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1 Nutrition of Broodmares

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12 KEY WORDS

13 Nutrition - Developmental Origins of Health and Diseases (DOHaD) - critical periods - gestation -
14 broodmare

15 KEY POINTS

16 - In normal conditions, forage availability can match mares' energy and protein needs but low
17 forage quality or breeding out of season requires nutritional supplementation. Micronutrient
18 availability, however, should be verified and often requires supplementation.

19 - Attention needs to be placed not only on the quantity of energy and nutrients but also on their
20 quality and characteristics.

21 - Mare nutrition and adiposity can influence the foal's long-term health and metabolism
22 (Developmental Origins of Health and Disease; DoHaD) and therefore excess nutrition can be as
23 deleterious as feed restriction.

24 - There is a need for more research on broodmare nutrition, taking into consideration genetics,
25 breed, breeding conditions and environment.

26 **SYNOPSIS**

27 Forage availability should cover most needs for mares bred during spring/summer. Nevertheless,
28 out-of-season breeding, lack of access to pasture or of good quality forage calls for nutritional
29 supplementation. Current evaluations of broodmare needs are based on fetoplacental tissue
30 requirements but do not consider endocrine changes nor the fact that maternal diet quality affects
31 long-term foal health. This paper first reviews pregnant mares' current nutritional recommendations.
32 Secondly, fetoplacental developmental stages during gestation are outlined, defining critical periods
33 in the context of the Developmental Origins of Health and Disease (DOHaD). Lastly, examples of how
34 maternal nutrition affects long term foal health are presented.

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41 INTRODUCTION

42 Nutrition and reproduction are central facets of life, highlighting the critical importance of optimal
43 nutrition for the broodmare. Our goal with this review is to provide the reader with a solid
44 foundation of knowledge regarding:

- 45 1) core broodmare and fetal physiology, as well as maternal nutritional requirements,
- 46 2) the influence broodmare nutrition can have on the future health and performance of the foal.

47 This review should enable readers to move beyond the basic dietary energy and nutrient
48 requirements and consider more precise formulation of diets for broodmares being kept in a wide
49 range of different environments.

50 The first step in any nutritional evaluation should be to evaluate the mare and the performance
51 sought. Once this has been well characterized, the diet and management best suited to that scenario
52 can be formulated. Gestation and lactation result in substantial increases in nutritional requirements.
53 Estimates of energy and nutrient requirements developed by equine nutritionists represent an
54 excellent starting point for formulating a broodmare's diet¹⁻³.

55 Nutrition, along with day length and ambient temperature, are important environment variables.
56 Over tens of millions of years of evolution, horses developed a seasonally polyestrous reproductive
57 physiology that resulted in most foals being born in late spring and early summer, thereby
58 synchronizing the nutrient requirements of late gestation and early lactation with environmental
59 energy and nutrient availability.

60 While those caring for broodmares can easily evaluate the mare and her environment (day length,
61 ambient temperature, and forage/diet characteristics), it is more challenging to know the condition
62 of the fetus or modify its environment. A primary histotrophic nutrition (based on uterine secretions)
63 transitions to hemo (based on exchange between maternal and fetal bloods) and histotrophic
64 nutrition following implantation⁴. The fetus progresses through various developmental stages all of

65 which may be influenced by the dam's nutrition. A growing body of research highlights the
66 importance of the link between maternal nutrition and developmental programming of the fetus.

67 Nutrition is customarily evaluated as a balance between the requirements of the horse and the
68 dietary supply. The objective is to find a balance that optimizes the long-term health and
69 performance for the broodmare and her foal. Finding this balance requires an understanding of over-
70 and undernutrition as well as the changes in requirements according to physiologic status.
71 Furthermore, we now appreciate that optimal nutrition goes beyond simple quantities and requires
72 consideration of the quality and form of the dietary energy and nutrients.

73 With the increasing incidence of obesity and metabolic syndrome in horses, in addition to effects on
74 mare fertility⁵, unforeseen effects may result, especially in terms of offspring health and metabolism.
75 Conversely under moderate maternal undernutrition, foal birth weight is not affected but long-term
76 metabolic consequences may still be observed in offspring. There is a relatively clear connection
77 between glucose/insulin homeostasis and metabolic consequences. However, other dietary
78 components should also be considered, despite the fact that current knowledge is limited.

79 **KEY POINTS**

- **Recommendations for dietary energy, protein, vitamins, minerals and water are available, but these should be considered a starting point, from which the unique characteristics of each breeding operation should be further considered.**
- **Practitioners should consider the environment that a broodmares' physiology has been well adapted to as they make choices regarding diet and management during different stages of gestation.**
- **Knowledge of the negative implications of over and under-nutrition, the metabolic and developmental impact of fiber, nonstructural carbohydrates and fats as dietary energy**

sources, and the potential benefits of precision feeding using supplements or ration balancers is invaluable when formulating diets for broodmares.

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CURRENT NUTRITION RECOMMENDATIONS

GENERAL ESTIMATION OF BROODMARE NEEDS

Intake during gestation needs to meet mare plus fetal growth requirements. Studies on fetal growth, however, are limited. Fetal growth curve data are based on aborted or stillborn animals⁶⁻⁸, thus potentially underestimating fetal growth at the end of gestation¹.

Historically, mare gestational nutritional requirements have been calculated based on the following assumptions:

- Accretion of uterine and placental tissues takes place mid-gestation^{7,8}. It is assumed that fetal adnexal tissue (placenta, amnion) and mammary development are linear to that of the fetus, as observed in the cow⁹, but this has not been demonstrated in the horse¹⁰.
- Fetal growth is best represented by an exponential growth curve with rapid fetal development occurring from day 240 of gestation to parturition¹⁰.
- The foal's weight at birth is assumed to be approximately 10% of the dam's nonpregnant mature body weight (BW).
- Uterine and placental tissues are metabolically more active (66.6kcal/kg) than the rest of the body (33.3kcal/kg BW) and therefore have higher energy needs¹⁰.
- The efficiency of using digestible energy (DE) for depositing fetal and placental tissue during gestation is assumed to be 60%¹¹.

Most of the factors above are considered in the estimate of energy and nutrient requirements for pregnant broodmares that have been developed around the world. Differences between the various estimates are often due to variation in interpretations of fetal, placental, and uterine growth data and estimates of changes in mare metabolism during gestation¹² (Personal communication, Manfred Coenen).

115 **ENERGY AND PROTEIN REQUIREMENTS AND RECOMMENDATIONS**

116 Lactation and rapid fetal development in late gestation represent periods of high requirements for
117 broodmares^{1,10}. Non-lactating mares in early and even mid-gestation have energy and protein
118 requirements either at or close to maintenance levels (**Figure 1**). Estimated energy requirements in
119 late gestation rise to between 1.3- and 1.5-times maintenance levels, while lactation can result in a
120 doubling of energy requirements.

121 Horses obtain energy effectively from their environment, primarily from forages. Total dry matter
122 intake (DMI) will likely range from 1.5 to 3.0% BW, and in most cases at the higher end of this range
123 in pregnant or lactating broodmares. Forages have most of their potential energy stored in the
124 chemical bonds of structural and nonstructural carbohydrates and horses have evolved for optimal
125 utilization of this particular environmental dietary energy source. Therefore, caregivers should focus
126 first on providing dietary energy from forages. Based on a host of published information, a rough
127 approximation of the DE content of most forages is between 1.5 and 2.5 Mcal/kg, with more mature
128 forages usually providing less DE¹⁻³. For most mares, forages should make up at least 50% of their
129 daily DMI, and in many cases may be close to 100%, if no energy rich concentrate/complementary
130 feed or vitamin and mineral supplement is needed. Once dietary forage has been optimized,
131 attention can shift to concentrates and/or vitamin and mineral supplements.

132 Mares in late gestation provided concentrates, in addition to grass forage, maintain body condition
133 and weight better than those on forage alone¹³. Grains and concentrates should really be viewed as a
134 complement or supplement to the energy and nutrients provided in the base forage diet (see
135 Chapters 1, 3 and 4). Grains contain high concentrations of starch, a nonstructural carbohydrate that
136 can be a valuable dietary energy source for broodmares. An approximation of the DE content of
137 grains is 2.5 to 3.8 Mcal/kg of dry matter (DM)¹⁻³, with some high fat grains providing even more. The
138 DE in most commercial concentrates containing mixtures of nonstructural carbohydrates, fiber, and
139 vegetable oil/fat will range from 3.0 to 3.8 Mcal/kg DM. In the vast majority of scenarios, grains and
140 concentrates should not constitute more than 50% of the daily DMI. A range of 5 to 30% is probably

141 appropriate in most cases, depending on the BCS of the mare, her health, and the quality and
142 availability of the forage. More details on starch intake are developed in Part 3 (Developmental
143 Origins of Health and Diseases; DoHAD).

144 Horses are somewhat unique as a grazing species due to their gastrointestinal anatomy and their
145 ability to digest and utilize dietary fats¹⁴. The location of the small intestine prior to the cecum and
146 colon, allows the horse digestive and absorptive capabilities for fats before those fats reach the
147 primary microbial populations in the cecum and colon. Adding dietary fat therefore can be an
148 effective strategy to increase dietary calories for broodmares¹⁵ while limiting the potential negative
149 effects of excess starch on offspring health (see Part 3). Research indicates that horses are likely
150 capable of digesting and absorbing dietary fat at concentrations of up to 200 g/kg DM density¹⁴. The
151 increased energy density of added vegetable fat/oil provides several possible benefits, including
152 flexibility to maximize fiber without sacrificing energy intake, especially when energy requirements
153 are high and DMI may be limited, and potential improvements in fat soluble vitamin absorption^{14,16}.
154 While horses may be capable of digesting and absorbing upwards of 15% to 20% dietary fat, forage
155 contains only 2% to 4% fat/lipid. In the authors' opinion, the potential benefits of adding fat are
156 more likely to be seen in the range of 5% to 10% dietary fat on a DM basis, calculated by evaluating
157 both forage and concentrate fat intake. The quantity and ratio of dietary omega-6 and omega-3 fatty
158 acids may influence inflammation, alter cell membrane fluidity, and gene expression but much more
159 work is needed in this area¹⁷. Most forages are rich in omega-3 fatty acids (e.g. alpha linolenic acid),
160 so diets that contain at least 50% forage are more likely to have a relatively low omega-6-to-omega-3
161 ratio¹⁷. If additional omega-3 fatty acids are desired, flaxseed or flax oil would likely be the most
162 practical to incorporate into the ration, but other sources such as fish and algae oils can also be used
163 depending on the budget and the palatability of the oil for the individual animal.

164 The pattern of change in crude protein (CP) requirements during gestation is similar to that of DE
165 (**Figure 1**). The CP requirements for non-lactating early gestation mares are near or at maintenance

166 levels and rise exponentially in the last third of gestation and rise again during lactation. Estimated
167 CP requirements vary around the world, likely due to different assumptions of protein utilization for
168 fetal, placental, and uterine development, as well as protein as an energy source in late gestation.
169 Of greater importance is protein quality, specifically digestibility and amino acid composition. Under
170 most circumstances, feeding the broodmare a higher quality protein will improve the mare's and
171 developing fetus's ability to utilize amino acids for tissue development. Available protein can be
172 estimated by subtracting the acid detergent insoluble nitrogen and the non-protein nitrogen from
173 the CP to provide a better estimate of the protein available for absorption in the horse's small
174 intestine¹. This information can be provided on demand by most laboratories. The quality of the
175 dietary protein is also improved by providing a composition of essential amino acids that most
176 closely meets the requirements of tissue development¹⁸. More research is needed to uncover
177 knowledge of broodmare's amino acid requirements, but it is assumed that lysine is the first limiting
178 amino acid and its concentration is approximately 4.3% of the CP requirement¹. Quality protein
179 sources include soybean meal, alfalfa, and certain milk byproducts, due to their amino acid
180 composition.

181 **VITAMINS, MINERALS AND WATER REQUIREMENTS AND** 182 **RECOMMENDATIONS**

183 Essential vitamin and mineral requirements needed to support optimal embryo and fetal
184 development are not clear. Vitamins A and E are normally high in fresh forages (**Table 1**)^{19,20}. Vitamin
185 D requirements should be met by the horse having sunlight exposure, thus mares maintained
186 predominantly indoors may require additional vitamin D from the diet (see also Chapter 4). Horses
187 maintained in an environment where they have sufficient access to immature fresh forages during
188 late gestation and early lactation will likely be meeting their requirements. In contrast, dried hay (and
189 especially hay that has been stored for a long time) will not be sufficient to maintain adequate
190 Vitamin A and E levels in pregnant mares when fed for several months²¹. Serum vitamins A and E
191 concentrations are higher in summer when pregnant mares are in pasture, compared to in winter,

192 when they are typically stabled and fed preserved forage^{19,22}. Various B-vitamins are found in forage
 193 and are also produced by microbes within the equine digestive tract. However, there is little known
 194 regarding B-vitamin requirements during gestation or their relative concentrations in forages.

195 **Table 1. Ability of forage to meet broodmare fat soluble vitamin**
 196 **requirements**

Vitamin	NRC Requirement (500 kg of body weight)				Fresh forage content (unit/day) ¹	Hay content (unit/day) ¹	Is forage adequate? ²
	0-120 d gestation	120-250 d gestation	250-340 d gestation	0-30 d lactation			
Vitamin A (kIU)	30	30	30	30	55-2,418 ³	3.6-593 ³	Likely inadequate in preserved forage/hay
Vitamin D (IU)	3300	3300	3300	3300	341-19,800	990-61,160	Yes, if sun-exposure is not greatly limited. Higher values found in sun-dried forage/hay compared to fresh pasture.
Vitamin E (IU)	800	800	800	1000	147.5-6,556 ⁴	164-3,458 ⁴	Likely inadequate in preserved forage/hay

197 ¹Forage and hay calculations based on 500 kg BW horse and 2% BW (DM basis) consumption of
 198 forage only

199 ²For more information, see Chapter 4 (Forage)

200 ³Calculated using the conversion 1 mg β-carotene = 333 IU Vitamin A during pregnancy²⁰

201 ⁴Calculated using the conversion 1 mg α-tocopherol = 1.49 IU Vitamin E¹

202

203 Mineral supply from pasture and hay is influenced by soil factors, plant species, state of vegetative
 204 growth, and fertilization/irrigation^{23,24}. Therefore, specific recommendations regarding the need for
 205 mineral supplementation are difficult to state as they are dependent on grass type, geographic
 206 location and season of the year. Many fresh forages will meet the macromineral needs (see also
 207 Chapters 1 & 4) of the mare during gestation for calcium (Ca), phosphorus (P) and potassium (K) but
 208 may be low in sodium (Na) and some trace minerals, including copper (Cu), zinc (Zn) and selenium
 209 (Se)^{23,25-28} (Table 2).

210 **Table 2: Ability of forage to meet broodmare mineral requirements**

Mineral	NRC Requirement (500 kg)				Cool season grass	Warm season grass content	Is forage adequate? ²
	0-120 d gestation	120-250 d gestation	250-340 d gestation	0-30 d lactation			

					content (unit/day)) ¹	(unit/day) ¹	
Calcium (g)	20.0	28.0	36.0	59.1	20-86	24-89	Yes, though supplementation may be needed during early lactation.
Phosphorus (g)	14.0	20.0	26.3	38.3	12-31	15-98	Yes, though supplementation may be needed during late gestation or early lactation if consuming mature (seed heads present) cool season grass.
Potassium (g)	25.0	25.0	25.9	47.8	37-269	63-298	Yes
Sodium (g)	10.0	10.0	10.0	12.8	0-36.8 ³	Not reported	Supplementation is often needed.
Chloride (g)	40.0	40.0	40.0	45.5	19.6-144 ³	Not reported	May require supplementation..
Copper (mg)	100.0	100.0	125.0	125.0	39-87	43-143	Most cool season grasses are too low in Cu to meet the requirements throughout gestation. Some warm season grasses may provide adequate levels.
Zinc (mg)	400.0	400.0	400.0	500.0	149-273	196-634	Supplementation needed.
Selenium (mg)	1.0	1.0	1.0	1.25	0.5-0.7	0.3-4.0	Depends on geographical region.

211 ¹Grass value calculations based on 500 kg BW horse and 2% BW (DM basis) consumption of forage
212 only

213 ²For more information, see Chapter 4 (Forage)

214 ³Values for general grass pasture obtained from <https://equi-analytical.com/common-feed-profiles/>

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216 Water requirements during gestation seem to be similar to that of maintenance. Observed intakes
217 range from 5.1 L/100kg BW²⁹ to 6.9 L/100kg BW³⁰ in pregnant mares and from 11.9 L/100kg BW to
218 13.9 L/100kg BW in lactating mares¹ and are influenced by several factors, including DMI and
219 environmental temperature. Availability of water is especially important for horses consuming dried
220 preserved forage, such as during cold seasons and when stalled^{31,32}. Water restriction during
221 pregnancy results in decreased feed intake and loss of BW³⁰. Thus, water restriction should be
222 avoided.

223 KEY POINTS

- **Published energy and nutrient recommendations are best viewed as starting values which can be tailored to meet individual scenarios.**

- Mares' requirements are continuously changing based on stage of gestation and lactation.

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NUTRITION OF THE BROODMARE:

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ADDITIONAL FACTORS TO CONSIDER

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GESTATION: A UNIQUE PHYSIOLOGICAL STATUS AFFECTING METABOLISM

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In early gestation, mares have more efficient glucose absorption ~~sugar ingested~~, which results in a

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higher postprandial blood glucose³³. They also have an enhanced endocrine pancreatic response,

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resulting in increased postprandial insulin secretion and basal hyperinsulinemia compared to non-

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pregnant mares³³. Therefore, mares dedicate the first part of gestation to glucose storage as fat or

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glycogen in peripheral tissues (adipose tissue, muscles and liver), in order to stock up for when fetal

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needs will increase. This is called "facilitated anabolism"³⁴. At the end of gestation, mares become

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more insulin resistant, have decreased peripheral tissue glucose tolerance and decreased pancreatic

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β -cell sensitivity, limiting the glucose storage in maternal tissues^{33,35-37}. These changes are associated

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with a pronounced increase in glucose absorption after meals^{33,37,38} (**Figure 2**). These physiological

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adaptations coincide with a strong increase in feto-placental glucose requirements at the end of

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gestation: almost 75% of the circulating maternal glucose is used by the uterus and fetal tissues³⁹.

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Age and parity may alter these metabolic changes in mares. For instance, primiparous mares have

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been shown to have higher insulin responses to feeding compared to multiparous mares in late

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gestation, which could mean impaired metabolic adaptation to gestation in primiparous dams³⁶.

243

In late gestation, mares have an increase in lipid mobilization, as observed through the following:

244 - Increased serum β -hydroxy-butyric acid⁴⁰ concentrations, a ketone which serves as an alternate
245 ATP/energy substrate when glucose availability is low⁴¹.

246 - Some authors observed an increase in plasma triglyceride concentration reaching a plateau from
247 the 7th month of gestation onwards^{42,43}, however, not all have observed such change^{40,44}.

248 - Plasma cholesterol concentrations are stable during gestation⁴⁵ and lower than in non-pregnant
249 mares⁴⁰, which may result from use of cholesterol for steroid synthesis^{46,47}.

250 Nitrogen metabolism also adapts to the pregnant state. During gestation, plasma total proteins
251 concentration varies^{40,42-44,48}, though lower than in non-pregnant mares^{40,43,44}. Plasma urea
252 concentrations are higher in late gestation mares than in non-pregnant mares, reflecting the increased
253 need for amino acids to support anabolic processes during gestation^{40,44}.

254 Metabolic changes are summarized in **Figure 3**.

255 **KEY POINTS**

- **During the end of gestation, maternal metabolism allows for maximum glucose redirection to the fetus to meet its needs for full growth.**
- **The high use of glucose by the fetus leads the mare to use mainly her lipid reserves to meet both her own and fetal needs. This highlights the importance of the first months of gestation for the build-up of lipid reserves. A BCS of 5 (1-9 scale), however, should be targeted to avoid the detrimental effects of overweight and obesity on both maternal and fetal health.**
- **If there has been insufficient lipid storage earlier in pregnancy the mare will need to also draw on her protein reserves to meet her own as well as the energy needs of the fetus.**

256 **CONSIDERING THE SEASON IN MARE'S NUTRITION**

257 Providing optimal nutrition for broodmares requires consideration of multiple factors, each likely to
258 be changing daily over the ~340 days of gestation. Feral and semi-feral horses manage excellent
259 reproductive performance without human intervention⁴⁹⁻⁵¹, even though body condition loss is often
260 observed in late gestation^{49,50,52}. Their success may be attributed to reproductive and feeding
261 strategies that evolved over 30 to 40 million years in temperate grassland environments enabling
262 adaptation to an environment that changed in a predictable manner with each season. Feral and
263 semi-feral horse herds today still foal and breed during some of the longest days of the year^{49,51}. The
264 connection of reproductive patterns with day length and nutrition are well recognized⁵³, with an
265 evolutionary benefit to synchronizing reproduction, growth, and lactation needs with the
266 environmentally available energy sources.

267 The diet is the primary source of energy, with adipose (and muscle) tissue serving as a supplementary
268 source when the diet is limited. For domesticated broodmares, the responsibility for nutritional and
269 reproductive management is that of the caregivers. In addition to gestational needs, changes in
270 energy requirements due to thermoregulation, feed acquisition and disease in broodmares have
271 been poorly studied. Optimal broodmare nutrition can be achieved by understanding and accounting
272 for each of these factors.

273 In **Figure 1**, the DE and CP requirements of broodmares during gestation are overlaid on day length,
274 one of the primary environmental variables that leads to changes in ambient temperature and forage
275 growth and availability. The day length curves represent day length experienced by mares that were
276 due in mid to late-winter (February), early to mid-spring (April), or early summer (June) in the
277 northern hemisphere. Those feeding broodmares can examine this figure and not only consider what
278 the broodmare's requirements are, but also the environmental energy and nutrient sources and
279 sinks by which she is being influenced. Here are a few examples.

- 280 - A broodmare at 320 days of gestation and due in February has both high DE and CP
281 requirements, yet day length is short, and ambient temperatures and fresh forage availability
282 are low. Her caregiver should provide high quality preserved forage and consider a
283 complementary concentrate feed to provide the required DE and CP (including essential
284 amino acids). Another broodmare at the same stage in gestation, but instead due in June has
285 identical requirements, but is in an environment where day length is long, and ambient
286 temperatures and fresh forage availability are high. In this case, the caregiver can provide
287 significantly less complementary feeds, based on what the mare's environment provides.
- 288 - A lactating broodmare at 40 days of gestation and due in February has high DE and CP
289 requirements, primarily related to lactation. Day length is increasing, but ambient
290 temperature and fresh forage availability are just beginning to rise. To meet the nutritional
291 demands of early lactation she will require high quality preserved forage and possibly a
292 complementary concentrate. Another broodmare at the same stage in gestation, but instead
293 due in June, has identical requirements, but is in an environment where day length has
294 already peaked, leading to higher ambient temperatures and likely plentiful fresh forage
295 availability.
- 296 - Finally, **Figure 1** highlights a nutritional opportunity during early and mid-gestation to
297 increase a broodmare's body condition score (BCS) when energy and nutrient requirements
298 are low (in a natural environment, *i.e.* if the mare is not overweight/obese). Obviously, this
299 period is shorter in the lactating mare, extending from late lactation to the last third of
300 gestation. An example would be a mare who foaled in mid-spring, was bred a month later,
301 and her foal had been weaned at the end of the summer. She should be able to take
302 advantage of good fall forage and relatively low energy and nutrient requirements of mid-
303 gestation to increase her BCS. Another example would be a mare with no foal at her side,
304 bred in March, taking advantage of spring forage to improve BCS. It will be much more
305 challenging to increase BCS during early lactation, even with good spring forage, or in late

306 gestation, because energy will be partitioned away from the mare and to the rapidly
307 developing fetus.

308 Body condition score (BCS) is an indicator of energy balance. BCS is a standardized subjective
309 evaluation of subcutaneous fat stores. The evidence seems to indicate a moderate BCS of 5 (1-9
310 scale⁵⁴) and 3 (1-5 scale^{55,56}) in the broodmare as a target through gestation. Fat stores provide
311 energy when the less predictable short-term environmental patterns of dietary energy result in a
312 deficit. Maintaining sufficient energy savings can help weather some of the unpredictability in other
313 energy sources and sinks. The majority of evidence indicates that domesticated broodmares are best
314 managed by maintaining a moderate BCS, but there remains some lack of clarity regarding how
315 changing planes of nutrition, and even changing BCS, may have positive or negative impacts on
316 reproductive performance and progeny success⁵. Future work should focus on investigating how
317 dietary energy and stored energy are communicated to the gonadotropic and somatotropic axes to
318 influence reproduction and growth⁵⁷. The knowledge uncovered here might allow for more precise
319 and nuanced modifications of the diet through gestation to optimize health and performance of the
320 offspring, but also the continued reproductive performance of the broodmare.

321 Key points

- **Feral mares are bred and foal in the longest days, which coincides with increased nutrient availability from grazing. In mid-gestation (120-250 days of gestation), the fiber content of the forage increases and nutrient availability, as well as day length decrease. Late gestation (250-340 days of gestation) begins with low nutrient availability and short-day lengths, but rapidly increasing nutrient availability coincides with exponential fetal growth.**
- **Body condition of the mare represents her energy savings, and hence her ability to provide for a rapidly developing fetus in late gestation and reproduce in the following breeding season. In most situations it is prudent to maintain a moderate BCS (5/9) throughout gestation, with the**

understanding that during lactation and late gestation, energy partitioning will first direct resources to milk and fetal development.

322 **FETAL NUTRITION DURING PREGNANCY**

323 **DEVELOPMENT AND ROLE OF THE PLACENTA**

324 During the first 40 days of the embryo's life, histotrophic secretions (endometrial glands secretions)
325 are the main source of nutrients for the embryo⁴. Briefly, the embryo enters the uterus around 6-7
326 days post-ovulation⁵⁸. At this time and for the next 20-25 days, the embryo is surrounded by a
327 capsule composed of glycoproteins which regulates the assimilation of uterine secretions^{4,59}.
328 Between 20 and 30 days, the embryo capsule disintegrates, so that the trophoctoderm (precursor of
329 placenta) is directly in contact with the endometrium⁶⁰. Trophoblastic cells (placental epithelial cells
330 involved in feto-maternal exchanges) develop and protrude into the endometrial glands which
331 facilitates histotrophic nutrition prior to implantation^{61,62}. Thus the embryo is solely dependent on
332 the uterine environment for its development during this period.

333 The following nutrition and metabolic factors affect the uterine environment in the mare:

- 334 - Maternal obesity and excessively increased insulin resistance (knowing that insulin resistance
335 is increased physiologically in response to gestation) in mares has been shown to increase
336 the expression of genes and/or proteins involved in inflammation, lipid homeostasis, growth
337 factors and cell stress in uterine secretion, endometrium and embryos^{63,64}. Moreover,
338 alterations in concentration of lipids involved in cell membrane integrity and signal
339 transduction was observed in embryos of obese mares⁶³.
- 340 - Conversely, supplementing the diet of overweight mares with omega-3 fatty acids rich fat
341 sources has been shown to increase the expression of genes involved in embryo and
342 trophoblast development⁶⁵ and to decrease expression of proteins involved in

343 inflammation⁶⁴. Nevertheless, this has not been shown to overcome adverse effects of
344 maternal obesity.

345 Although there is so far little knowledge on specific nutritional needs in early gestation in the mare,
346 the quality of maternal nutrition should not be neglected at this stage.

347 The placenta is a complex organ involved in gestation maintenance, feto-maternal exchange,
348 metabolism, hormones synthesis and immunity. In the mare, two different placentas develop during
349 gestation (**Figure 4**):

350 **-A transient trophoblast** (chorionic girdle) from 30 to 120-140 days of gestation⁴.

351 **-A definitive non-invasive placenta** that forms close interdigitations (microcotyledons) with the
352 endometrium from 40 days. Two trophoblasts are involved in feto-maternal exchanges. The
353 hemotrophic trophoblast lines the microcotyledons in close contact with the endometrium⁶⁶ and
354 ensures exchanges between maternal and fetal bloods. The histotrophic trophoblast is located at the
355 basis of microcotyledons and collects uterine gland secretions. Therefore, both hemotrophic and
356 histotrophic nutrition play essential roles for fetal development.

357 Of interest is that the placental microvilli lengthen and branch out throughout gestation⁶⁷ and can
358 adapt to a certain extent to adverse maternal nutritional conditions. For instance, in moderately
359 undernourished mares, normal fetal growth was observed⁶⁸ thanks to placental adaptations:

- 360
- increased volume of microcotyledonary vessels and
 - increased expression of genes involved in amino and fatty acids catabolism as well as vitamin
362 transport⁶⁹.

363 However, placental structural adaptations cannot overcome severe undernutrition⁷⁰.

364 **DEVELOPMENTAL ORIGINS OF HEALTH AND DISEASES (DOHaD) AND CRITICAL PERIODS OF**
365 **EMBRYO AND FETAL DEVELOPMENT**

366 The concept of Developmental Origins of Health and Diseases (DOHaD) stipulates that fetal
367 adaptations to an adverse *in-utero* environment induce permanent changes in the fetus that are
368 revealed as the individual ages or in the presence of an adverse postnatal environment. First
369 demonstrated in humans^{71,71,72}, this phenomenon has also been shown in animal models and
370 domestic animals^{73,74}, including horses⁷⁵⁻⁷⁸.

371 Adverse effects on fetal and post-natal development have been shown to differ, depending on the
372 gestational stage at which they were applied⁷². This implies the existence of *critical periods of*
373 *development* that are directly correlated to the timeline of fetal organ development and maturation.
374 Mechanisms underlying these effects involve modification of gene expression without changing of
375 DNA structure (epigenetic mechanisms⁷⁹) which are sensitive to the environment and can persist
376 until adulthood.

377 Critical periods of development can be defined depending on the organ concerned (**Figure 5**). In the
378 horse, by day 35, the embryo has completed most of its organogenesis^{4,80} and is referred to as a
379 fetus⁴. This time of gestation also coincides with the onset of placentation. These differences
380 between organs have an important impact on fetal development in response to maternal feeding as
381 the embryo/fetal organ development and maturation is dependent on the maternal environment
382 (metabolism and nutrition). For more detailed information and references, see Figure. 6.

383 Although DOHaD and the importance of critical periods have been well described in animal models
384 and some domestic species, so far, only limited data are available in horses. Nevertheless, maternal
385 nutrition has been demonstrated to affect foal metabolism, onset of osteochondrosis and the
386 maturation of reproductive organs (**Figure 7**)⁷⁸.

387 **KEY POINTS**

- The horse embryo depends solely on nutrients from uterine glands until 30-40 days post-ovulation. Uterine environment may vary depending on maternal nutrition and metabolism.
- Obese mares may have a more inflammatory endometrial environment, which could impact embryo health and development in the first month of gestation.
- Organogenesis is largely completed at 40 days post-ovulation, but organs continue to mature afterwards, and critical periods of development vary between organs.
- Maternal environment (and nutrition) from early gestation has long term effects on offspring development.

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391 **DEVELOPMENTAL ORIGINS OF HEALTH AND**
392 **DISEASE**

393

394 Nutrition of the broodmare during gestation and lactation is not only important for her own health
395 and fertility but also for the development and health of her foal. The limited information available in
396 horses is detailed below.

397 **MATERNAL ENERGY RESTRICTION**

398 Moderate (70-80% of energy requirements) undernutrition does not appear to affect *in-utero*, nor
399 pre-weaning postnatal growth of the foal^{68,81,82}. Placental⁶⁹ (increased vascularization and nutrient
400 transport) and maternal⁶⁸ (decreased insulin secretion following a glucose challenge, lipid

401 mobilization) adaptive mechanisms seem to be sufficient to sustain fetal growth. However, moderate
402 maternal undernutrition is associated with delayed testicular maturation at 12 months of age
403 (beginning of puberty), reduced insulin sensitivity at 19 months of age, and reduced cannon width
404 from 19 months of age⁸³. Furthermore, severe undernutrition leads to *in-utero* growth retardation
405 (IUGR)⁷⁰.

406 **ENERGY OVERFEEDING AND OBESITY**

407 Because horses are herbivorous, their body condition varies according to season and the nutritional
408 availability of pasture⁵². A healthy horse in outdoor conditions will generally have a higher BCS in
409 summer than in winter⁸⁴. A horse is considered overweight when its BCS exceeds 6⁵⁴ (or 3.5 if using
410 the 1-5 scale^{55,56}) and obese when its BCS exceeds 7⁸⁵ (or 4 using the 1-5 scale). Obesity can also be
411 chronic, as some horses maintain a high BCS throughout the year, with no seasonal variation⁸⁴; see
412 Chapter 7.

413 A mare can be overweight due to short-term overnutrition during pregnancy (“excess gestational fat
414 deposition”). Alternatively, obesity can result from long-term overnutrition and/or metabolic
415 disease. These two scenarios may have different effects on foal health and development:

- 416 - Obesity in late gestation: Overnutrition during pregnancy, leading to obesity in late gestation,
417 does not affect foals’ birthweight^{81,86}. Nevertheless, reduced weight and thoracic perimeter
418 at 2 months of age have been described when excess maternal nutrition is continuous from 2
419 months gestation⁸⁷. This may be due to decreased milk production in overnourished mares
420 during the first 2 months of lactation⁸⁷. When overnutrition begins later (8th month of
421 gestation), foals' growth between birth and 3 months of age was not affected⁸² (later effects
422 have not been studied).
- 423 - Long-term obesity: Maternal obesity from the time of insemination, together with decreased
424 insulin sensitivity and increased plasma concentrations of inflammation biomarkers in late

425 gestation, did not affect the birth weight, nor the growth of foals when monitored until at
426 least 18 months of age^{88,89}.

427 - Nevertheless, maternal obesity was associated with increased systemic inflammation,
428 decreased insulin sensitivity and increased incidence of osteochondrosis in foals⁸⁸. Maternal
429 adiposity at the base of the tail, as measured by ultrasound, has also been positively
430 correlated to the same measurement in 4 months old foals⁹⁰.

431 **THE SOURCE OF ENERGY MATTERS**

432 **USE AND EFFECTS OF STARCH**

433 Epidemiological observations demonstrated that risks for a foal to develop osteochondrosis were 11-
434 fold higher when the broodmare's diet included 'concentrated feeds' during gestation, compared to
435 forage only⁹¹. This study, however, did not consider the quantity nor the source of the concentrates
436 given to the mares, albeit experimental studies performed using starch-rich barley as a concentrate
437 validated this observation⁶⁸. Nevertheless, in field conditions, forage is sometimes not available in
438 sufficient quantity and quality to cover the mare's needs and the provision of an energy-rich
439 concentrated feed remains a practical necessity. To decrease the potential detrimental effects of
440 starch on foal development, starch quantity per meal and per day has to be closely monitored.

441 The results from several experimental studies, where the source of energy used was known can help
442 build these recommendations:

443 - Study 1⁶⁸: Mares received 1.7g of starch/kg BW per meal as barley in addition to hay and haylage,
444 or hay and haylage only during the last 4.5 months of gestation. Mares fed with barley produced
445 more foals affected with osteochondrosis lesions at six months of age (45%) compared to mares fed
446 with hay and haylage only (17%). This difference was not observed at 12 and 18 months of age,
447 with some lesions spontaneously resolved and some new lesions in different individuals⁸³.

448 - Study 2 (MR, PCP personal communication): Mares were fed with either a maximum of 0.75g of
449 starch/kg BW per meal (range 0.40-0.75, n=5), or a minimum of 1.1g of starch/kg BW per meal

450 (range 1.1-1.6, n=5) during the last 2 months of gestation. Both groups received the same amount
451 and type of forage during gestation. As a result, 12-month-old foals born to mares fed the high-
452 starch meals experienced a higher incidence (80%) of osteochondrosis lesions, as compared to foals
453 of mares fed low-starch meals (20%) (**Figure 8**). Unfortunately, foals were not monitored further.

454 These results indicate that excess starch provided to mares per meal has an impact on the
455 osteoarticular development of foals. However, the role of starch source has not been fully
456 investigated. **Regardless, for now, the authors recommend that starch+sugar intake in pregnant**
457 **mares should not exceed 1g/kg of BW per meal.** Limits per day are currently unknown.

458 Feeding the broodmare with starch-rich concentrates may also affect colostrum quality as it has
459 been shown to decrease the IgG colostrum concentration at birth, in comparison to mares fed with
460 forage only^{12,92}. A French epidemiological study showed that mares producing foals with
461 osteochondrosis lesions had colostrum that was poorer in IgG compared to mares that produced
462 foals that remained healthy⁹³.

463 **USE AND EFFECTS OF FATS**

464 Because the diets richer in starch were also more energy dense in the previously mentioned studies,
465 discrimination between the effect of starch and that of energy content *per se* on the foals'
466 osteoarticular development is impossible. Feeding pregnant mares with a diet rich in starch (corn,
467 >1g starch/kg BW per meal) was shown to alter the glucose metabolism of foals during pre-weaning
468 growth compared to a diet rich in lipids (corn oil, <0.15g starch /kg BW per meal, 14% DM fat). These
469 results indicate that vegetable oil/**fat may be a good way to increase the energetic density of the**
470 **diet** of pregnant mares, without increasing the starch content, thus limiting detrimental effects on
471 foal's development⁹⁴.

472 Fatty acid composition may be important as some fatty acids have immunomodulatory properties,
473 and could therefore affect pathways involved in fertility, but also in inflammation. Essential fatty
474 acids are also involved in fetal neuronal development. Thus, dietary fatty acids could affect

475 maternal/uterine environment quality and subsequently embryo and fetal development. This is
476 particularly important for mares fed dry forage and concentrates, as omega-3 to omega-6 ratios are
477 low in dry forage and especially in cereals, in contrast to grass and fresh forage^{17,95,96}. As horses
478 evolved grazing on fresh grass, the dietary omega-3 contents and omega-3/omega-6 ratio are most
479 probably important, especially around conception. However, there is little confirmed information
480 regarding the exact quantities and ratios that might be optimal.

481 For now, supplementing mares with fat sources rich in omega-3 fatty acids has only been shown to
482 increase the total omega-3 and DHA transfer from the dam to the fetus at birth^{97,98} and to increase
483 lymphocyte proliferation in 7 days old foals⁹⁹. No other effects on colostrum quality nor foal growth
484 have been demonstrated⁹⁷⁻⁹⁹. The effects of maternal supplementation with omega-3 fatty acid
485 during gestation on maternal and foal metabolism are still unknown. Both fish/algae and flaxseed oils
486 have been studied independently but more studies are needed to compare the efficiency of both
487 sources. For now, we recommend flaxseed oil as it is more practical.

488 **USE AND EFFECTS OF PROTEINS**

489 Protein needs are increased during gestation in mares. The quality of proteins, and especially the
490 content of essential amino acids, such as lysine and threonine, is crucial for foal development¹. It
491 must be noted that although the role of protein excess in foals in the development of
492 osteochondrosis lesions has been ruled out¹⁰⁰, to the best of our knowledge, no studies have been
493 performed on the effect of overall protein quality fed to broodmares on the long-term health of the
494 foals.

495 As an example, L-arginine is an essential amino acid during pregnancy and growth in the horse. The
496 particular abundance of arginine in mare's milk seems to indicate that L-arginine may be needed in
497 much larger proportions in foals than in the offspring of other species¹⁰¹. Supplementation with L-
498 arginine (100g/day) during the last 4 months of gestation to primiparous mares improved their
499 glucose metabolism, increased placental expression of genes involved in glucose and fatty acid
500 transport but did not affect placental and birth weights nor growth of foals monitored until 2 months

501 of age⁴⁸. In a study where mares' parity was not described, supplementation with 100g of L-
502 arginine/day from 21 days before foaling increased uterine arterial blood flow and shortened the
503 gestational length by 12 days, without affecting the placental and foal weight at birth¹⁰². Effects on
504 gestational length were, however, not observed in another study supplementing 50g of L-
505 arginine/day in pregnant mares from 90 days before foaling¹⁰³.

506 Further studies are needed to determine the effect of protein deficiency or excess, as well as the
507 effect of protein quality during gestation, on foals' long-term health. Interestingly, alteration of
508 protein intake in other species has been shown to affect the behavior, health and lifespan of the
509 offspring¹⁰⁴. Because some amino acids can affect absorption and cell use of other amino acids,
510 dietary amino acid contents should be checked in accordance to the known optimal ratios, which
511 may change between the different physiological states¹.

512 **KEY POINTS**

- **Over and undernutrition of the mare are detrimental to foal's health. The energy content of the mare's feed should be considered according to mare's BCS and DMI.**
- **Forage should be the basis of a broodmare's diet.**
- **Broodmares should not receive more than 1g of starch+sugar/kg BW per meal in order to limit detrimental effects of non-structural carbohydrates on foal's metabolic and osteoarticular health.**
- **Vegetable oil/fat may be a good way to increase the energy content of the diet.**
- **The quantity (and ratio to omega- 6 fatty acids) of omega-3 fatty acids may be important.**

513 **FEED SUPPLEMENTS: USEFUL FOR IMPROVING THE HEALTH OF THE FUTURE** 514 **FOAL?**

515 As presented in section 1.3, geographic location, season, soil factors, plant species, state of
516 vegetative growth and fertilization/irrigation can affect the amino acid and fatty acid profiles, as well
517 as the vitamin and mineral content of the forage. Moreover, utilizing cereal grains to provide

518 additional energy can alter the balance between minerals. Depending on these factors,
519 supplementation is not always needed and should be carefully thought out.

520 Some vitamins and minerals easily cross the placenta to be delivered to the fetus during gestation.
521 On the other hand, some are weakly transported through the placenta and their storage in colostrum
522 is therefore essential for the newborn foal. For instance, vitamins A and E are poorly transferred
523 through the placenta but are concentrated in colostrum¹⁰⁵, while iodine is actively transferred
524 through placenta and is also rich in colostrum and milk¹⁰⁶. Some other nutrients, like copper, will be
525 stored in the fetal liver during gestation and used during fetal growth to compensate for low milk
526 concentrations¹⁰⁷.

527 **VITAMINS**

528 Studies on the effects of vitamin excess and deficiency on the health of foals are lacking. In other
529 species, it has been shown that maternal imbalance in D and B-group vitamins could affect not only
530 *in-utero* growth, but also long-term growth, metabolism diseases and behavior of the offspring¹⁰⁸. As
531 presented in [section 1.3](#), vitamin E, D and β -carotene concentrations are high in fresh grass in spring
532 and summer, implying that supplementation may not be needed if mares are kept in pasture and
533 bred between spring and summer²¹. Conversely, mares bred out of season or fed dried forage would
534 benefit from vitamin supplementation as observed in the following studies.

535 Natural vitamin E (RRR- α -tocopherol) oral supplementation, fed above the NRC requirements (200-
536 300%)¹, has been shown to increase the concentration of vitamin E in colostrum, milk and plasma of
537 neonatal foals as well as the immunoglobulin concentration in colostrum and plasma of 3 days old
538 foals, compared to mares fed a diet deficient in vitamin E (15-30% of NRC requirements)¹⁰⁹.
539 Moreover, oral supplementation with β -carotene (1000mg/day) to mares fed with hay and
540 concentrates from 2 weeks before foaling, increased the concentration of β -carotene in colostrum
541 and plasma of foals at 1 day of age¹¹⁰. To our knowledge, long-term effects of these supplements on
542 foal health and development have not been studied yet. The observed increased insemination

543 success with β -carotene supplementation, however, may imply an effect on the uterine
544 environment, and then, on embryo and fetal development¹¹⁰.

545 **MINERALS AND MICROMINERALS**

546 **CALCIUM AND PHOSPHORUS**

547 The effects of an inverse calcium:phosphorus ratio during pregnancy have not been studied but may
548 negatively impact the foal's bone and articular development. Mares consuming diets providing 80%
549 of the NRC requirement for calcium (Ca:P = 1.1, lower limit) during late gestation gave birth to foals
550 with thinner and weaker cannon bones which persisted through the period of observation (10
551 months of age)¹¹¹.

552 **COPPER**

553 Copper is a micromineral essential for the development of cartilage and bone. Although pregnant
554 mare copper supplementation above NRC requirements (200-300%) have been shown to decrease
555 the prevalence of articular cartilage lesions in growing foals^{112,113}, there is, so far, no substantial
556 evidence that pregnant mares should be supplemented over the recommendations if the diet is
557 correctly balanced (especially the Cu:Zn ratio)^{1,114}. Maternal copper supplementation does not affect
558 milk copper concentration nor foal plasma concentration but increases foal liver copper storage¹⁰⁷.
559 These results imply that fetal liver copper storage is essential for foal's osteoarticular health,
560 especially because supplementing the foal after birth will not counter the detrimental effects of *in-*
561 *utero* deficiencies¹¹³.

562 **SELENIUM**

563 Selenium deficiencies during gestation have been associated with white muscle disease in foals, a
564 myodegenerative pathology, affecting skeletal and cardiac muscles and leading to the death of the
565 foal in most cases¹¹⁵. The form of selenium distributed to pregnant mares is potentially important, as
566 inorganic and organic selenium are not absorbed and incorporated into body tissues equally^{116,117}. In
567 fact, supplementing the mares with selenium yeast in the 2 last months of gestation increased the
568 expression of genes involved in proliferation and cellular immune response in lymphocytes of

569 growing foals, compared to mares supplemented with sodium selenite¹¹⁸, which may imply improved
570 foal immunity. Moreover, supplementation with selenium yeast (0.65ppm vs. 0.35ppm Se in total
571 diet [650% vs. 350% of NRC requirements]) during the last 4 months of gestation has been shown to
572 increase the selenium concentration in the plasma and muscle of foals, but without affecting the
573 glutathione peroxidase activity in foal's plasma¹²¹. Special caution must be paid to selenium excess as
574 optimal range is narrow, i.e., the level of toxicity close to the recommended amounts (0.2mg/100kg
575 BW is recommended in pregnancy, safe upper limit is considered to be 1mg/100kg BW¹). Organic
576 forms of selenium may have a stronger beneficial effect on foal development compared to inorganic
577 selenium, but more studies are needed to confirm these effects.

578 **IODINE**

579 Thyroid function is involved in metabolism, bone development and growth. Foals have a very high
580 iodine serum concentration at birth that slowly decreases during growth¹⁰⁶, which correlates to
581 triiodothyronine (T3) and thyroxine (T4) plasma concentrations⁸⁸. Transplacental iodine transport
582 may therefore be efficient. Strong excess or deficiency in iodine of the maternal diet have been
583 linked to congenital hypothyroidism in foals, which can be characterized by thyroid gland hyperplasia
584 and musculoskeletal abnormalities in foals as well as increased gestational length¹¹⁹. More work is
585 needed to study the effects of iodine intake on long-term foal development. Seaweed
586 supplementation can cause iodine excess, therefore, iodine levels in seaweed supplements have to
587 be carefully considered before feeding seaweed to pregnant mares.

588 **OTHERS**

589 Other minerals and microminerals are also involved in metabolism regulation (chromium),
590 inflammation and oxidation (iron), bone and teeth development (fluorine) and their imbalances may
591 also impact the long-term health of the offspring. Mineral supplementation should be developed in
592 accordance with the balance between minerals and microminerals, as it can affect their absorption
593 and cell use¹. More work is needed to develop specific recommendations for pregnant mares.

594 **USE OF PROBIOTICS**

595 The intestinal microbiota in early life can impact metabolic health, growth and behavior of the
596 individual¹²⁰. The equine microbiota influences the risk of resistance to endo-parasites¹²¹, colic¹²² and
597 metabolic syndrome¹²³. However, few studies have focused on the effect of the mare's gut
598 microbiota on foal health. Few prebiotics have been tested in pregnant mares so far, despite a large
599 number of yeast and bacteria strains (~~genetic variants~~) available on the market. Effects observed
600 from one strain of probiotics cannot be extrapolated to other strains. Safety of strains and effective
601 dosing are unknown, which calls for a cautious use of these nutraceuticals in mares (see also Chapter
602 2 and 10).

603 Pregnant mare probiotic supplementation, however, has shown some beneficial effects on foal
604 health and development. Pregnant mares were supplemented with live yeast (*S. cerevisiae* CNCM-
605 I1079, 7.10¹⁰CFU/day) from 8 days before to 4 days after foaling. Their foals had a decreased quantity
606 of *E. coli* and enterobacteria in the feces at 10 days of age, an increased proportion of normal-looking
607 feces and a tendency to an increase in the average daily gain from birth until 20 days of age¹²⁴. In
608 another study, the supplementation of pregnant mares with fermented feed products from 45 days
609 before foaling until 60 days after did not affect the fecal pH of mares, nor the fecal concentration of
610 culturable bacteria, but increased the maternal fecal proportion of acetate. Moreover, foals born to
611 supplemented mares had an earlier establishment of gut microbiota and gut function, possibly
612 leading to an increased weight between 19 and 60 days of age¹²⁵.

613 In conclusion, studies on the long-term effect of probiotics during pregnancy and/or growth are
614 needed to help develop recommendations on the use of these supplements in breeding horses. It is
615 also worth noting that safety in pregnant animals has not been tested for most supplements.

616 The effects of other nutritional supplements on other aspects, such as muscular and cardiovascular
617 development as well as bone strength and resistance remain to be studied in the horse.

618 **KEY POINTS**

- **Supplementation must be carefully thought out as some supplements have not been tested for safety.**
- **Vitamins and minerals in excess can be as detrimental as deficiencies for the health of both the mare and the foal.**
- **Nutritional balance is important when supplementing amino acids, vitamins and minerals.**
- **More studies are needed to confirm beneficial effects of supplements in pregnant mares on long-term health of the foals.**

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625 **CONCLUSION**

626 Although the basic recommendations for broodmare nutrition are known, as described in the first
627 part of this chapter, there are many variations in the needs of mares according to season and
628 possibly breed, age or even parity. Combined with the discordant studies, more research is therefore
629 needed. The mare's diet can positively or negatively affect her foal's health. Limiting intake of
630 especially starch and sugar rich concentrates and maximizing the intake of forage may help prevent
631 non-transmittable diseases such as osteochondrosis and possibly, in longer term, equine metabolic
632 syndrome. Long term studies are urgently needed to answer these questions.

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FIGURE LEGENDS

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1008 **Figure 1. Pregnant lactating and non-lactating mares' energy and protein requirements relative to**
1009 **maintenance, according to time of gestation and compared with day length.** The symbols represent
1010 the digestible energy or crude protein requirements relative to maintenance of broodmares with or
1011 without a foal at their side during gestation as determined using the French, German, and North
1012 American feeding standards for horses¹⁻³. The lines represent the calculated day length at any point
1013 during gestation for foals due in February, April, or June for a northern latitude of 35 degrees, as an
1014 indicator of ambient temperature and forage availability. The colored regions represent important
1015 stages of gestation, represented by pre-implantation, endometrial cups and organogenesis (0-120 d),

1016 moderate fetal and organ growth (120-240 d), and rapid fetal development (240-340 d). Those
1017 interpreting this figure should consider the synchrony between day length, a proxy for the
1018 broodmare's environment, and energy and nutrient requirements during gestation. (Data from
1019 references 1-3.)

1020 **Figure 2. Evolution of glucose metabolism during pregnancy in mares. A. Changes in plasma**
1021 **glucose concentration after a meal in non-pregnant (black, n=4) and pregnant mares at <270 days**
1022 **(green, n=6) or >270 days (red, n=5) pregnancy.** Pregnant and especially late pregnant mares are
1023 more efficient in absorbing sugar ingested. **B. Changes in plasma insulin concentration after a meal**
1024 **in non-pregnant (black) and pregnant mares at <270 days (green) or >270 days (red) gestation.**
1025 Pregnant mares produce more insulin in response to plasma glucose increase, but this response does
1026 not change between early and late gestation. **C. Insulin sensitivity in early (<155 days, n=12) and**
1027 **late (>280 days, n=37) gestation in French-Anglo Arabian mares.** Insulin sensitivity decreases as
1028 gestation progresses. ([A,B] adapted from Fowden AL, Comline RS, Silver M. Insulin secretion and
1029 carbohydrate metabolism during pregnancy in the mare. *Equine Veterinary Journal*. 1984;16(4):239-
1030 246. doi:10.1111/j.2042-3306.1984.tb01919.x; [C] from Robles M, Couturier-Tarrade A, Derisoud E,
1031 et al. Effects of dietary arginine supplementation in pregnant mares on maternal metabolism, placental
1032 structure and function and foal growth. *Scientific reports*. 2019;9(1):1–19; with permission.)

1033

1034 .

1035 **Figure 3. Evolution of the mare's metabolism during gestation.**

1036 Changes in carbohydrate, protein and lipid metabolism allow the mare to provide for the needs
1037 of the fetus while having limited food availability in winter.

1038

1039 **Figure 4. Transient invasive and definitive non-invasive placentas. A. Development and roles of the**
1040 **chorionic girdles. B. Structure of the definitive chorioallantois.** ([A] adapted from Allen WR,
1041 Wilsher S. A Review of Implantation and Early Placentation in the Mare. *Placenta*. 2009;30(12):1005-
1042 1015; and Allen WR, Stewart F. Equine placentation. *Reproduction, Fertility and Development*.
1043 2001;13(8):623–634; and Wooding FBP, Burton G. *Comparative Placentation: Structures, Functions*
1044 *and Evolution.*, Springer, 2008; [B] from Steven DH, Samuel CA. Anatomy of the placental barrier in
1045 the mare. *J Reprod Fert*. 1975;Suppl. 23:579-582; with permission.)

1046 **Figure 5. The timing of organ development in the equine embryo and fetus.** Horizontal lines
1047 indicate specific day of gestation while vertical arrows indicate periods of gestation where
1048 observations were made.

1049 **Figure 6. The timing of organ development in the equine embryo and fetus, detailed version.** Each
1050 organ is separated by horizontal lines and represented by an icon. Page 1 features teeth, pancreas,
1051 liver and heart. Page 2 features bones and cartilage, muscles, gonads and a summary of neurons,
1052 lungs, pituitary gland, mammary glands and kidneys. For each organ, a timeline expressed in days
1053 post-ovulation presents the major developmental events, described in brown boxes. Detailed results
1054 in fetal insulin production are also provided for pancreas (tables and figures). For muscles, the blue
1055 line over the timeline highlight a period more than a set point. References are written directly in the
1056 figure for clarity.

1057 **Figure 7. The principles of the Developmental Origins of Health and Disease in the horse.**

1058 **Figure 8. The incidence of osteochondrosis at 12 months of age was higher in foals born to mares**
1059 **fed with high-starch meals (>110g/100kg BW) compared to foals born to mares fed with low-starch**
1060 **meals (<75g/100kg BW) (MR, PCP personal communication).**

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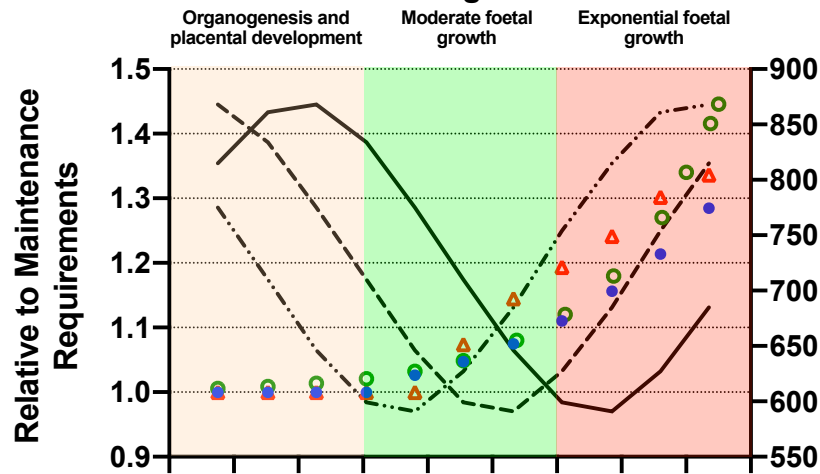
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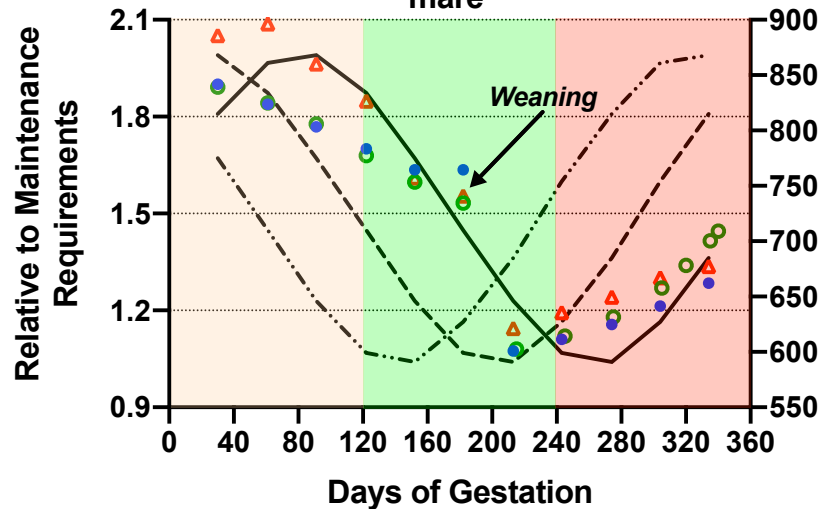
1066

▲ French - DE ● German - DE ● NRC - DE

A. Digestible energy requirements non-lactating mare

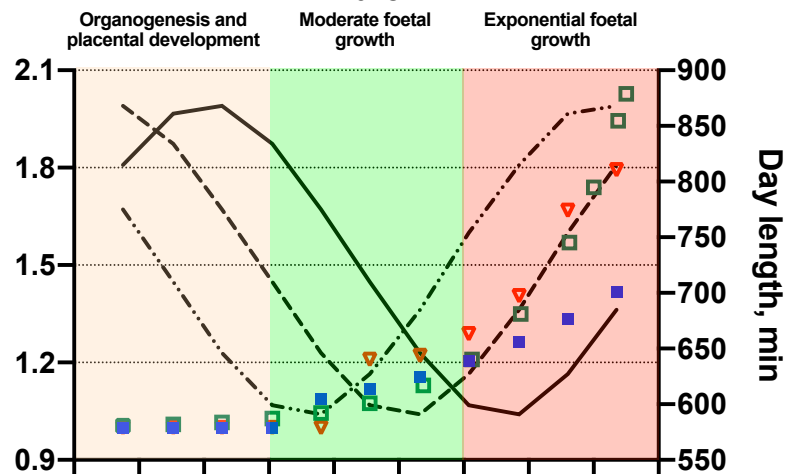


B. Digestible energy requirements lactating mare

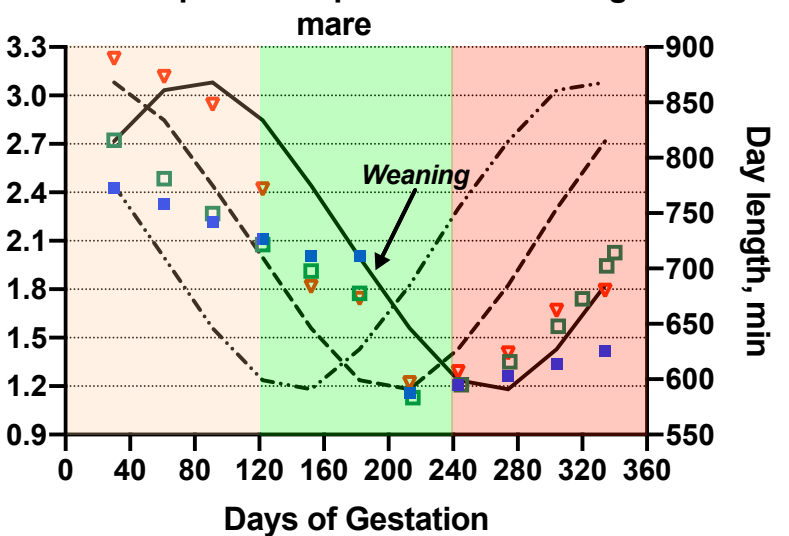


▼ French - CP ◻ German - CP ◼ NRC - CP

C. Protein requirements non lactating mare

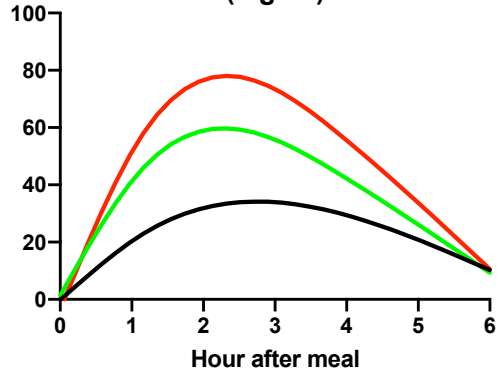


D. Crude protein requirements lactating mare

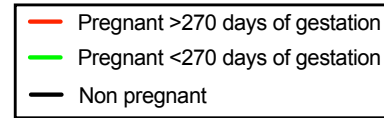
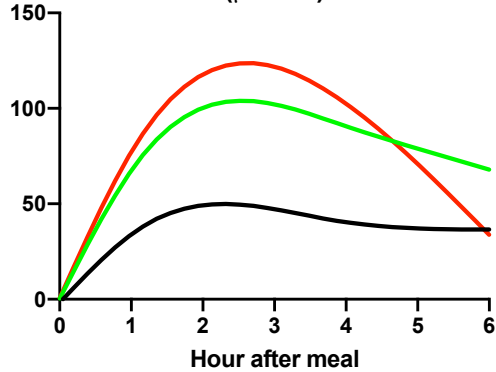


Due in:
 — Feb
 - - - Apr
 ··· June

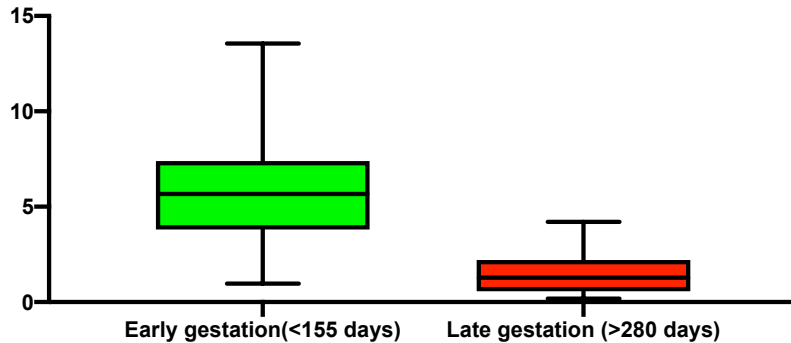
A. Changes in plasma glucose concentration (mg/dL)



B. Changes in plasma insulin concentration ($\mu\text{U/mL}$)

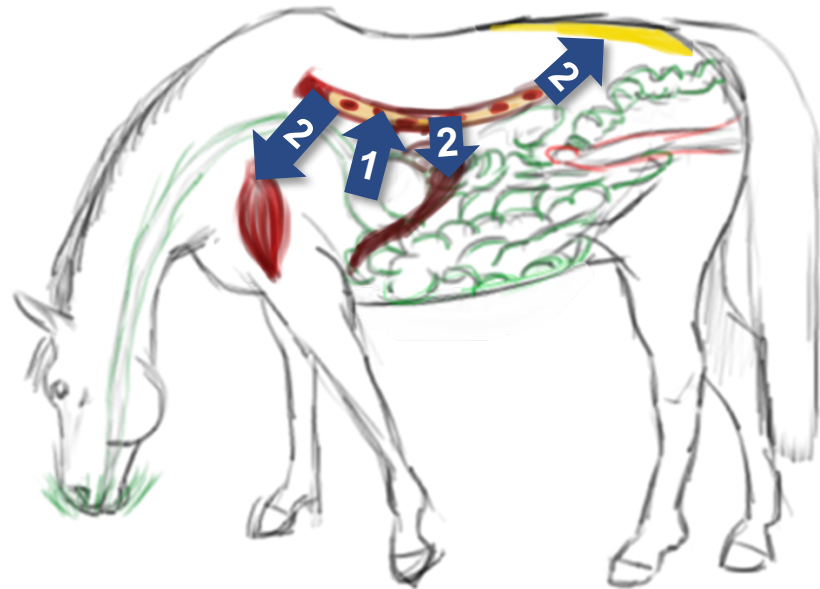
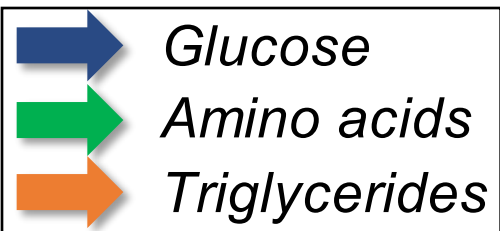


C. Insulin sensitivity ($\times 10^{-4}$ L/mUI/min)



Early gestation

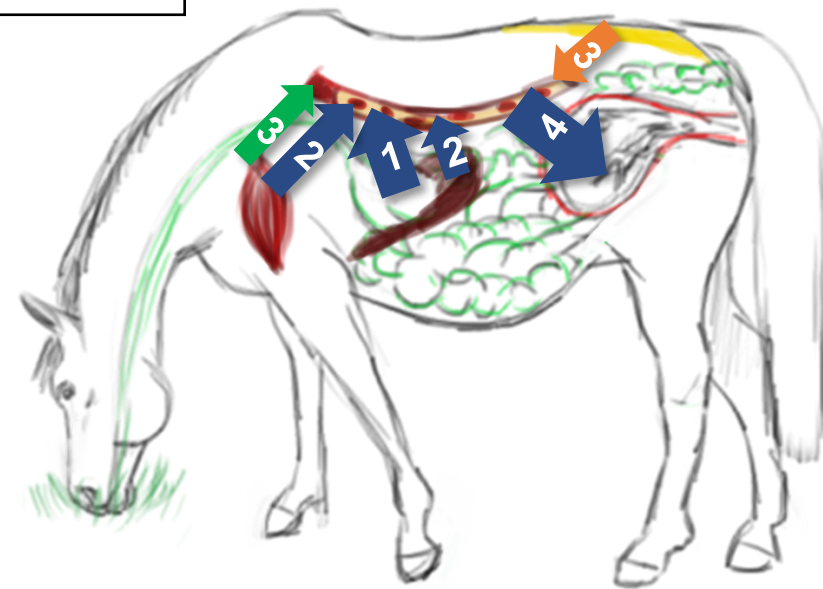
The mare stores energy in peripheral tissues



1. Increased intestinal glucose absorption
2. Increased glucose storage as fat or glycogen in adipose tissue, muscles and liver
« **Facilitated anabolism** »

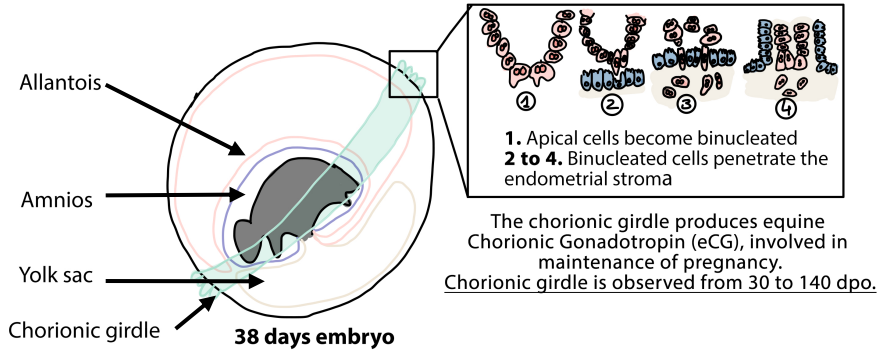
Late gestation

Energy stores are used to meet mares needs

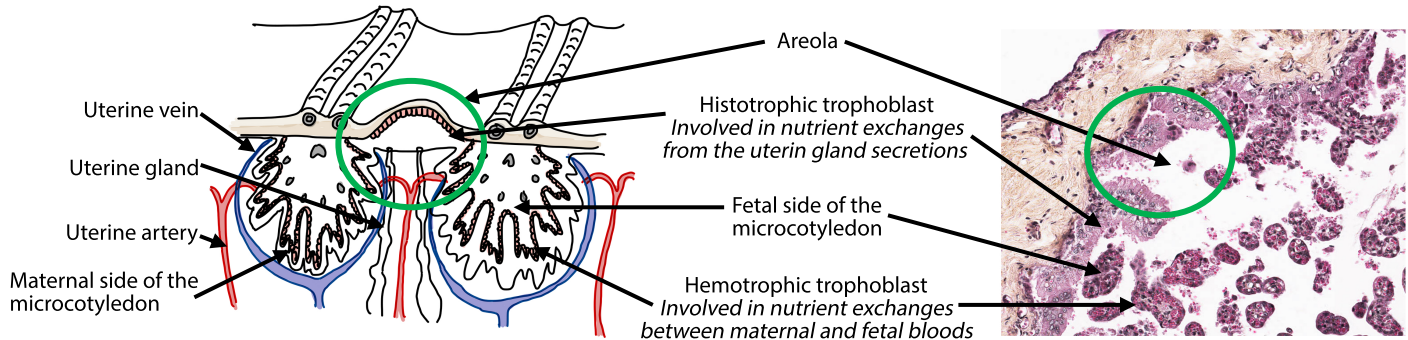


1. Strong increased intestinal glucose absorption
2. Hepatic glucose production and muscle glycogen degradation
3. Muscle protein and adipose tissue fatty acid degradation to sustain maternal needs
4. 75% of circulating glucose is used for fetal growth

A. The transient invasive placenta



B. The definitive non-invasive placenta



MUSCLES



BONES AND CARTILAGE



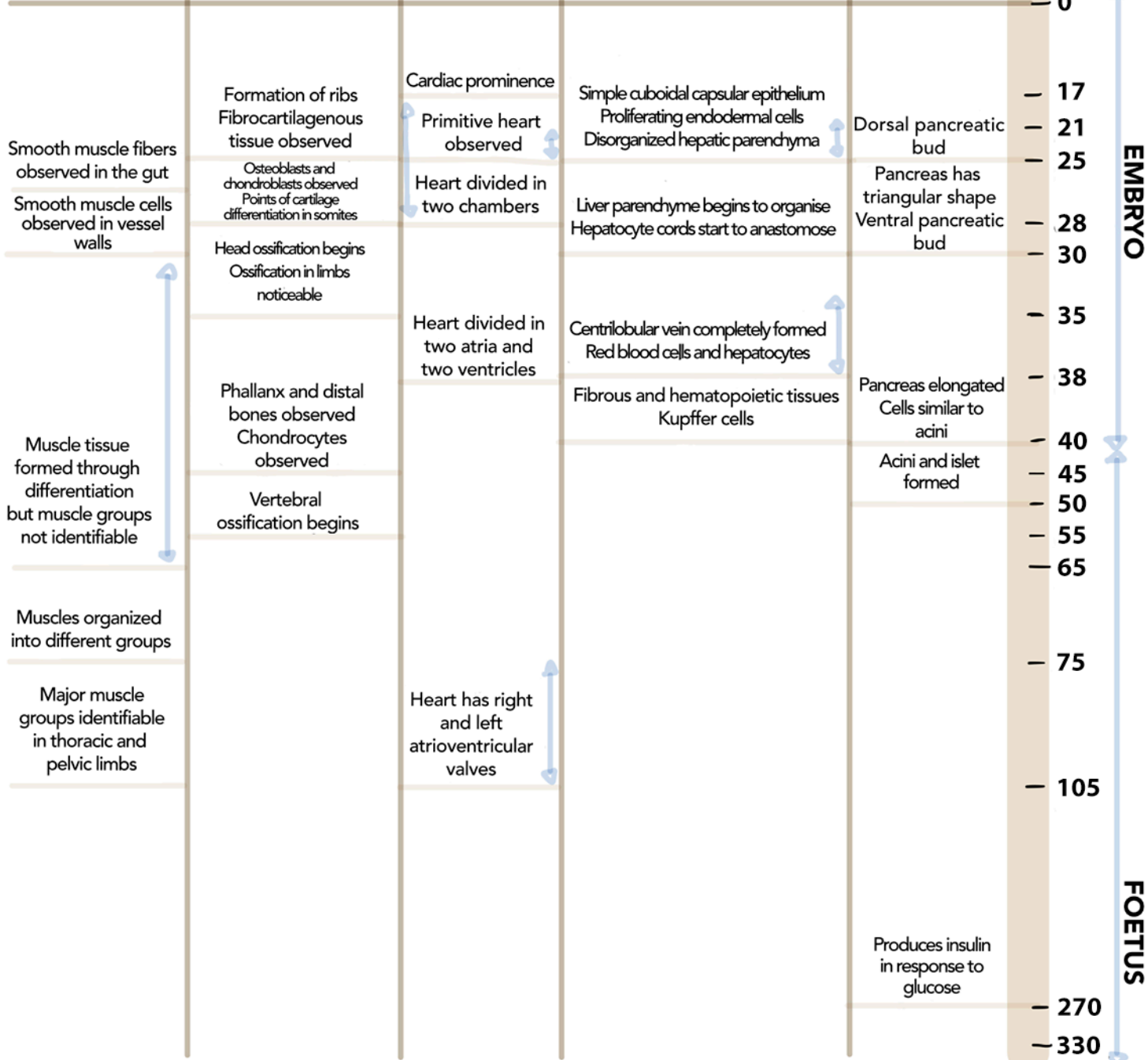
HEART



LIVER

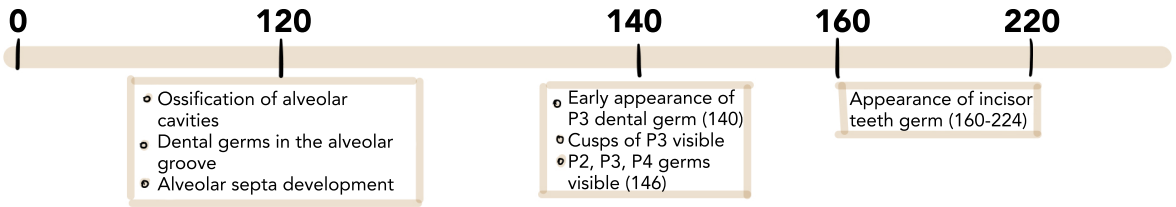
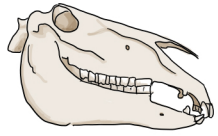


PANCREAS



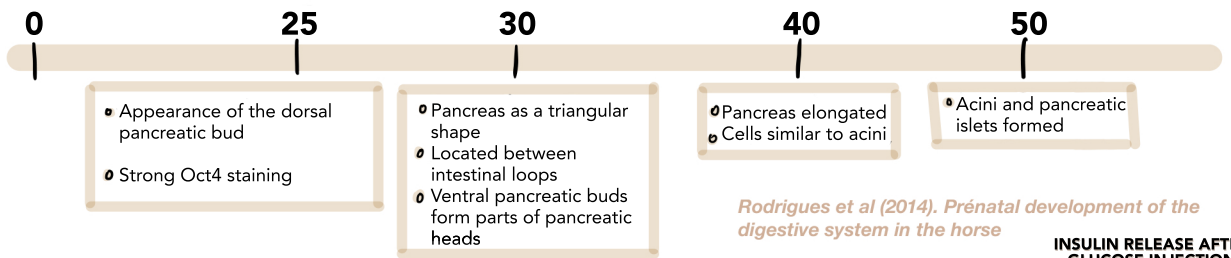
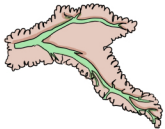
EQUINE FETAL DEVELOPMENT

TEETH



Soana et al (1999). The teeth of the horse: evolution and anato-morphological and radiographic study of their development in the foetus

PANCREAS

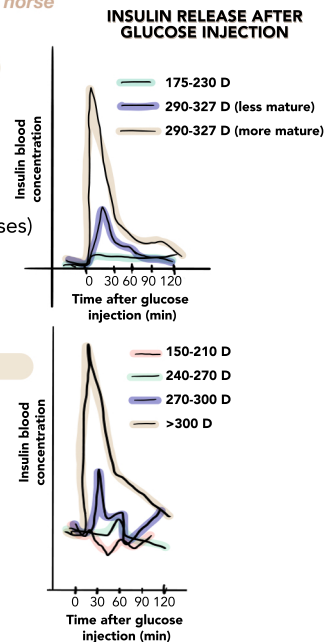


Rodrigues et al (2014). Prénatal development of the digestive system in the horse

	175-230 DAYS	290-327 DAYS
Basal insulin ($\mu\text{U/mL}$)	6 ± 1.1	9.05 ± 1.4
Basal glucose (nmol/L)	2.79 ± 0.36	3.09 ± 0.22
Insulin after glucose infusion	No effect	Increased insulin release (even more in more mature fetuses)

Less mature => cortisol < 15ng/mL
More mature => cortisol > 15ng/mL

Fowden et al (2005). Maturation of pancreatic b-cell function in the foetal horse during late gestation



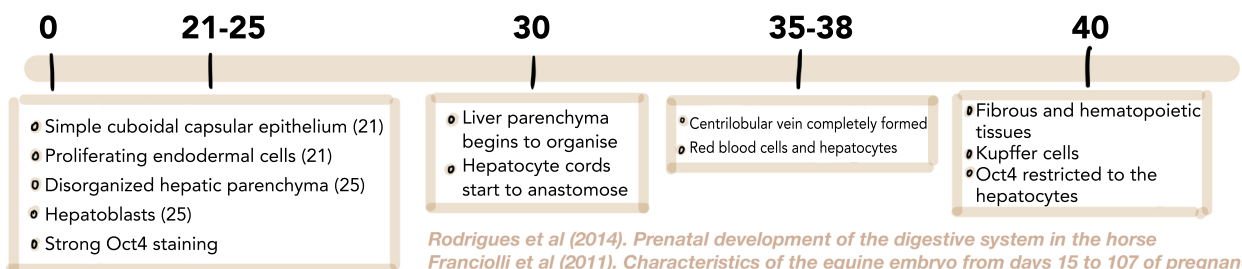
	150-210 DAYS	240-270 DAYS	270-300 DAYS	>300 DAYS
Basal insulin ($\mu\text{U/mL}$)	8.0 ± 1.0	7.0 ± 1.5	6.5 ± 1.0	9.0 ± 2.0
Basal glucose (nmol/L)	2.41 ± 0.19	3.09 ± 0.24	2.59 ± 0.21	2.77 ± 0.33
Insulin after glucose infusion	No effect	No effect	Small rise	High rise

Fowden and Silver (1980). Pancreatic b-cell function in the foetal foal and mare

+ From 260 days, equine pancreatic α cells are functional but are unresponsive to variations in glycaemia until after birth

Fowden et al (1999). Pancreatic a-cell function in the foetal foal during late gestation

LIVER

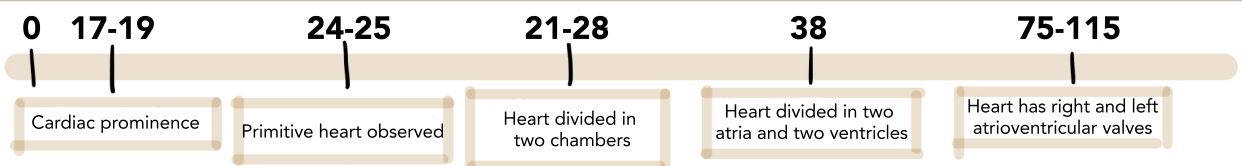


Rodrigues et al (2014). Prenatal development of the digestive system in the horse
Francioli et al (2011). Characteristics of the equine embryo from days 15 to 107 of pregnancy

The liver is an active site of hematopoiesis at 100 days (but maybe before)

Battista et al (2014). Haematopoiesis in the equine foetal liver suggests immune preparedness

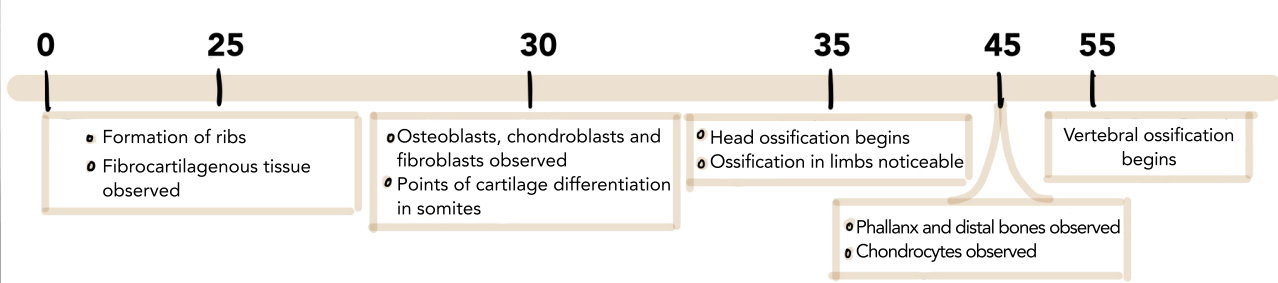
HEART



Beating and discernible from 20 days in the ventral quadrant

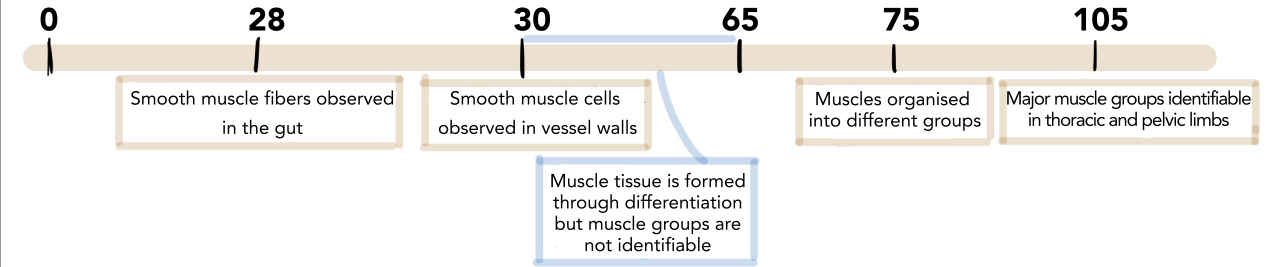
Rodrigues et al (2014). Prenatal development of the digestive system in the horse
Francioli et al (2011). Characteristics of the equine embryo from days 15 to 107 of pregnancy
Allen and Wilsher (2009). A review of implantation and early placentation in the mare
Rodrigues et al (2014). Embryonic and fetal development of the cardio respiratory apparatus in horses from 20 to 115 days of gestation

BONES AND CARTILAGE



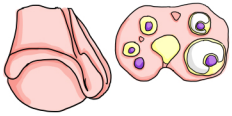
Barreto et al (2016). Organogenesis of the musculoskeletal system in horse embryo and early fetuses
 Francioli et al (2011). Characteristics of the equine embryo and fetus from days 15 to 107 of pregnancy
 Acker et al (2001). Morphologic stages of the equine embryo proper on day 17 to 40 after ovulation

MUSCLES



Barreto et al (2016). Organogenesis of the musculoskeletal system in horse embryo and early fetuses

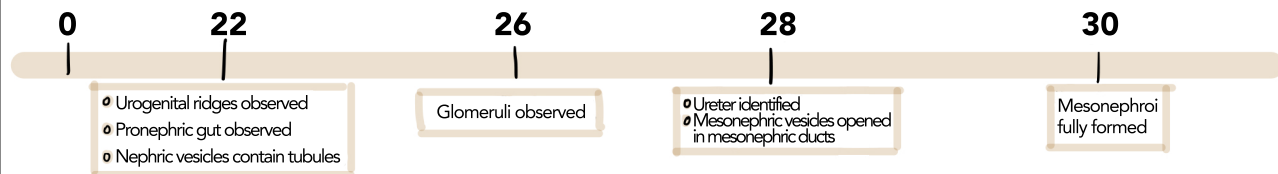
GONADS



Cole and Hart (1933). The development and hormonal content of fetal horse gonads.
 Sakai (1955). Studies on the development of the embryonic ovary in swine, cattle and horse.
 Francioli et al (2016). Characteristics of the equine embryo and fetus from days 15 to 107 of pregnancy
 Bergin et al (1970). A developmental concept of equine cryptorchism

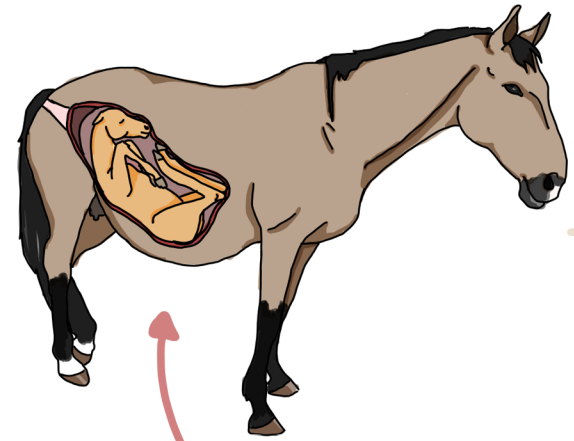
MISCELLANEOUS

- Onset of neurulation at 13 days
- Lung buds are observable at 24 days
- Formation of the pituitary gland between 31 and 48 days (depending on the study)
- Formation of the mammary gland at 80 days



Acker et al (2001). Morphologic stages of the equine embryo proper on days 17 to 40 of ovulation
 Francioli et al (2016). Characteristics of the equine embryo and fetus from days 15 to 107 of pregnancy
 Gaivao et al (2014). Gastrulation and the establishment of the three germ layers in the early horse conceptus

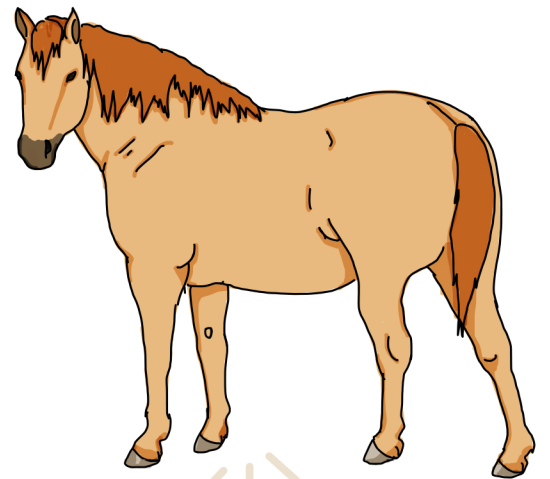
**Modifications of
maternal
environment**



EPIGENETICS
Adaptations of foetal
development

PLACENTA
Programming agent of
foetal development

PREGNANCY

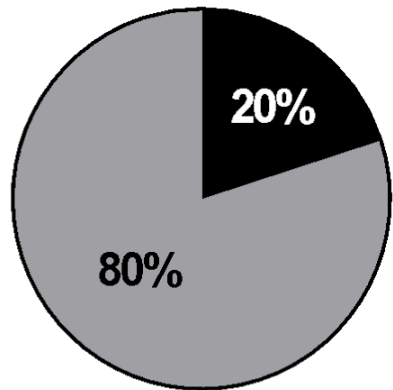


PHENOTYPE
Increased risk of
pathologies or improved
phenotype at adulthood

Metabolism and insulin resistance
Osteochondrosis
Reproductive maturity
Bone growth and development
...

OFFSPRING

Low-starch group (n=5)



High-starch group (n=5)

