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Abstract

Several hundred astronauts have experienced spaceflight for periods of up to 15 months on visits to the International Space Station (ISS). Each astronaut's health is monitored and there is clear evidence that their calorie intake only meets around 80% of the recommended daily allowance. There is concern that this underconsumption may have negative consequences on astronauts' mental and physical health during the planned interplanetary missions which will last about three years. There are many hypotheses for the calorie deficit and we have focused on just one; the concept that chemical contaminants in recycled air and water could change the flavour quality of meals during spaceflight and therefore affect food intake. Using detailed NASA data on the composition of ISS recycled air and water, we applied the Dose-over-Threshold (DoT) concept to identify contaminants that might be odour active and could change the perceived overall food flavour. However, because of the large variation in published odour threshold values, the DoT concept delivered inconclusive results. The limitations of the DoT concept and ways to improve it are discussed.

Keywords: space food, odour interaction, flavour perception

Introduction

The welfare of astronauts is a key factor in space exploration. Since the first human spaceflight in 1961, and the launch of the International Space Station (ISS) over two decades ago, much has been learnt about the changes that occur to the human body during spaceflight over periods of three months to one year. One factor that is still not explained is why astronauts only consume around 80% of their daily calorie needs [1, 2]. While this seems to be tolerable for (short) visits to the ISS, the proposed crewed mission to Mars will take around three years and the weight loss could be detrimental to astronauts' physical health and mental wellbeing. Although there could be many reasons for underconsumption, one hypothesis is that the conditions onboard the spacecraft alter the perceived flavour of food [3] and Earth-based studies have established that flavour quality is linked to palatability of food, as well as food intake [4, 5].

Within the ISS, air and water are extensively recycled to make the ISS more self-sufficient. Close monitoring of recycled air and water quality is carried out to ensure these supplies are safe for the astronauts [6, 7]. However, the recycled air and water contain contaminants, some of which could affect the flavour perception of food in space and decrease food intake. For example, NASA has identified certain contaminants that reduce water consumption (RWC) due to poor taste at very high levels, but that are acceptable at the levels reported by the regular analyses [8]. Further, ISS air contains a range of volatile compounds and a ten-fold higher carbon dioxide concentration compared to the levels found on Earth. Detailed analyses of ISS air and water samples from different missions are available from the NASA archives [9-12], where the concentrations of a wide range of contaminants (several hundred) are reported. The data published by NASA has focused primarily on safety but it is well-documented that some contaminants in potable water are detectable by smell and taste, well below the safety levels set for health reasons (see Table 9 in [13]). Despite the detailed chemical analyses of ISS air and water, our search of the space literature found no systematic studies on the potential taste activity, or odour activity, of these contaminants.

Current methods to relate the perceived intensity of taste and aroma compounds with their concentrations are limited to Stevens Law and the Dose-over-Threshold (DoT) concept (concentration of a compound divided by its odour threshold). Stevens law states that perceived intensity is related to concentration through a power law function, with different flavour compounds having different exponents; unfortunately, there are limited data available on the values of these exponents. In contrast, threshold data on a range of taste and odour compounds are available, through experimental [13, 14] or calculated values [15]. Therefore, the DoT concept is really the only way to assess the potential flavour intensity of the compounds listed in the NASA analyses. Experimental values of odour threshold (OT) range over several orders of magnitude, apparently due to variation in odour

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presentation to panellists, as well as the difference between human assessors [16], so a mean or median value is usually taken when calculating the DoT value, where values >1 indicate detectable odour or taste intensity while values <1 indicate a lack of detectable odour/taste.

A limitation of the DoT concept is that it considers each flavour compound individually, whereas there is a considerable amount of data that inter- and intra-actions between taste and odour compounds can deliver detectable odour when one or more of the compounds is below its individual taste/odour threshold. Studies in the 1960s measured the odour intensity of sub-threshold mixtures using sensory analysis and showed that there were some "additive" effects. More recently, the published data has been reviewed [17, 18] and it is clear that sub-threshold interactions do occur, not just in fundamental studies using model mixtures, but also in real food and beverage products.

Therefore, assessing the potential odour/taste activity within the ISS air and water supplies is severely limited due to the following factors:

1. The DoT concept relies on the availability and accuracy of odour and taste threshold data.
2. The threshold data in compilations and individual publications cover a few hundred compounds only and time-intensive sensory analysis is the primary method to obtain threshold values.
3. Data are recorded as the detection and/or recognition threshold concentrations.
4. Published odour threshold values vary significantly due to differences in methodology as well as human variation and it is difficult to decide which value to use.
5. The DoT concept treats each flavour compound as a discrete entity and ignores the well-documented interactions between flavour compounds.
6. There is strong evidence of interactions between odour compounds that change perception.

Experimental

Data sources

Literature searches covered the mainstream food and flavour journals as well as journals associated with space travel (for example, *Aviation Space and Environmental Medicine*, *New Space*, *Advances in Space Research*) and publications from the American Institute of Aeronautics and Astronautics. In the absence of science-based information on astronauts' perception of space food, anecdotal information was obtained by a web search. The NASA archives contain reports, presentations and policy documents, which can be found at https://ntrs.nasa.gov/. There are also datasets that can be downloaded from https://nasa.github.io/data-nasa-gov-frontpage/. Data from the European Space Agency can be found at https://www.esa.int/About_Us/ESA_Publications/(archive).

Results and discussion

The RWC compounds identified by NASA as potentially flavour-active in the ISS water supply are shown in Table 1, along with their concentrations in samples of potable ISS water. Values vary across the different samples taken, so high and low levels are quoted in Table 1.

Table 1. Estimation of the sensory effect of RWC compounds in ISS potable water supplies

Compound	Lowest level [a]	Highest level [a]	OT in water [b]	DoT level/OT	DoT level/OT
	µg/L (ppb)	µg/L (ppb)	µg/L (ppb)	Low	High
Methylethylketone	5	20	8400	0.0006	0.024
Dichloromethane	5	20	9100	0.0005	0.0022
Chloroform	5	20	2400	0.0021	0.0083
Ammonia	2	34	1500	0.0013	0.022
Acetone	3	34	20000	0.0002	0.00017
Methylamine	125	125	2400	0.052	0.052
Trimethylamine	125	125	0.20	625	625
2-Mercaptobenzothiazole	40	320	1760 [c]	0.0227	0.182
Phenol	4	20	790	0.0005	0.0025

a) Data taken from Appendix 4 in Straub *et al*. [9]. The data in the reference are quoted in increments e.g., <5 or <20 µg/L but, to calculate DoT values they have been quoted in the Table as discrete values.
b) Odour threshold values [19] were determined in drinking water as the concentration in water that would elicit a detectable odour in the headspace.
c) The odour threshold (water) of 2-mercaptobenzothiazole is taken from Nielsen [20].

Table 1 uses OT data from a single source [19] (with the exception of 2-mercaptobenzothiazole, taken from [20]) to calculate the DoT values, in an attempt to produce DoT values that could be compared with each other. On this basis, only trimethylamine shows a DoT >1, however, the OT value for trimethylamine in Table 1 (0.2 μg/L; [19]) is much lower than the values quoted elsewhere (500 and 1700 μg/L; [14]), so it is debatable whether trimethylamine is perceivable at the concentrations present in ISS water. Given the use of chlorine to disinfect drinking water, there are limited data on the flavour thresholds values of some organochlorine compounds [13]. Using the Amoore & Hautala OT data, neither of the organochlorine compounds in Table 1 will be perceivable at their concentrations present in ISS water, and even using the lowest reported OTs, only dichloromethane has a DoT >1 if the OT is taken as 4.5 μg/L. A study of other compounds in ISS water depends on the availability of odour threshold data, requiring searches on individual compounds to establish the OT ranges. Our experience is that a web search can identify OT values in various scientific and commercial web sources although the units used vary. It is not always apparent whether the values are quoted as the OT in air or the OT above aqueous solutions and further searching and calculation is required to validate the values.

The examples given above illustrate the difficulty when applying DoT values to evaluate whether a contaminant could change the flavour of ISS water. A similar situation is found when examining the contaminants in air. Air circulation within the ISS lacks the convection element found on Earth (cold air cannot sink to the ground in microgravity!), so fans are used to circulate air and it is acknowledged that this is partially successful, but does lead to higher localised concentrations of contaminants in certain areas of the ISS. The stand out difference is that CO_2 levels in ISS air are around 0.4%, 10-fold greater than on Earth. In humans, gaseous CO_2 is not detected at concentrations up to 30% [21], but the presence of CO_2 in carbonated beverages suggests its detection is through the conversion of CO_2 into carbonic acid by the enzyme carbonic anhydrase (Figure 1).

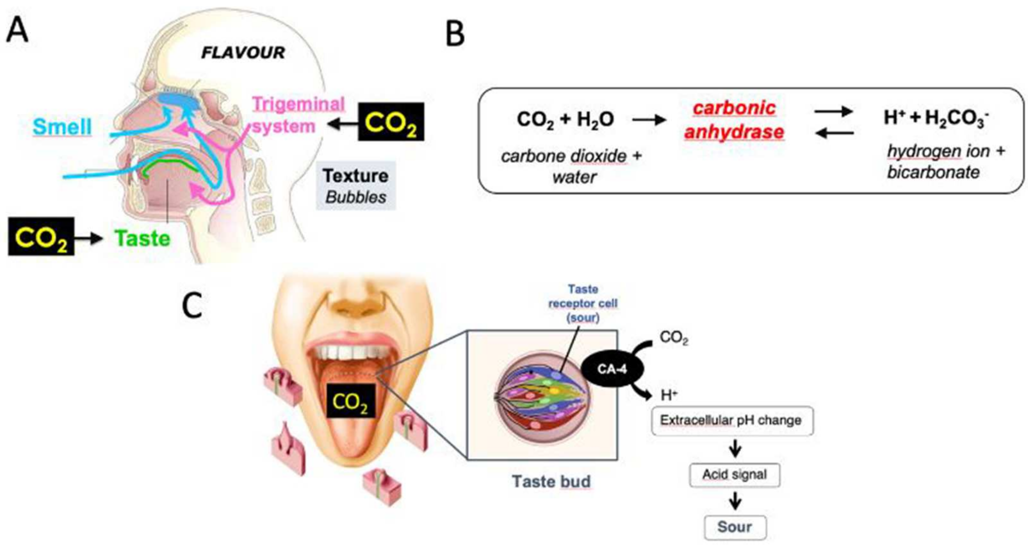

Figure 1: *Schematic representation of carbonation perception. (A) CO_2 is odourless to human but activates the taste and trigeminal systems. (B) The reaction catalysed by carbonic anhydrase (CA). (C) CA operates in CO_2 sensing and provokes a taste response to acidity. Reproduced from [3].*

Carbonic acid has been reported to activate not only the TRPA1 but also the sour taste receptors. Most published work on the effects of CO_2 on flavour perception comes from studies on carbonated beverages where decreases in sweetness and increases in bitter after-taste have been noted [3]. Recirculated ISS air also contains numerous other volatile organic compounds (Figure 2) that are derived from two main sources: the metabolic products from the astronauts and "off-gassing" of volatile compounds from the construction materials used within the ISS [22]. Depending on the level of physical activity by the astronauts, and the nature of the payloads that are uploaded to carry out different types of scientific experiments, the concentrations of airborne contaminants can vary from day to day, although CO_2 levels are kept fairly constant by the recycling plant because elevated levels are known to adversely affect astronauts [23].

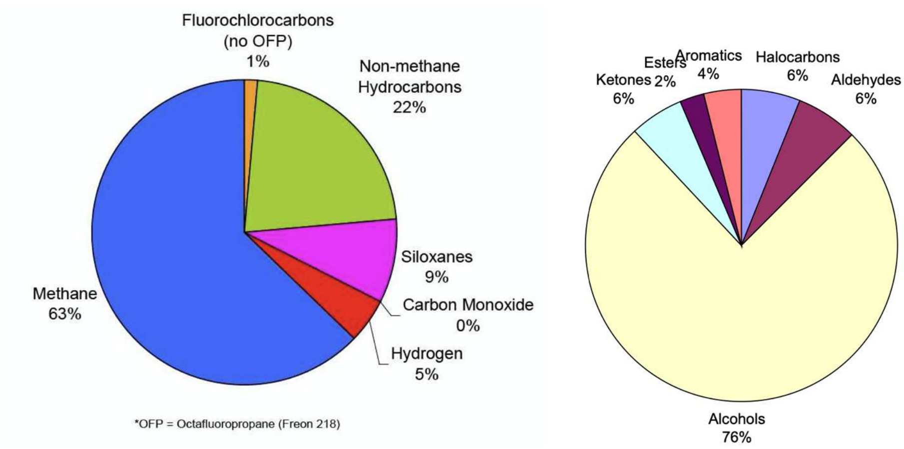

Figure 2: *Composition of volatile compounds in ISS air (volume basis). Left hand pie chart shows composition excluding nitrogen and oxygen, right hand chart shows breakdown of non-methane hydrocarbons [22].*

In Figure 2, siloxanes are a class of compounds released through off-gassing, while methane, ketones, alcohols and aldehydes are produced by human (or microbial) metabolism [22]. DoT analysis of the volatile compounds listed by NASA suggests that only the C2 to C7 aldehydes and n-butanol are potentially odour active [3], while methane is described in the literature as odourless. Although the data on chemical analysis of ISS water and air is detailed and robust, systematic information on astronauts' perception of the odour inside the ISS or the taste of food in space was not found in our literature search. The anecdotal information from astronauts during debriefing or during public interviews is also scarce and variable (see [3] for more information). Carrying out conventional sensory tests in orbit is currently restricted, due to the small numbers of participants available, as well as the difficulty in delivering odours or tastes under microgravity conditions.

Conclusion

Our attempts to use the DoT concept to identify compounds that might cause changes in flavour quality during spaceflight have led to inconclusive results and there are many reasons for this. Obviously, the factors described in the Introduction play a role (variation in odour threshold values, potential odour interactions) and this is not helped by the lack of sensory data from space-based experiments. To make further progress, it is possible to design Earth-based experiments to reproduce some of the conditions on the ISS and test whether they affect flavour perception of food samples. For example, the effect of higher CO_2 levels on flavour perception of a test food could be assessed by a sensory panel, while exposed to atmospheres containing 0.04 and 0.4% CO_2, providing a suitable ventilation system could be designed and the safety of the panellists could be ensured. Designing Earth-based experiments to determine whether the levels of odour-active contaminants found on the ISS could affect the perceived flavour of food are possible, but could not easily reproduce the effects of microgravity nor the composition of the ISS atmosphere. For contaminants found in the ISS potable water supply, it is technically feasible to add selected contaminants to food and drink samples and test whether their addition causes a significant sensory change. The potential sticking point is the sheer number of compounds found in the ISS air and water supplies, as well as the need to obtain permission from the safety and ethical perspectives. The situation may be made easier by the extensive testing that has been carried out to assess the safe levels of contaminants for astronauts over extended exposure periods. Space-based experiments are possible but there are restrictions on the weight, size and time needed to set up and execute experiments. Sensory experiments would have to be longitudinal-type studies since the number of participants during any one mission is limited to two to three astronauts. Studies would involve choosing odour or taste stimuli that could be measured in individual astronauts before, during and after the spaceflight, and repeated over several missions to get sufficient data that could be statistically analysed. The stimulus would have to be light, easy to use and reproducible, so the options are really limited to using something like odour pens as the stimuli. In turn, these experimental design choices restrict the results that could be obtained and only simple measures could be studied, such as determining odour intensity or odour threshold of single compounds. Both outputs are far away from the ultimate goal of determining whether a contaminant can alter the flavour of a space food to such an extent that it is under-consumed.

The other conclusion of this work is to question whether the DoT concept is a useful and valid tool to identify odour-active compounds. The wide variability of odour thresholds reported in the literature means that compounds may, or may not be odour active, depending on which OT value is to be believed. Genetic variability in the human taste and odour receptors is well known [24], and accounts for some of the variation, while anatomical and physiological differences can affect the degree to which flavour stimuli are transferred to the receptors [25].

Therefore, it could be argued that any sensory panel will produce a different set of threshold values due to genetic and physiological differences. It is difficult to see how an "average" panel could be convened to provide a set of benchmark threshold values. Could molecular biology help by assembling odour and taste receptors that are representative of the general population and determining threshold values using EC_{50} data? This is possible, but it still does not address the strong evidence that some flavour compounds can affect flavour perception below their odour thresholds. The evidence for odour-odour interactions is compelling [17]. Psychophysical data from the 1960s, showed that subthreshold levels of one odorant could change the perception of another odorant (see, for example, [26]) and more recent work has found similar interactions in a vodka-based beverage [27]. Besides the psychophysical effects, interactions may occur at other stages in the flavour perception process. For example, competition for enzymes at the peri-receptor level can change the odour profile reaching the odour receptors and therefore change perception [28]; some compounds appear to modulate the signal from the receptors [29], while others act as antagonists at the odour receptors [30]. There are also taste-odour interactions at subthreshold levels that alter the sensory properties [31] or the neural coding patterns [32]. Given the complexity of the data, Artificial Intelligence (AI) is a potential tool to analyse the data available. AI studies have focused on the link between odour structure and odour quality through the DREAM project [33] and similar work on bitterness has also been reported [34, 35]. These reports do not consider the intensity of the odour or bitter compound, nor do they calculate thresholds. A method to calculate odour thresholds based on physicochemical properties was proposed in 2002 [36] and a recent publication described the use of machine learning to predict odour-odour interactions [37]. AI is a powerful tool but, for a successful outcome, high-quality data is still needed and it is unclear how and where this data will come from. Identifying the problems in using DoT values is simple, but finding a solution to provide flavour researchers with a more sophisticated tool to understand how interactions affect flavour perception is a massive task and will require a truly multidisciplinary effort to obtain quality data from sensory, genetic and physicochemical sources, then combine the datasets to investigate the overall effect of odour-odour, taste-taste and taste-odour interactions. Until progress is made in these areas, it is difficult to test the hypothesis that contaminants in the recycled air and water of spacecraft can alter the flavour of food and decrease food intake during spaceflight. Spiking some food samples with known levels of contaminants is theoretically possible but raises ethical and safety issues, and deciding which of the several hundred contaminants to use makes experimentation more trial and error than sharply focused.

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