associations linked to other technologies owing to the name of the technology or the type of manipulations involved. It can be expected for example that the term '*in vitro*' will activate attitudes, ideas or emotions linked with *in vitro* fertilization or with *in vitro* laboratory practices like the more contested biotechnology or growth processes in bioreactors. Alternatively, the use of other names like 'artificial' or 'synthetic' may evoke thoughts or strengthen perceptions of unnaturalness. Finally, ethical concerns (which may play in favor of cultured meat as far as animal welfare is concerned, and as far as the technology is not too much perceived as 'tampering with nature' or 'playing God') and socio-cultural differences were identified as factors shaping consumer reactions to novel agro-food technologies.

Frewer *et al.* (2011) also concluded that especially technologies characterised as having a 'bioactive' component raise particular concerns among people. This is mainly because of feared possible unpredictable effects, the risk of uncontrolled use and ethical concern, more so than because of perceptions of unnaturalness or unfamiliarity. Rollin *et al.* (2011) pointed in addition to effects from information and media coverage, as well as the objective (factual) and subjective (perceived) knowledge of consumers, and the possible role of product labelling. They explicitly referred to the role of media, the content of media reporting and the quantity of media coverage as determinants of consumer acceptance or rejection. An interesting remark is the fact that even positive intended information can fuel consumer resistance because it can increase awareness of previously unknown risks (Verbeke *et al.* 2007). Driessen and Korthals (2012) mentioned the fact that the development of cultured meat had already given rise to heightened media attention in the Netherlands, for example, and this prior to the highly publicized tasting of the first cultured meat burger in August 2013 in London (Hopkins 2015). Goodwin and Shoulders (2013) analysed the media coverage about cultured meat in the United States (U.S.) and the European Union (prior to the August 2013 cultured burger tasting) and concluded that print media were primarily supporting the idea of cultured meat production. Problems associated with conventional or traditional meat production as well as the advantages of cultured meat were mostly discussed in the print media, and information sources included mainly proponents of cultured meat, which may have positively influenced initial consumer reactions. However, details on the technology described by the print media were felt to be too technical and possibly confusing for the wider public. A more recent analysis of Western media coverage after the August 2013 cultured burger tasting (Hopkins 2015) concluded that mass media provided a quite distorted picture of the obstacles in the path of cultured meat acceptance, notably through portraying mainly vegetarian consumers' reactions and referring mainly to cultured meat's future potential as a meat substitute for vegetarian or vegan consumers who still constitute only a niche market in most countries.

When evaluating the aforementioned criteria more specifically against the case of cultured meat, three major issues seem to predominate. The first issue pertains to the perceived (un)naturalness of 'factory-growing meat'. The perceived unnaturalness of the manufacturing process could lead to strong reticence among the general public and consumers, considering that the process represents yet another manipulation of nature to the advantage of man. In other words, although cultured meat may contribute to solving major ethical concerns with respect to livestock farming and animal slaughter for human consumption, and may contribute to the alleviation of hunger problems in the world, the technology for producing meat might as well be perceived as intervening and messing too much with nature. Although the perceived (un)naturalness can be expected to be one of the most problematic issues for cultured meat (Hopkins and Dacey 2008), it has been argued also that a product may be natural even if produced in an unnatural way, and that the natural or unnatural status of a product does not necessarily mean the product is good or bad (Welin 2013). In addition, the artificial character of cultured meat may be seen by others as an advantage since production in a fully controlled environment prevents eventual harmful consequences of natural meat production (e.g., zoonotic risks) where animals are also increasingly perceived to be reared under rather unnatural conditions (Hopkins and Dacey 2008). Besides, *in vitro* cell culture involves the use of natural biological mechanisms and a similar technology is widely accepted in other areas, such as medical applications or *in vitro* fertilization (Welin and van der Weele 2012). With respect to the manufacturing process and its operational scale, Post (2014) argues that the acceptance of cultured meat might further depend on the concrete implementation of the technology in future food production. He gives the example of homemade beef in an incubator with a similar appearance as any other commonly used kitchen appliance. Cultured meat produced in one's own kitchen (i.e., kind of 'self-made') is according to Post (2014) likely to be perceived quite differently (and perhaps as less unnatural) than cultured meat produced on large industry scale in a factory by a multinational food company. Hence, homemade or 'home-cultured' meat may perhaps be more acceptable to consumers.

A second major issue pertains to possible repulsion or the so-called 'yuck factor' as the typical initial reaction that consumers might feel at the idea of eating cultured meat (Pluhar 2010). As with many other new foods or technologies applied in the food chain, the very idea of commercializing a novel product generates fear. In the case of cultured meat,

potential neophobia may be exacerbated first, because food is not like any other product and second, because both simple aversion to new foods (food neophobia, Pliner and Hobden (1992)) and fear for unknown or unfamiliar technologies (food technology neophobia, Cox and Evans (2008)) may reinforce each other for this specific product. The cultural and identity dimensions of food, together with the fact that the product's constituents will enter the body as a result of biological transformations occurring after its ingestion, may accentuate this potential fear and therefore the likelihood of reticence to purchase cultured meat. Furthermore, it has been shown that disgust reactions are particularly strong towards unfamiliar foods from animal origin, mostly owing to their expected aversive textural properties and reminders of livingness or animalness (Martins and Pliner 2005).

By contrast, the promoters of cultured meat argue that once the manufacturing process has been fine-tuned and explained to the public, consumer repulsion may decrease. Furthermore, this type of reticence is in no way specific to the case of cultured meat (Hopkins and Dacey 2008; Bhat and Bhat 2011). For example, the launching of products such as surimi or tofu sparked considerable debate; their novel nature generated much concern in Western societies before these products became established, even though they consisted of a raw material which was familiar to the general public. In addition, if consumers were fully aware of the conditions and technologies currently associated with livestock production, animal slaughter, or meat processing, many of them might feel disgust as well and turn away from eating meat.

The third major issue relates to the perceived healthiness or consequences for personal health from eating cultured meat. The possible risks associated with the manufacturing and distribution of a new 'technological' product that has not been validated or assessed for its effects on human health, may induce concern among consumers. As seen with genetically modified organisms (GMOs), the launching of cultured meat is bound to be controversial and its large-scale acceptance may depend on the progressive unveiling of the advantages and/or disadvantages of the product together with guarantees from trustworthy public authorities and market participants. Issues such as how safety controls are performed and guaranteed, how credible and transparent the information is, and how regulatory structures and procedures are set up are major challenges in this respect (Driessen and Korthals 2012).

3. Preliminary insights from consumer studies

Vanhonacker *et al.* (2013) investigated consumer interest in available substitutes for meat in the context of a more sustainable food choice in Flanders (Belgium). Although many consumers may already have changed their meat consumption habits in Western Europe during the last decade because of consecutive meat safety crises since the mid-nineties (Verbeke *et al.* 1999, 2005), the readiness to further reduce meat consumption seemed quite prominent. Consumers' claimed willingness to reduce meat consumption was very high with 72% of the sample reporting to be willing to decrease their meat consumption in the coming years. In the same study, 73% of the participants reported a willingness to shift to more ecologically friendly meat substitutes, 45% to hybrid meat types (presented as mixtures of animal-based and plant-based protein) and 35% to plant-based protein instead of meat. By contrast, only 5% reported to be willing to shift to insect-based protein. Multiple reasons can be found for intentions to reduce meat consumption, ranging from the often-mentioned meat safety, healthiness and animal welfare concerns to the more recent awareness about the ecological impact, sustainability issues and frauds facing traditional livestock and meat production and commercialization. While cultured meat may provide an answer or partly solution to these issues, it remains to be investigated whether consumers will also perceive cultured meat and its way of production as a solution that is realistic, feasible and effective.

Mattick and Allenby (2012) highlighted the possible positive and negative economic, social and environmental implications of a shift to what they call "factory-grown meat". They pointed to a considerable amount of uncertainty with respect to regulatory issues, technology adoption and production processes. Their overview flagged important social, political, cultural and ethical challenges and finally, they pointed to public perception and the likelihood of consumer acceptance which were explicitly referred to as largely unknown and un-investigated thus far.

Sustainable consumer acceptance of cultured meat will depend on the product-related expectations and experienced performance upon product usage. Besides perceptions about how the product has been produced, the product will be evaluated in terms of attributes that provide consumers with relevant benefits that ultimately yield satisfaction and possible repeat purchase. As with any food product and if adequately informed, consumers will not be willing to compromise on food safety. Expectations in terms of taste, healthiness, affordability and sustainability will also have to be met. Even if consumers are willing to try this novel product, such willingness does not reveal much about the likelihood of repeat purchase or a sustainable change of eating habits. Saeed *et al.* (2013) showed how the trial of meat products can change quality perceptions and influence the formation of future purchase intentions, in particular in those cases where positive expectations were

not confirmed during trial. By lack of product experience thus far, consumers can be expected to form expectations based on the information received (e.g., mass media coverage) and based on image transfer from more familiar technologies and products. The positioning of cultured meat as a substitute or as a complement for conventional meat will be very important because consumers are likely to refer to products with a similar positioning in the market when forming product-related expectations.

While numerous studies exist on consumer acceptance of novel agro-food technologies such as genetic modification, food radiation, nanotechnology and cloning, studies about consumer reactions to the concept of cultured meat are still very scarce at this moment. Based on an exploratory poll flagged as 'unscientific' by the author herself because of its exploratory nature, Pluhar (2010) reported that the initial U.S. consumer reaction to cultured meat was mainly one of repulsion owing to associations with horror and the possible use of objectionable additives in a laboratory setting. In a recent study exploring public sense-making around cultured meat and involving participants from different European countries, Marcu *et al.* (2015) and Verbeke *et al*. (2015) found that consumers raised many questions about diverse issues such as product safety, nutritional content, price, as well as about technological procedures, scientific uncertainties, and social, economic, and cultural implications relative to current livestock production and agribusinesses. These questions encapsulated both concerns and curiosity. Their study also revealed that much of people's reasoning around cultured meat mirrored reasoning seen or heard previously around other biotechnologies such as GMOs or animal cloning. The authors concluded that cultured meat production is likely to inherit considerably from previous technological controversies, and therefore participation of, and interaction with the broader public will be crucial in the future development and marketing of cultured meat.

Nevertheless, a quantitative study in the Netherlands performed in February 2013 (thus, prior to the August 2013 cultured burger tasting) with about 1 300 participants indicated that most people (79%) had never heard of cultured meat. Only few had heard of it and claimed to know what it is about (14%) (Flycatcher 2013). After explaining the technique and the possible advantages and disadvantages associated with cultured meat production, nearly two-thirds (63%) supported the idea of producing cultured meat. More than half of the participants (52%) in that study claimed to be willing to try cultured meat while almost one quarter was doubting (23%) and another quarter reported they would never want to try it. In a similar vein, in an internet poll organized by The Guardian in the United Kingdom (U.K.) in 2012, 68% of the participants indicated they would be willing to eat "lab-grown meat" (The Guardian 2012).

4. Primary exploratory consumer study about cultured meat

4.1. Materials and methods

We performed an exploratory study on consumers perceptions of cultured meat through a web-based survey in Flanders (the northern Dutch-speaking part of Belgium) during April 2013. The study used a convenience sampling procedure and targeted mainly a student population. Hence, the exploratory insights obtained from this study mainly apply within the characteristics of the sample, whereas generalization to the overall population remains speculative. The sample (n=180) contained an almost equal share of men (45%) and women (55%), but it was biased towards younger age (73% younger than 30 years) and higher education (60% with higher education). First, participants were asked about their meat consumption habits and possible reasons to eat less meat. Details about items and measurement scale are presented with Table 1. The next section of the survey focused on cultured meat. The primary term used in the study was '*in vitro* meat', but it was explicitly mentioned that 'cultured meat' is an alternative and often used term with the same meaning. After probing the unaided awareness about cultured meat, basic background information about cultured meat was presented. Expectations about cultured meat were measured for five attributes using seven-point semantic differential scales (Table 2). Three statements were also included comparing expectations about cultured meat directly with traditionally produced meat in terms of expected price, taste and sustainability. Next, participants evaluated the production of cultured meat as a substitute for conventional production of meat in terms of 'good', 'feasible, 'acceptable', 'effective', 'long term solution (to the problems facing livestock production)'. Finally, claimed willingness to try, purchase and eventually also pay a price premium for cultured meat were measured, first, after the provision of basic information about cultured meat and, a second time after additional information was presented (see footnote Table 3). The additional information stressed the problems facing conventional meat production and explicitly referred to the potential of cultured meat production as a possible solution. Note that this type of additional information reflects the viewpoints of proponents of cultured meat, which is consistent with the dominant media coverage seen thus far (Goodwin and Shoulders 2013). The last part of the questionnaire registered socio-demographics including gender, age and education level.

4.2. Results

Most participants were meat eaters who almost never ate

vegetarian meals (61.1%). While some claimed to eat both meat and vegetarian meals on regular basis (22.8%), 16.1% of the participants claimed to eat mostly vegetarian meals. Mean scores around the midpoint (4) of the scale were reported for possible reasons to reduce meat intake, except for intending to eat less meat because it is too expensive. This suggests that the price of meat is not a major argument for most participants to reducing meat intake. When comparing the three segments based on meat consumption, more extreme values were observed. Consumers who ate vegetarian meals more frequently, agreed more strongly that being against the practices in traditional meat production, wanting to consume more in an ecologically friendly way, and being more convinced that eating less meat is healthier were stronger motivations for them intending to reduce or stop meat consumption (Table 1).

Similarly as in the Netherlands where 14% of the study participants had heard of cultured meat and claimed to know what it is about (Flycatcher 2013), 13% of the participants in our study stated to have heard of cultured meat and to know what it is about (Table 2). Half of the participants (51%) had never heard of cultured meat while 36% reported to have heard about it but not to know what it is about. These findings show that cultured meat was hardly known among Flemish consumers, at least before the August 2013 cultured burger tasting and consecutive media coverage. There were no significant differences in the claimed awareness of cultured meat between the three meat consumer groups (P=0.809).

After basic information about cultured meat was provided, participants expressed their beliefs and expectations about it. In general, participants believed cultured meat would be safe, nutritious, ecological and ethical (Table 2), while they scored neutral in terms of expected healthiness. Compared to traditional meat production, cultured meat production was expected to be more sustainable, but yielding slightly less tasty and more expensive meat. Cultured meat was generally positively evaluated as a possible substitute for traditional meat in terms of perceived goodness, feasibility, acceptability and effectiveness (Table 2). The expectations about cultured meat and cultured meat production as an alternative for traditional meat production did not differ significantly between the three meat consumer groups (F-tests, all P>0.05), except for expected healthiness (P=0.004). Cultured meat was perceived (or expected to be) as healthier by consumers who ate both meat and vegetarian meals compared to those who mostly ate vegetarian meals. A possible explanation may be that consumers eating mostly vegetarian meals are more strongly convinced that meat is simply less healthy than the plant-based or other types of meat substitutes they have gradually adopted, while they may perceive cultured meat still as 'meat', and thus as being less healthy for them. This finding suggests first, that vegetarian consumers may perceive meat as unhealthy no matter whether it has been traditionally produced or cultured, and second, that vegetarian consumers are generally satisfied with the alternatives they have adopted and thus see little or no reason for returning to consuming (cultured) meat.

Two out of three participants (67%) indicated that they would maybe be willing to try cultured meat if it was available on the market. One quarter (24%) indicated surely wanting to try it (Table 3). Additional information stressing the environmental problems associated with conventional livestock and meat production, resulted in 43% of the participants claiming to surely, and 51% claiming to maybe wanting to try cultured meat. About half of the participants who initially claimed not to be willing to try cultured meat, changed their opinion after receiving the additional information into 'maybe willing' to try it, but none of them switched to 'surely wanting to'. In a similar vein, 29% of those initially 'maybe wanting' to try cultured meat switched from 'maybe' to 'surely' wanting to try cultured meat. In addition, those who claimed initially to be willing to try cultured meat (i.e., before receiving the additional information) did not change their mind afterwards. As a result, providing additional information on the benefits of producing cultured meat (relative to the problems facing traditional livestock production) positively impacted the claimed willingness to try it, resulting in a higher proportion

Table 1 Possible reasons to reduce or stop eating meat, and mean scores (SD) on 7-point interval scales (1=Totally disagree, 7=Totally agree) for the total sample (n=180) and meat consumer groups

"I may plan to reduce or stop eating meat because …"	Total sample (n=180)	Meat consumers (61.1%)	Meat and plant-based meat substitute consumers (22.8%)	Mostly plant-based meat substitute consumers (16.1%)
I am against the practices in traditional meat production	3.99 (1.75)	3.41 e	4.32 f	5.72 g
I want to behave more ecologically friendly and therefore eat less meat	3.94 (1.99)	3.12 e	4.51 f	6.24 g
I am convinced that eating less or no meat is healthier	3.52 (2.05)	2.86 a	4.02 b	5.28 c
I believe meat is too expensive	2.45 (1.62)	2.08 a	2.85 ab	3.28 b

a, b, c indicate significantly different means using Scheffe Post Hoc comparison tests (P<0.05); e, f, g indicate significantly different means using Dunnett T3 Post Hoc comparison tests (P<0.05).

Table 2 Awareness (%) and expectations about cultured meat (7-point semantic differential scale) and evaluation of *in vitro* meat as an alternative for traditionally produced meat (1=Totally disagree, 7=Totally agree) (*n*=180)

Awareness about cultured meat: "Have you heard about *in vitro* meat?"	%	
Yes, and I know what it means	13.0	
Yes, but I do not know what it means	36.0	
No, I have never heard of *in vitro* meat	51.0	
Expectations about cultured meat	Mean	SD
Not healthy (1)–very healthy (7)	3.98	0.92
Not safe (1)–very safe (7)	4.64	1.24
Not nutritious (1)–very nutritious (7)	4.59	1.13
Not ecological (1)–very ecological (7)	4.91	1.26
Not ethical (1)–very ethical (7)	4.73	1.62
Much more expensive (1)–much cheaper than traditional meat (7)	3.31	1.52
Much less tasty (1)–much tastier than traditional meat (7)	3.38	0.90
Much less sustainable (1)–much more sustainable than traditional meat (7)	5.12	1.28
"I believe *in vitro* meat as a substitute for traditional meat is …"	Mean	SD
Good	4.61	1.41
Feasible	4.35	1.43
Acceptable	4.58	1.44
Effective	4.53	1.41
A long term solution	4.84	1.63

Table 3 Frequency (%, *n*=180) of participants claiming to be 'not', 'maybe' and 'surely' willing to try, purchase and pay a price premium for cultured meat

	Basic information about technology[1)]			Additional information about benefits[2)]		
	Not	Maybe	Surely	Not	Maybe	Surely
Willing to try	9.4	66.7	23.9	6.1	51.4	42.5
Willing to purchase	11.7	68.9	19.4	5.6	58.1	36.3
Willing to pay more	42.2	43.9	13.9	36.3	27.9	35.8

[1)] Basic information: "*In vitro* meat, which is also called 'cultured meat', is meat produced in a laboratory using stem cells from an animal and a suitable growth medium. This way, it may be possible to cultivate basically one million ton of meat muscle tissue by using stem cells from one animal. This could be an alternative to traditional meat as we know it nowadays. The product should not be confused with meat substitutes like tofu or quorn because it is real meat, only it has not been obtained as part of a living animal." This basic information was combined with the visual flowchart "How it works" based on Daily Mail (2012).

[2)] Additional information: "Currently about one-third of Earth's land area is agricultural land. About two-thirds of this agricultural land is used for cultivating livestock, which is responsible for about 18% of the greenhouse gas (GHG) emissions. This is more than the transportation sector. The environmental problems associated with livestock production could partially be reduced by no longer producing meat in the traditional way but instead produce meat *in vitro*. This could lead to a 96% reduction of GHG emissions compared to traditional meat. By culturing meat in a lab, one could also prevent diseases such as mad cow disease and microbiological infections, such as *Salmonella*. Also the fat composition of the meat can be improved, for example by enriching the meat with omega-3 fatty acids." Note that this information message explicitly points at the environmental burden of traditional livestock production, while it is univocally positive about culturing meat and stressing possible benefits only.

who indicated "surely" to be wanting to try it (43% after receiving additional information, *vs*. 24% initially). Findings for 'willingness to purchase' largely follow the same pattern. These findings are generally consistent with the findings from quantitative studies in the Netherlands and the U.K. where also a majority of consumers indicated they would (maybe or surely) be willing to try this novel food product.

The findings of our study finally suggest that price will be an important factor for consumers. Four out of ten participants (42%) were not willing to pay a price premium for cultured meat compared to traditional meat, and this percentages only decreased slightly after receiving additional information about the environmental benefits of cultured meat relative to traditional meat production (Table 3). Of those willing to pay more for cultured meat, 79% did not want to pay more than 50% extra compared to traditional meat.

5. Discussion

The list of possible criteria shaping future consumer acceptance of cultured meat is extended and ranges from perceived risks and benefits related to the technology and the product, over trust in science, society and regulation, to public involvement in the product development and media coverage about the issue. Generally speaking, there are two major types of acceptability criteria for cultured meat. The first is of moral order: is the technology acceptable and does it not transgress the laws of nature? This dilemma in itself is not new, as demonstrated by the discussions provoked by the adoption of other new food technologies like

biotechnology in industrialized countries. One important dimension of such a debate relates to the society's perceived need for the technology in question (or lack thereof), this being assessed from a cost/benefit balance of introducing and implementing the technology. In the case of cultured meat, the major expected benefits, as opposed to possible moral objections against the application of the technology, would be reduced animal suffering, reduced production of greenhouse gasses and the creation of a new source of proteins with the potential of feeding the growing world population (Post 2012). Future studies and debates should clarify whether these benefits are worth the costs, and whether these are indeed also perceived as such by the public and consumers.

The second type of acceptability criteria concerns the acceptability of the physical product that is released on to the market, with all its attributes ranging from its intrinsic sensory quality, healthiness, safety, sustainability, up to its price, market positioning and branding. The topic of investigation in the present paper is still purely hypothetical. The likely reception of cultured meat by consumers can hardly be predicted at present because (apart from the prototype tested in August 2013) no finished product has yet been introduced on the market. There is, in fact, a considerable gap between culturing a relatively small quantity of cells *in vitro* and developing a marketable product. It seems risky to rely on a few tests carried out by the project financiers (such as People for the Ethical Treatment of Animals (PETA), i.e., stakeholders with a vested interest) using 'artificial chicken' products which indicated their good reception by consumers (Driessen and Korthals 2012). Major challenges ahead pertain to further improving the product and its production process in order to make it mimic traditional meat (based on the insights of the present study, notably in terms of sensory characteristics and price), up-scaling the process and making it more resource- and cost-efficient, and dealing with regulatory and intellectual property issues (Post 2014). The expectation is that a cultured burger could become marketable by 2020 at an expected price of 65 US$ kg^{-1} (Post, personal communication).

Most of the published consumer studies date from before the August 2013 cultured burger tasting. As a consequence, and despite the fact that scientific evidence was already available about the technological feasibility of culturing meat, these studies were dealing with a hypothetical issue for the 'Far Future' in consumers' perceptions. The limited number of studies—most of which are qualitative and exploratory until this stage—suggest that consumers are quite skeptical towards the idea of culturing meat and eating it, which seems to be largely due to anchoring cultured, *in vitro* or synthetic meat to biotechnologies. On one hand, preliminary quantitative data—including the primary data reported in this paper—indicate that only a minority of consumers definitely reject the idea of trying cultured meat. On the other hand, consumers' claimed willingness to try cultured meat does not say much about the likelihood of repeat purchase or sustainable behavioral change.

Our exploratory study further suggests that the likelihood of acceptance increases with the provision of additional information that stresses the benefits of cultured meat relative to traditional meat, notably in terms of its environmental benefits. It should be noted that the information provided to our study participants was univocally positive about cultured meat, i.e., stressing only possible benefits without mentioning possible risks or uncertainties, and that the specific wording of questions may have caused bias to some of the results. Although consumers may be willing to try cultured meat sometime in the future, data about consumer beliefs and expectations support the idea that it will be very important to mimic conventional meat as good as possible with respect to taste, mouth feel or texture, nutritional value, and appearance (Post 2014). Providing cultured meat that mimics the characteristics of traditional meat without creating an extremely expensive product will be a major challenge. Based on our study, if cultured meat mimics conventional meat at an affordable price, it may have the potential to be widely accepted among consumers.

Apart from the conditions governing the acceptability of cultured meat by consumers and the general public, the objectives of the various stakeholders in the future production and marketing chain of cultured meat are also worth analyzing. The motivations of different research teams and their financing agencies may not always be convergent: some may consider this product as a substitute to traditional meat, addressing consumers who are sensitive to emerging societal questions facing traditional livestock production such as animal well-being and the environmental impact of livestock production, while planning to continue eating meat. Others may see it as a substitute for plant-based protein products, which are typically positioned towards the vegetarian market but often qualified as ersatz and unappetizing by traditional meat consumers. Finally, still others may consider that cultured meat may help to win back the vegetarians to eat meat by offering additional diversity to the food available. The finding of our study that vegetarians have a less favorable perception of cultured meat's healthiness supports the idea that taking the reactions of vegetarians as a benchmark might be a risky strategy towards the future positioning and adopting of cultured meat (Hopkins 2015).

Goodwin and Shoulders (2013) finally pointed out that the meat industry might need to closely monitor how traditional meat is covered in the media and communicate in a more proactive way. It can indeed be expected that attitudes towards food in general and towards traditional meat in

particular will play an important role in future consumer acceptance of cultured meat. Worsening beliefs that traditional meat is healthy, nutritious, safe or sustainable, and stronger intentions to reduce traditional meat consumption (i.e., evolutions that are clearly seen in industrialized countries nowadays) may help paving the path for alternatives such as cultured meat. By contrast, cultured meat will not be the sole alternative to traditional meat in the future. Plant-based meat substitutes, algae, and insects, for example, may benefit from a so-called 'first mover' advantage if these meat substitutes manage to meet consumer expectations and satisfy them. A gaining market presence of these substitutes, which is in line with the dietary shift away from muscle meat consumption as already seen in many Western countries, may reduce the perceived necessity for more far-reaching innovations and technological developments such as cultured meat.

6. Conclusion

The present paper reviewed the diversity of criteria shaping future consumer acceptance of cultured meat. Acceptability criteria are of moral order related to the technology and its application, and related to the physical product, its expected quality attributes and the possible benefits and risks these imply. Conclusive consumer insight about cultured meat is still very scarce. Primary exploratory findings reported in this paper suggest that most of the consumers hesitate when asked the question whether they would be willing to try cultured meat in the future. Only a small minority definitely reject this idea. The findings also suggest that benefits in terms of sustainability of cultured meat relative to traditional meat are recognized by consumers, and that the provision of information that stresses these benefits increases consumers' claimed willingness to try, purchase and (to a lesser extent) pay for cultured meat sometime in the future. Further studies into personal and environmental determinants—notably personal motivations and information effects—that may shape consumer perceptions, expectations, and the likelihood of acceptance or rejection of cultured meat are recommended.

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