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Lactation in Farm Animals
Biology, Physiological Basis, Nutritional Requirements, and Modelization

Edited by Naceur M'Hamdi

Lactation in Farm Animals - Biology, Physiological Basis, Nutritional Requirements, and Modelization

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Edited by Naceur M'Hamdi

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Veterinary Medicine and Science

Volume 3

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Scope of the Series

Paralleling similar advances in the medical field, astounding advances occurred in the Veterinary Medicine and Science in recent decades, fostering a better support to animal health and more humane animal production, a better understanding of the physiology of endangered species, to improve the assisted reproductive technologies or the pathogenesis of certain diseases, where animals can be used as models for human diseases (like cancer, degenerative diseases or fertility), and even as a guarantee of public health. Bridging the Human, Animal and Environmental health, the holistic and integrative "One Health" concept intimately associates the developments within those fields, projecting its advancements into practice.
This book series aims to tackle a variety of fields in the animal-related medicine and sciences, providing thematic volumes, high quality and significance in the field, directed to researchers and postgraduates. It aims to give us a glimpse into the new accomplishments in the Veterinary Medicine and Science field. By addressing hot topics in veterinary sciences, we aim to gather authoritative texts within each issue of this series, providing in-depth overviews and analysis for graduates, academics

and practitioners and foreseeing a deeper understanding of the subject. Forthcoming texts, written and edited by experienced researchers from both industry and academia, will also discuss scientific challenges faced today in Veterinary Medicine and Science. In brief, we hope that books in this series will provide accessible references for those interested or working in this field and encourage learning in a range of different topics.

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Preface

The physiology of lactation has attracted scientists involved in research with farm animals for a long time.

Lactation in Farm Animals: Biology, Physiological Basis, Nutritional Requirements, and Modelization is organized into two sections and divided into seven chapters. In this book, the authors discuss lactation strategies, milk composition, small ruminant lactation, nutritional requirements, prebiotic supplements in animal nutrition, and modeling and optimizing lactation. This book presents in-depth reviews of selected topics in lactation and milk production written by experts in their respective areas.

The editorial team assembled 18 authors to write the chapters. These contributors represent diverse expertise from academia, government research, and development institutions to ensure scientific precision and knowledge in lactation physiology and milk production. This book is not meant to be a treatise on the subject but presents basic information on the subject in a concise, easily understandable style.

Chapter 1 looks at maternal investment during lactation, which is higher than during gestation, and is the most energetically expensive period in a mammal's life cycle. Pinnipeds (seals, sea lions, fur seals, and walruses) are one of the principal groups of aquatic mammals that are adapted to reside on land and at sea. During lactation, they secrete and rapidly transfer lipid-rich and energy-dense milk to the pup and rely on land or ice to give birth and nurse their pups. As a consequence, foraging at sea and nursing of the young on land are separated by space and time. Lactation strategies in pinnipeds have evolved to meet particular environmental conditions, and because of their worldwide distribution they have evolved two main lactation strategies: a fasting strategy and a foraging strategy. Both strategies rely on energy reserves for the production of energy-dense and nutrient-rich milk. In comparison with the milk of land and marine mammals, the milk of pinnipeds is characterized by (1) high milk fat concentration and (2) the virtual absence of lactose. These two main differences in milk composition are a result of the lactation strategies adopted by pinnipeds and their unique lactation physiology in which they need to transfer high energy-rich milk in a short period of time while conserving water.

In Chapter 2, Maghreb areas are characterized by rainfall seasonality and scarcity resulting in a low fodder potential. In these arid and semiarid regions, small ruminant production is the main source of income for farmers, and sheep (*Ovis aries*) and goats (*Capra hircus*) are generally confronted with severe nutritional deficits during feed scarcity periods, which exacerbate disease and health problems and result in low performance. Interestingly and despite the importance of milk performance to the dairy industry, very few works have studied the potentialities of the mammary gland through the lactation period in both sheep and goats elevated in the Maghreb areas. Nevertheless, understanding the different mammary gland patterns throughout lactation is essential to improve dairy production and reduce poverty and vulnerability in rural farming systems in these developing areas.
The main objective of this review is to analyze the lactation processes as well as

to underline the mammary gland morphological patterns, health and physiology traits, and evaluate milk potentialities of the main breeds of goats and sheep raised in Maghreb.

Chapter 3 focuses on the feeding of dairy sheep, which has to start exactly at the beginning of the last two months of gestation (the last third of gestation) and not after lambing. Indeed, during this critical physiological stage, the rumen is compressed by the uterus. Therefore, the ewe can no longer ingest the amount of food that can satisfy its ingestion capacity (2–2.5 kg DM/100 kg of weight/speed), which leads to a controversial situation: on the one hand, needs are high (maintenance and gestation), and on the other hand, ingestion capacity is decreasing. To solve this issue, ewes should be given a supplement based on good quality food that is neither heavy nor favors rapid digestive transit. Thus, this supplement must be a concentrated feed distributed at a rate of 0.3 UF/ewe/day during the last two months of gestation. This feeding technique makes it possible to have vigorous lambs at birth, a satisfactory colostrum production that makes it possible to give lambs the antibodies necessary for their passive immunity, and therefore reduce the perinatal mortality rate, as well as allow good triggering of milk production, which will increase the quantity produced and the peak of lactation. In general, the ratio must always be balanced in energy and protein. Indeed, if the ratio is a surplus of energy, then it can cause infertility in ewes. If it is a surplus of protein, then the urine will be stored in the liver and transformed into urine. However, if the excess is intolerable, it will persist in the liver and cause mortality of the animals, caused by diseases such as alkalosis. In addition to proteins and energy, ewes must receive the necessary minerals, mainly Ca and P, during pregnancy and lactation. A deficiency of Ca at the end of gestation will cause milk fever (hypocalcemia), which will not be recoverable later. Finally, excessive watering should be avoided after a water shortage to prevent diarrhoea.

In Chapter 4, innovative development in the dairy industry is only possible due to scrupulous research, nutrition, genetics, management strategies, and their oriented implementation. The high risk of contagion is due to occasional bouts and improper feeding of nutritional contents, which are the ultimate cause of debility, economic loss, and resources. To avoid the prevalence of such harm to dairy animals' proper nutritional content, management of hygiene is required. For this, the term "probiotic" was coined in the 1960s, which is a curious mixture of Latin (Pro = for, in favor of) and Greek (Bios = life). Probiotic, discovered by Elie Metchnikoff in the early twentieth century, is defined as "Live microorganisms which when administrated in an adequate amount to an organism body confer a health benefit on the host and alter the gastrointestinal tract flora into the beneficial form." The nature of probiotics is relevant to human, animals, and plants. But, here we will focus on the probiotics of animals because we are dealing with dairy animals.

Chapter 5 looks at blood indicators, which are used as tools to diagnose metabolic disorders. The present review aims to study the relationships among body condition score, milk yield, and reproduction and biochemical parameters in dairy cows. Live weight and body condition are indicators of dairy cows' health, milk productivity, and reproduction. Therefore, many authors have investigated the effect of body condition score at calving and of change in body condition score on productive and reproductive performance, on lactation curve parameters, and on post-partum disease occurrence. Moreover, results showed that cows calving at the highest body condition score lost more subcutaneous fat; a condition score change did not exceed 1.05 units. The change in body condition score was positively associated with peak and total milk production. In addition, the decline in dairy reproductive performance may be due to a hampered process of metabolic adaptation. Adaptation to the negative energy balance is a gradual process. The use of risk factors is more appropriate and discussed. Among them are the body condition score and its derivatives, feed intake, the calculated negative energy balance, and metabolic parameters like the plasma concentration of insulin or the triacylglycerol content in the liver. Moreover, factors that play a role in the link between declined reproductive performance and the metabolic situation of the cow during lactating are discussed.

In Chapter 6, the mathematical representation of milk production against time represents one of the most successful applications of mathematical modeling in agriculture. Parametric functions have represented the preferred tools used to fit average curves. However, the increased availability of records per individual lactation, the increase in lactation length, and the genetic evaluation based on test day records have shifted the interest of modelers towards more flexible and general linear functions, such as polynomials or splines. Modeling extended lactation presents one of the suggested orientations for future research. In these contexts, the present study focuses on evaluating the goodness of fit of mathematical models for the adjustment of the standard and extended lactation curve (overall and individual) of Holstein cows in Tunisia. Several different mathematical models were used (parametric, Legendre polynomials, and splines). Goodness of fit of the seven parametric models, Wood (WD), Dhanoa (DH), Wilmink (WIL), Logarithmic (LOG), inverse Polynomial (IP), Cubic (CUB), and Guo & Swalve (GS), was generally acceptable to describe the shape of the standard lactation curve. However, these models overestimated initial milk yield and underestimated yields around peak production. For FP and PP, the WD, DH, and LOG models were unsuitable to describe the curve at the beginning of lactation and around the nadir point. All models fitted individual lactation curves of PP and MY better than FP. The WIL model was more advantageous to fit the overall and individual lactation curves for MY, FP, and PP. The mathematical properties of polynomial and non-parametric models were examined to fit the individual lactation curves for MY, FP, and PP. Spline regression models showed the best fit for all milk yield traits. The performance of Legendre orthogonal polynomials and quadratic splines was strongly affected by the models' order and the number of knots. Conversely, in extended lactations, the CSPL7, QSPL7, LEG6, and AS models gave the lowest values. The goodness of fit tends to decrease as the length of lactation increases for all models. Examination of residual distributions showed that non-parametric models with 6–7 knots were the best for predicting yield at all stages of lactation, and according to several statistical criteria were the best to fit standard individual lactation curves and, in particular, extended curves.

In Chapter 7, making a decision on the number of milkings per day for each ruminant is a key factor to optimize the use of machine milking. Currently, this decision is mainly taken from yield and stage of lactation data, but no udder capacity is taken into account. Milk is stored in the udder in alveolar and cisternal compartments. Milk partitioning in the udder varied widely according to species, breed, lactation stage, parity, and milking interval. The increase in milking frequency has improved milk production in dairy ruminants. However, this practice reduces the milk composition, fertility, and productive life. To avoid increasing the number of milkings per day and reducing milk losses, a strategy based on the selection of ruminants with large udder cisterns to store a large quantity of milk was adopted. Animals with large cisterns tolerate extended milking intervals and milked faster with simplified routines. Ultrasonography will be a useful tool to measure udder cisterns and to predict high-yielding animals. In practice, we propose to use the evaluation of the udder cistern area as a criterion for udder milk storage capacity, establishing the optimal milking frequencies for each ruminant according to the production system.

This book presents an updated and unique approach to the topics and is designed to augment related books in the existing market. The editorial team is comprised of individuals with significant experience in the science and milk production.

We hope that the book will be useful for students and researchers in milk production, nutrition, physiology, and other related fields.

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Section 1

Biology, Physiological Basis and Nutritional Requirements

Chapter 1

Lactation Strategies and Milk Composition in Pinnipeds

Federico German Riet Sapriza

Abstract

Maternal investment during lactation is higher than during gestation, and it is the most energetically expensive period in a mammal's life cycle. Pinnipeds (seals, sea lions, fur seals, and walruses) are one of the principal groups of aquatic mammals that are adapted to reside on land and at sea. During lactation they secrete and rapidly transfer lipid-rich and energy-dense milk to the pup, and they rely on land or ice to give birth to and nurse their pups, and as a consequence, foraging at sea and nursing of the young on land are separated by space and time. Lactation strategies in pinnipeds have evolved to meet particular environmental conditions, and because of their worldwide distribution, they have evolved into two main lactation strategies: fasting strategy and foraging strategy. Both strategies rely on energy reserves for the production of energy-dense and nutrient-rich milk. In comparison with the milk of land and marine mammals, the milk of pinniped is characterized by (a) high milk fat concentration and (b) the virtual absence of lactose. These two main differences in the milk composition are a result of the lactation strategies adopted by pinnipeds and their unique lactation physiology in which they need to transfer a high energy-rich milk in a certain period of time while conserving water.

Keywords: milk, lipid, protein, pinnipeds, pup, seal, sea lion, walrus, foraging, fasting, marine mammals

1. Introduction

Maternal investment during lactation is higher than during gestation, and it is the most energetically expensive period in a mammal's life cycle [1, 2]. In early postnatal life, the neonate is unable to feed itself; hence, it has to rely on the mother for its food supply in the form of milk, and this process of milk production is known as lactation [3]. As a consequence of the full dependence on the female during lactation, parental investment will have a direct effect on the growth rate and survival of the nursing offspring. On the other hand, mammal reproductive success will be influenced by parental age, experience and foraging strategies, and food availability; but also by factor associated to the offspring such as time of weaning, sibling competition, and litter size [4].

Pinnipeds (seals, sea lions, fur seals, and walruses) are one of the principal groups of aquatic mammals that are adapted to reside on land and at sea [5, 6]. There are three taxonomic groups of pinnipeds, Otariidae, the sea lions and fur seals; Odobenidae, the walrus; and Phocidae, the true seals, and they have adopted distinctive lactation strategies [6, 7]. They rely on land or ice to give birth and nurse their pups, and as a consequence, foraging at sea and nursing of the young on land are separated by space and time [6, 7]. While staying on the terrestrial environment, for some species, the mother and the pup are vulnerable to potential terrestrial predators; therefore, pinnipeds have evolved strategies to diminish the risk of predation [7, 8]. Other issues that concern the survival of the pup are (1) the buildup of an insulation layer against heat loss and (2) the supply of enough energy to enable the pup to sustain itself during periods of fasting. These issues are tackled by secreting and rapidly transferring lipid-rich and energy-dense milk to the pup [9, 10]. Lactation strategies in pinnipeds have evolved to meet particular environmental conditions, and because of their worldwide distribution, they have evolved into a diversity of lactation strategies [7, 8, 11]. In this chapter the lactation strategies of pinnipeds are described; and the milk composition of pinnipeds and how its composition varies in relation to maternal factors are discussed.

2. Lactation strategies in pinnipeds

2.1 Foraging lactation strategy: sea lions and fur seals (Otariidae)

Otariids have adopted a lactation strategy known as the "foraging lactation strategy" or as "income breeders," and it is characterized by the mother alternating between nursing the pup on land and periods of foraging at sea (**Figure 1**) [12]. The perinatal period is known as the time period in which the otariid mother stays on land with the pup after giving birth. During this period, which last about a week, the pup-mother bond is established.

The duration of lactation in otariids ranges from 4 months to 3 years (**Table 1**) [7] and may have evolved as a consequence to environmental predictability associated with latitude [11]. The predictability and productivity of the marine environment have had a crucial role in shaping the maternal strategies observed in pinnipeds. For instance, in higher latitudes marine productivity is seasonal and radical; however, very predictable. The duration of lactation in pinnipeds is usually short in higher latitudes, whereas in lower latitudes, the seasonal pattern of marine productivity is more constant throughout the year, and as a result, the duration of lactation in pinnipeds is usually longer (**Table 1**). Notwithstanding, every few years pinniped inhabiting lower latitudes are exposed to unpredictable productivity due to El Niño/La Niña (El Niño Southern Oscillation or ENSO) conditions, [13]. El Niño Southern Oscillation events have a profound effect on climate and ocean

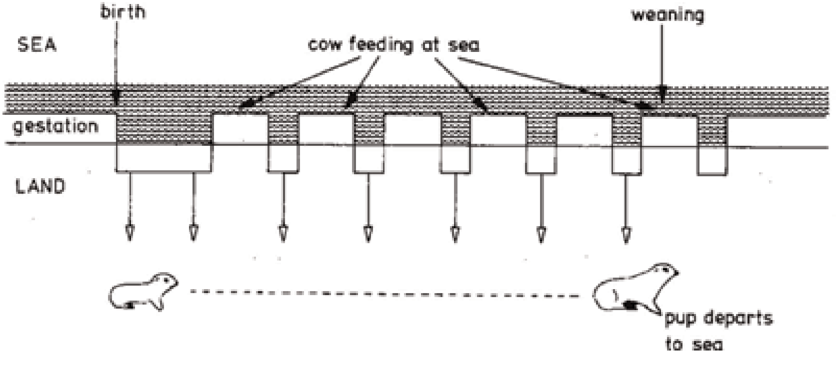

Figure 1.
Maternal foraging strategy of otariid seals (from [7]).

Species	Lactation (months)	Source
Northern fur seal *Callorhinus ursinus*	3–4	[23, 25, 32]
Antarctic fur seal *A. gazella*	4	[4, 26, 32]
South American sea lion *Otaria flavescens*	5–12	[5, 7]
California sea lion *Zalophus c. californianus*	6–12	[17, 19, 33]
South American fur seal *A. australis*	6–24	[7, 16, 34]
Juan Fernandez fur seal *A. philippii*	7–10	[35]
Subantarctic fur seal *A. tropicalis*	10	[9, 36]
Australian fur seal *A. pusillus doriferus*	11	[30]
Guadalupe fur seal *A. townsendii*	9–11	[32]
Steller's sea lion *Eumetopias jubatus*	11–12	[37–39]
New Zealand fur seal *A. forsteri*	11–12	[7, 40, 41]
New Zealand sea lion *Phocarctos hookeri*	~12	[42]
Galapagos sea lion *Zalophus c. wollebaeki*	~12	[5, 21]
Cape fur seal *A. pusillus pusillus*	~12	[7, 43]
Walrus *Odobenus rosmarus*	12–36	[5, 7, 44]
Galapagos fur seal *A. galapagoensis*	12–36	[7, 21, 32]
Australian sea lion *Neophoca cinerea*	15–18	[1, 2]

Table 1.
Duration of lactation period in fur seals, sea lions, and walruses.

ecosystems [14]. Upwelling zones in the eastern Pacific undergo a negative transition from normal highly rich productivity to profoundly decreased productivity [15]. Pinnipeds which prey at the top of the food chain are severely affected by low food availability, which in turn disrupts normal maternal foraging and attendance patterns, suckling patterns, pup growth, and pup behavior [16, 17].

During El Niño conditions, changes in the maternal attendance pattern (nursing behavior) and maternal diving behavior of South American fur seals (*Arctocephalus australis*) have been recorded [18]. Shortage of food availability due to ENSO conditions resulted in low maternal foraging success and prolonged stay at sea searching for food at high-energy cost. Consequently, South American fur seals nursing mothers were unable to replenish their energy reserves to confront the high-energy cost of lactation. California sea lions (*Zalophus californianus*) responded in a similar manner to ENSO conditions by extending significantly their foraging trips [19], and pup milk intake was lower than in years without El Niño conditions [17]. During years of shortage of krill near South Georgia, lactating Antarctic fur seal (*Arctocephalus gazella*) females made fewer and longer trips that resulted in decreased mass and growth of pups [4]. The maternal foraging trips doubled in time, and as a consequence, the mortality of pups increased to 32%, 68% which died from malnutrition [20].

Among otariid species they share very similar breeding and lactation strategies (see **Figure 1**) [7]. In low-latitude otariids, such as Galapagos fur seals, during pregnancy they spend extended periods of foraging at sea in order to store energy in the form of lipid, and then they arrive at the colony 2–3 days before giving birth. Thereafter the mother nurses the pup during the perinatal period (5–10 days), and then she starts her attendance pattern that consists of foraging trips at night and return to the colony in the morning [21]. Foraging trips lasted around 2 days [21], whereas suckling attendance periods lasted from half a day to one and a half days, the length of which is related to the age of the pup [22]. The tropical Galapagos fur seals have the longest lactation period in otariids that lasts from 1 to 3 years (**Table 1**). Their conspecific, the Galapagos sea lions (*Zalophus californianus wollebaeki*), attended their pups almost every day and foraged during the day and returned at night [21].

In comparison with otariids inhabiting low latitude, species with high-latitude distribution have shorter lactations period (e.g., Antarctic fur seals, northern fur seals *Callorhinus ursinus*, and subantarctic fur seals *Arctocephalus tropicalis* (see **Table 1**)). Antarctic and northern fur seals wean their pups at the age of 4 months, while subantarctic fur seals wean their pups at the age of 10 months (**Table 1**) [5]. Pregnant Antarctic fur seals arrive at the colony 2 days prior parturition, and their perinatal period lasts for about 5–7 days, and then the mother alternates foraging at sea for 3–5 days with attendance periods of 3–10 days [23, 24]. Similarly, pregnant northern fur seals arrive to the colony 12 hours to 2 days prior to the birth and nurse their pup during the 6–7 days perinatal period before commencing their first post-partum foraging trip that could last 4–7 days [23, 25].

The mean duration of foraging trips of lactating northern fur seals lasted for 6–8 days and was longer than in Antarctic fur seals, while their attendance period lasted from 36 hours to 2 and a half days. Interestingly, subantarctic fur seals have one of the longest attendance pattern recorded in fur seals. The females arrive ashore 1–2 days prepartum and then spend 8 days nursing the newborn, thereafter alternating long foraging trips of 11–23 days with long maternal attendance periods ashore of up to 4 days [26, 27]. This attendance pattern is constant throughout the whole period of lactation and until the pup is weaned at 10 months of age (**Table 1**) [26].

In conclusion, otariids inhabiting low latitudes are exposed to a marine environment with very unpredictable low food productivity, while otariid mothers raising their pups at high latitudes have to deal with a more predictable marine environment with high seasonal productivity.

Given the degree of the predictability of the food productivity in the marine environment, one may expect to observe shorter lactation duration in subpolar otariid species due to the short high-productivity seasonal period. However, some species data contradict this argument and cannot be sustained.

Therefore, it could be argued that the duration of lactation in otariids might be a result of the seasonal availability and predictability of food sources, while foraging trip duration and rate of energy transfer are determined by the distance from the breeding site ashore to the food source at sea [6]. Some investigators have raised the question whether milk composition in otariids is directly or indirectly influenced by interspecific differences in the duration of foraging trips at sea [9, 10, 21, 28–31].

2.2 Fasting lactation strategy: *seals* (Phocidae)

Phocid maternal strategies differ from that of the otariids, mainly by a shorter lactation period and maternal fasting throughout the whole lactation period (**Figure 2** and **Table 2**). Phocids have adopted a lactation strategy known as the fasting lactation strategy making them capital breeders [12]; however, not all phocid species are embedded into this strategy. Pregnant phocid females arrive at haul-out sites a few days before pupping, and when nursing is completed, the pup is abruptly weaned (**Figure 2**) [5]. Phocid seals that breed on pack or fast ice are known as pagophilic seals, while seals that breed on dry land are known as land-whelping seals [7].

Ice-breeding seals or pagophilic seals (breed on pack or fast ice) [7] have evolved remarkable breeding and lactation strategies in order to reduce predation pressure.

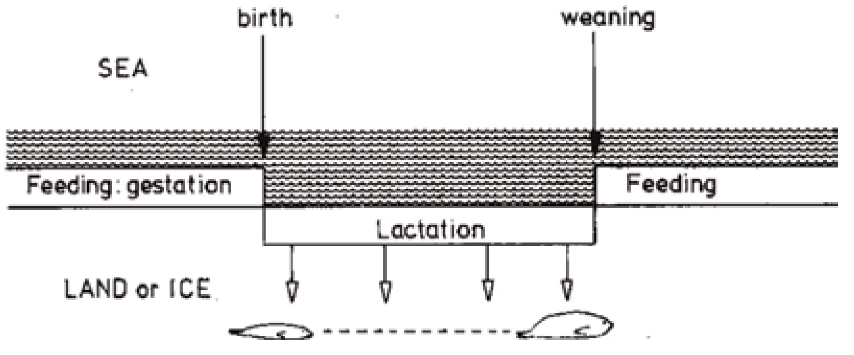

Figure 2.
Diagram of the breeding and lactation strategy of true seals, phocids, known also as the fasting strategy, and capital breeders [7].

Species	Lactation period (days)	Source
Pack ice		
Hooded seal *Cystophora cristata*	4	[48]
Harp seal *Phoca groenlandica*	12–13	[49]
Crabeater seal *Lobodon carcinophagus*	14–21	[50]
Bearded seal *Erignathus barbatus*	12–24	[51]
Gray seal *Halichoerus grypus*	16	[5]
Caspian seal *Phoca caspica*	21	[52]
Ribbon seal *Phoca fasciata*	21–28	[53]
Spotted seal *Phoca largha*	28	[5, 54]
Leopard seal *Hydrurga leptonyx*	~30	[55]
Fast ice		
Weddell seal *Leptonychotes weddellii*	35–42	[56]
Ringed seal *Phoca hispida*	36–41	[57]
Baikal seal *Phoca sibirica*	60–75	[58]
Land		
Harbor seal *P. v. richardsi*	21–35	[52]
Southern elephant seal *Mirounga leonine*	23	[59, 60]
Northern elephant seal *M. angustirostris*	28	[61, 62]
Harbor seal *Phoca vitulina vitulina*	28–42	[63]
Harbor seal *P. v. concolor*	33	[52]
Hawaiian monk seal *Monachus schauinslandi*	~42	[64, 65]
Mediterranean monk seal *M. monachus*	42–49	[65, 66]
Harbor seal *P. v. Stejnegeri*	90	[52]

Table 2.
Duration of lactation (days) in true seals (phocids) breeding on three different substrates: pack-ice, fast-ice, and land.

In order to do so, phocids have shortened the duration of lactation, and they have inhabited higher-latitude breeding substrate in which terrestrial predator area is almost nonexistent [7]. However, fast-ice phocids such as ringed seals

(*Phoca hispida*) are preyed by polar bear and arctic fox and have avoided predation pressure by giving birth and nursing their pups in snow and ice dens [45, 46]. If predation is nonexistent or basically avoided by choice of breeding site, then any variations in the maternal strategies must be related to other ecological factors such as stability of breeding substrate.

There are some advantages and disadvantages for phocid breeding on ice packs (ice floating on the sea surface). Seals have a rapid access to deep waters; however, ice packs provide little shelter and are an unstable substrate at the mercy of wind and sea surface currents that could drift away the ice pack separating the mother and pup. As a consequence of the instability of the pack-ice breeding, pagophilic seals have the shortest lactation period in pinnipeds (4–30 days) [5, 7, 47]. On the contrary, in more stable environments such fast-ice or land, seals are able to extend the duration of the lactation period (36–75 days).

The shortest lactation period in pack-ice-breeding species has been reported in the hooded seal, *Cystophora cristata*, that nurses pups for only 4 days [47], and the harp seal, *Phoca groenlandica*, for 12–13 days [67], while the longest lactation period has been recorded in seals that breed on fast-ice and land (**Table 2**). In comparison with the duration of lactation in Baikal seals and the Mediterranean monk seals, southern (*Mirounga leonina*) and northern elephant seals (*Mirounga angustirostris*) have significantly shorter periods of 21 and 28 days, respectively (**Table 2**). The short lactation duration described in phocid in comparison with otariids and maternal fast during the nursing period influence the milk composition and the dynamics of energy transfer from mother to pup. Moreover, the high milk energy content in phocid could be a result of the short lactation duration in which a large amount of energy in the form of milk lipid and protein is transferred to the nursing pup in a limited time.

Two distinctive lactation strategies have been observed in ice-breeding seals (e.g., hooded seals and gray seals, *Halichoerus grypus*). In the first lactation strategies, seal mothers nurse their pup with very energy-rich milk during a very short lactation period (**Tables 2** and **3**). This lactation strategy involves the pup being very inactive and in most cases does not enter the water for many weeks, and they are abruptly weaned, and then the pup must withstand a long postweaning fasting period [68].

The second lactation strategy is observed in bearded seals *Erignathus barbatus* and ringed seals *Phoca hispida* and has the longest lactation duration among ice-breeding phocids. In addition, nursing mothers do not fast entirely during the lactation period, the energy content in milk is lower, and pups are more active. It was argued that only otariids have evolved a foraging lactation strategy in which lactating females have pup attendance periods on land alternated with foraging trips at sea.

Research about the energetics and diving behavior of harbor seals (*Phoca vitulina*) has demonstrated that maternal body mass has important consequences for lactation strategies in phocid species and that some phocids have adopted an "otariid like-lactation strategy" [69]. This may in fact suggest that ice-breeding seals such as bearded and ringed seals, with long lactation duration and lower energy-rich milk, are unable to sustain lactation while fasting. There is data that support the hypothesis that these seals have adopted an "otariid-like" maternal foraging cycle [57, 70, 71]. An otariid-like foraging cycle behavior may have evolved in small body size phocids, such as the harbor seal, as a result of depletion of maternal body energy reserves in the form of lipid during the lactation period [6]. The maternal body size of harbor seals is slightly larger than most otariids, suggesting that the body size may be limiting the amount of energy reserves (lipid)

Species	Milk composition (%)				
	Lipid	Water	Protein	Sugar	Ash
Australian sea lion[+] [2, 28]	28.35[a]	56.9 ± 9.9	9.9 ± 2.5	—	0.9 ± 0.3
	47.15[b]	—	—	—	—
	55.4[c]	—	—	—	—
Steller sea lion [37]	24	—	—	—	—
South American sea lion [81]	38.6 ± 3.1[a]	48.9 ± 3.1	11.1 ± 1.2	—	0.8 ± 0.1
California sea lion [17]	31.7[a]	59.0	8.5	0.3	—
	43.7[b]	—	—	—	—
Galapagos sea lion [21]	32.4[a]	—	9	—	—
	25.1[b]	—	—	—	—
New Zealand sea lions [82]	21.3 ± 8.1	67.9 ± 8.8	9.4 ± 2.4	0.4	0.48 ± 0.06
Galapagos fur seal [21, 83]	29.4 ± 5.9[a]	—	9.9 ± 1.4[a]	0.1	0.9 ± 0.1
	—	—	14.0 ± 0.9[b]	—	—
Guadalupe fur seal [10]	~41	—	—	—	—
Juan Fernandez fur seal [29]	41.4 ± 5.8	—	11.9 ± 2.0	1.2 ± 0.4	0.7 ± 0.1
Subantarctic fur seal [10]	45.0 ± 3.7[a]	40.7 ± 4.5[a]	13.4 ± 1.4[a]	—	—
	51.9 ± 4.9[b]	33.3 ± 4.0[b]	11.6 ± 1.3[b]	—	—
	52.3 ± 6.0[c]	33.3 ± 4.9[c]	11.5 ± 1.2[c]	—	—
South American fur seal [84]	36.5 ± 4.2	—	9.1 ± 0.8	—	—
Australian fur seal[*] [30]	32.7[a]	54.6[a]	9.9[a]	—	0.7 ± 0.1
	47.7[b]	39.1[b]	11.0[b]	—	—
	47.9[c]	44.3[c]	12.3[c]	—	—
Cape fur seal [85]	23.2[a] ± 8.2	58.1 ± 6.8	10.8 ± 1.2	—	2.0 ± 0.6
Northern fur seal [7, 86]	45.6	36.4	12.4	0.1	0.6
Antarctic fur seal [3, 9]	39.8 ± 6.7	41.3 ± 9.3	18.1 ± 5.8	—	0.7 ± 0.1
Walrus [79]	24.1	59.9	7.8	—	0.59

[a]*Early lactation*
[b]*Mid lactation*
[c]*Late lactation*
**Values estimated from regression equations (see Arnould and Hindell) [30]*
[+]*Values were averaged.*

Table 3.
Milk composition of otariids and walrus.

that can be stored. The demand of energy from her limited body's stored reserves (blubber) to produce milk and to maintain her own energy needs may not be enough [6, 72–74].

Taken into consideration the small maternal body size of harbor seals, it is very likely that at least half of the phocid species with similar small body size may have adopted the "otariid-like" maternal foraging cycle [73]. There is evidence that shows that lactating harbor seal started to forage at sea when the gain of energy, to restore energy reserves, was highest and the uncertainty of pup mortality was the lowest [73]. Maternal body size has been shown to play an important role in shaping lactation strategies in pinnipeds [8]. For instance small body size phocids, cannot store enough energy in the form of blubber (lipid) to support the high cost of lactation, and thus, there are physiological limits that are interacting and influencing their lactation strategy [6, 69].

Northern and southern elephant seals have a similar breeding pattern, and a wide variety of social behavior traits (age, sex, and season) are a result of well-defined seasonal cycles and making of large colonies. Within the group of land-whelping seals, elephant seals have one of the shortest lactation periods, lasting 23 days in southern elephant seals and 28 days in northern elephant seals. During this period the pup has a rapid growth rate [59, 75], and it is followed by a long postweaning fasting period (2–3 months) [76]. Notwithstanding during this period, male pup steals milk from other mothers in order to grow bigger, and this is driven by a marked sexual dimorphism in elephant seals, i.e., there is a selective advantage in increased size in males (**Figure 3**).

A mentioned before, small maternal body size phocids species have adopted alternative "otariid-like" lactation strategies within their group. In this context it may be possible to raise the question what are the factor/s or selective pressure that are governing the maternal strategies in phocids and are they the same as in otariids.

The influence of latitude on the lactation strategies, as described in otariids, have not been suggested for phocids. However, there are environmental factors associated with latitude that may have influenced the evolution of lactation strategies in phocids [11]. The duration of lactation in phocids has evolved, driven by the selective pressure of the breeding substrate and the cost of milk production, and to some extent predation [11]. However, the argument about predation pressure may not apply for most land-breeding phocids since they breed on predator-free islands. Consequently, there must be other selective pressures, apart from the breeding substrate, that caused the shortening of the lactation duration in phocids [11].

In conclusion, the lactation strategy adopted by most phocids is quite unique. Their lactation period is very short in comparison with otariids, and they fast for the entire lactation. As a result they need to store enough energy in body reserves (blubber) in order to produce the most nutrient-rich, energy-dense milk among mammal species. Due to phocid large maternal body size, they store large amount of energy and can withstand the high cost of lactation while fasting. However, small body size phocids such as harbor seals are unable to withstand the cost of lactation due to body nutrient depletion and have adopted an "otariid-like" lactation strategy in which the mother forages at sea.

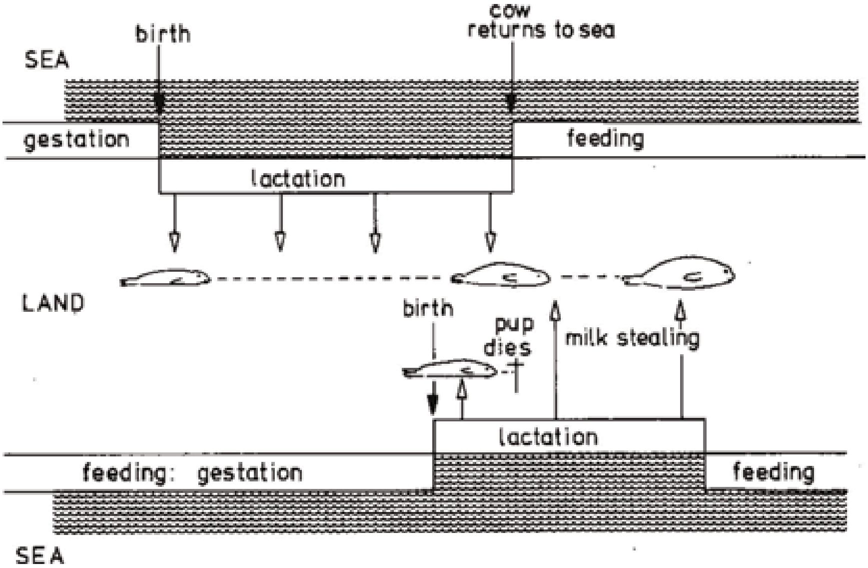

Figure 3.
Fasting lactation strategy in phocids, the northern elephant seals Mirounga angustirostris [7].

2.3 Aquatic lactation strategy: Odobenidae (walrus)

Recapitulating, a third lactation strategy, known as aquatic strategy, has been described in pinnipeds that differ from that of the capital (phocids) and income breeders (otariids). In the northern hemisphere, in high latitudes, two subspecies of walruses occur, namely, the Atlantic walrus, *Odobenus rosmarus rosmarus*, and the Pacific walrus *O. r. divergens* [77]. Walruses are most social among pinnipeds species, and they are usually found in a group on ice floes hauling out, resting, molting, and whelping [78]. In fact, the migration pattern of mother pups pairs is associated with ice movement [79]. At some point in their reproductive cycle, all pinniped species need to return to land or ice to give birth and nurse their pup, and eventually the mother and the pup venture into the sea to search for food. However, walruses have adopted an aquatic lactation strategy in which the mother gives birth to the pup on ice floes, and after the perinatal period (few days), the mother returns to the sea with the pup. Nursing of the pup occurs in the water and on land and ice, and when the mother dives to search for food, the pup remains at the surface [44].

The lactation period lasts for 2 years, and at the age of 5 months, the pup starts to consume solid food, mainly benthic invertebrates [80]. Fisher and Stewart [80] suggested that the long duration of lactation might be associated with the specific mode of feeding of walruses. The main prey of walruses are bivalves (benthic fauna) that inhabit the bottom of the sea [80]. In early stages of lactation, the pup must learn how to dive and search for food at the bottom of the sea, and this may explain the extended duration of lactation that apparently should increase the weaned mass and the survival chances of the pup [44].

Species	Milk composition (%)				
	Lipid	Water	Protein	Sugar	Ash
Harp seal [93–96]	35.8 ± 1.8[a]	51.4 ± 1.8[a]	10.4 ± 0.5[a]	0.69–0.79[a]	0.61
	35.4[b]	32.4 ± 0.4[c]	7.7 ± 0.2[c]	0.65[c]	—
	57.1 ± 0.5[c]	—	—	—	—
Hooded seal [7, 97]	56.3[a]	49.8	6.2[a]	0.86[a]	0.86
	61.0[b]	—	4.7[b]	1.05[b]	—
	61.1[c]	—	5.1[c]	0.99[c]	—
Gray seal [51, 98]	39.8 ± 2.8[a]	45.0 ± 2.1[a]	11.2 ± 0.8[a]	0.7[a]	0.69
	55.6 ± 1.6[b]	3.0 ± 1.4[b]	9.4 ± 0.14[b,c]	0.8[b,c]	—
	60.0 ± 1.86[c]	28.6 ± 1.3[c]	—	—	—
Bearded seal [7, 97]	49.5	46.4	6.8	0.05	0.6
Weddell seal [99, 100]	53.6[a]	43.6	14.1	0.02	—
Harbor seal [6]	50	—	—	—	—
Southern elephant seal [59, 101]	16.1 ± 7.0[a]	70[a]	12.6 ± 2.3[a]	0.28 ± 0.10	—
	39.5 ± 15.2[b]	33[c]	10.7 ± 2.8[c]	—	—
Northern elephant seal [61]	24[a]	75a	5–12	<0.25	—
	47[b]	35[c]	—	—	—
	54[c]	—	—	—	—
Crabeater seal [102, 103]	35[a]	—	10[a]	1.1–1.9	1.04[a]
	50[b]	—	10.8	—	0.93[b]

[a]*Early lactation*
[b]*Mid lactation*
[c]*Late lactation*

Table 4.
Milk composition in true seal, phocids.

In comparison with the milk of pinniped species, the milk produced by walruses contains the lowest lipid and protein concentration (**Table 4**). The low-energy content of milk may be explained by the very long duration of lactation, and hence, there is less pressure in terms of maternal energy reserve depletion and for rapid transfer of energy-rich milk to the pup. Walruses inhabit the same marine environment as pagophilic phocid seals and thus must face the same high thermoregulatory needs and predation pressure. Walruses have evolved an aquatic lactation strategy in which foraging at sea and nursing their pup are not spatially and temporally separated. As a consequence they are able to extend their lactation period, lower the maternal cost (nutrient depletion), and lower pup mortality.

3. Milk composition in pinnipeds and other mammals

Milk is secreted by the mammary glands, and it is a complex fluid that contains five main components, water, lipids, proteins, sugars, and minerals [87–89]. Several of these can be divided further into more specific components. The concentrations of all the components in milk may vary both between species and within species at different stages of lactation and under different nutritional and environmental condition. Extensive reviews of the comparative composition of milk across species can be found elsewhere [87, 90–92]. The milk of pinnipeds differs substantially from other mammals in (a) high-fat concentration in milk and (b) virtual absence of lactose. These differences are a consequence of their lactation strategies and physiology in which the rapid transfer of energy-rich milk and the conservation of water are essential.

Pinnipeds are a group of mammals that produce the richest energy-dense milk, and fat is the major contributor to the energy content of milk. Milk fat concentration varies considerably between pinnipeds species and within species (see **Tables 3** and **4**). Overall phocids produce milk with a higher concentration of fat than otariids although some otariids produce milk with high-fat concentrations (**Tables 3** and **4**). In most species the milk fat concentration varies in response to suckling, and as the mammary gland is being emptied, pinnipeds are not an exception. As in other mammals, milk fat concentration is influenced by stage of lactation and by nutritional status [88]; however, it is not clear how the latter is mediated in pinnipeds. This and other factors that affect milk composition in pinnipeds and in particular milk fat concentration are discussed further (see subsection factors that influence the milk composition) in this chapter.

Milk proteins are either caseins or whey proteins, and the kind and number of protein varies significantly between mammal species [104]. Proteins that are most common in milk are caseins, blood serum albumin, immunoglobulins, and alpha-lactalbumin, and the beta-lactoglobulin family is only found in the milk of ruminants and some species of artiodactyls [104].

Protein such as casein has a nutritional function and is a source of amino acids for the suckling offspring. There is some knowledge about milk proteins and their function in terrestrial mammal; therefore, little can be suggested for homologous proteins found in the milk of pinniped. A whey protein, such as alpha-lactalbumin, has not been found in otariid milk and is practically absent in phocid milk [84, 105, 106]. The protein alpha-lactalbumin is crucial for biosynthesis of lactose in milk, and therefore, the absence of lactose in pinniped milk has been associated with the lack of this protein [86]. By comparison with bovine milk, casein micelles found in northern fur seals milk were significantly larger, but the reason for this has not been addressed [86]. Caseins have been reported to account for 44–72% of the total protein in phocid milk [87, 107], whereas in otariids, such as northern fur seals and Galapagos fur seals, casein accounted for 52 and 75%, respectively [83, 86, 108].

Moreover, pinniped milk has slightly higher amino acid concentration than in the milk of terrestrial mammal. However, both pinniped mammal species have similar range values for the proportion of total essential amino acids, total branched-chain amino acids, total sulfur amino acids, and most individual amino acids in relation to the total amino acids [83, 109]. Furthermore, the amino acid pattern and total amino acid concentration of milk were affected by stage of lactation in terrestrial mammals but not in pinnipeds [83, 109, 110]. This is contrary to Davis et al. [110] study that suggested that changes in amino acid pattern and total amino acid concentration during lactation were unrelated to phylogenetic order.

There are a great variety of saccharides in milk [111, 112]; however, lactose (disaccharide) is the dominant sugar, and it is synthesized in the mammary gland.

Notwithstanding, the milk of marine mammals contains only traces or no lactose at all. For instance, in human milk more than 100 oligosaccharides or saccharides that contain three or more monosaccharide residues have been observed. The chemical structures of around 80 have been reported [113]. In comparison with measurements of the concentrations of milk fat and protein, carbohydrates have been given little attention in pinnipeds, but data have been reported for Australian fur seals and hooded seal [114], harp seal [106], crabeater seal (*Lobodon carcinophagus*) [102, 115], and Arctic harbor seal (*Phoca vitulina vitulina*) [116]. It has been reported that phocid milk contains several oligossacharides of unknown structure, low concentrations of free lactose, and traces of glucose and galactose [102, 114, 115]. In the milk of most mammals apart from pinnipeds and cetaceans, lactose is the predominant component of carbohydrates [117]. As a consequence, pinnipeds have among the lowest milk carbohydrate concentration of any mammal. The chemical characterization of carbohydrates in hooded seal, crabeater seal and Australian fur seals, California sea lions, and northern fur seals has revealed that, unlike phocids, otariid milk does not contain free reducing saccharides or lactose [86, 102, 105, 106, 114, 118]. The biological function of milk oligosaccharides in phocids may be similar to that in terrestrial mammals, but this does not apply to otariids since they produce milk without free saccharides [114]. The concentration of carbohydrates in Antarctic fur seal milk decreases significantly throughout lactation [3], and similar data on the specific carbohydrates concentrations during the lactation period in otariids species is not available.

Lactose is a carbohydrate usually present in the milk of mammals but is lacking or virtually absent in pinniped milk. The protein α-lactalbumin is an essential component of the lactose synthetase complex, and it is not present in otariid. However, low activity of the protein α-lactalbumin in the milk of northern fur seals have been reported [119] which suggests an altered α-lactalbumin molecule with low biological activity rather than its complete absence in the milk of otariids [120]. The absence of lactose in otariids milk and the presence of traces of lactose in phocids milk are consequences for the need of water conservation [84] and consequently associated to the evolutionary history of pinniped. The need for water conservation is directly related to the secretion of lactose into milk. The later causes movement of water to maintain isotonicity with other body fluids [121] and consequently loss of water.

Furthermore, the virtual absence of lactose in milk could be associated to the inability of otariid to digest this carbohydrate. Most mammalian species are able to digest lactose through intestinal lactase activity, but some pinniped species' intestinal disaccharidases appear to be low [120, 122, 123]. For instance, lactose intolerance in California sea lions pups and adults has been demonstrated [124]; however,

Species	Minerals in milk (mg/kg)													
	Ca	**P**	**Na**	**K**	**Mg**	**Fe**	**Zn**	**Cl**	**Al**	**Cu**	**Ba**	**Cr**	**Mn**	**Cd**
Harp seal *Phoca groenlandica* [95]	950	708	699	456	104	53	3.6		3.6	1.8	1.8	0.6	0.6	0.1
Giant panda *Ailuropoda melanoleuca* [125]	1.3		0.8	1.7	0.2									
Southern elephant seal *Mirounga leonina* [84]			990	1360										
Northern elephant seal *M. angustirostris* [61]			770	720										
Northern fur seal *Callorhinus ursinus* [86]	567	1193	521	838	141	3.5	9.0	1191		3.7				
Juan Fernandez fur seal *A. Philippii* [126]	731	872												
Galapagos fur seal *A. galapagoensis* [21]	630			1670										
California sea lion *Zalophus californianus* [5]	885	1003	1060	2030										
Polar bear *Ursus maritimus* [127]	290	230												
Black bear *Ursus americanus* [127]	410	280												
Sea otter *Enhydra lutris* [128]	1060	1250												
Spinner dolphin *Stenella longirostris* [129]		1070						455						
Pantropical spotted dolphin *S. attenuata* [129]		1250						468						
Blue whale *Balaenoptera musculus* [130]	310	210	80	130	20			110						
Pygmy sperm whale *Kogia breviceps* [131]	1500	1700												
Weddell seal *Leptonychotes weddellii* [5]			530	570										
Donkey *Equus asinus* [132]	1200	700												
Horse *E. caballus* [132]	800	500												
Common zebra *E. burchelli* [132]	800	500												
Cow [87]	1250	960	580	1380	120			1030						
Human [87]	330	150	150	550	40			430						

Table 5.
Mineral constituents of milk of different species with emphasis on marine mammals.

intestinal lactase activity has been shown in crabeater seal pups [122]. Furthermore, it is also possible that the primary lack of sugar in the milk of pinniped resulted in the loss of the ability to digest lactose. The identification of specific carbohydrates in milk and the role of carbohydrate in milk secretion and as source of energy in pinniped warrant further investigation [3, 86, 114, 118, 121].

Minerals are important component in milk and are present in a variety of chemical forms (see **Table 5**). The major cations in milk are sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg), while the major anions are phosphorus (P) as phosphate, chloride (Cl), and citrate [87, 121]. For instance, there are differences between the ratio Ca/P in pinniped milk (0.5–0.9:1) and terrestrial mammals (1.6:1), and the reason for the inverse Ca/P is unknown [121] (**Table 5**). Na^+, K^+, and Cl^- are the main ions in the aqueous phase of milk of terrestrial mammals, and they play a crucial role in determining milk volume [121]. The amount of lactose secreted determines the volume of milk secreted, and this mechanism maintains the concentration of the ions relatively constant. These solutes act to maintain the isosmotic conditions (same osmotic pressure) between milk and blood by drawing water into the alveolar lumina [121]. Given that lactose is virtually absent in pinniped milk, it is unclear how pinniped controls the secretion of the aqueous phase while maintaining water conservation.

It is likely that in the absence of lactose, the control secretion of the aqueous phase is associated with the higher concentration of Na^+, K^+, and Cl^- and the ratio of Na^+/K^+ (1:1) in pinnipeds in comparison with mammals (Na^+/K^+ is 1:3) [121].

The mechanism controlling the secretion of water in pinnipeds is quite different from that in terrestrial mammals and that further investigation in this area is warranted.

4. Factors that influence the milk composition in pinnipeds

Lactation strategies and milk composition are such important aspects of the reproduction in pinnipeds that they have been the subject of several investigations [5–7, 133–135]. The milk composition of the majority of the pinnipeds species has been described (see **Tables 3** and **4**). Great attention has been given to the factors (stage of lactation, attendance pattern, or maternal body condition) that affect the milk composition in phocid [61, 94, 97, 98]; however, in otariids it is unclear how these factors are influencing its composition. There are methodological issues in the data collection of milk samples that bias the results of the composition analysis and make our understanding of the lactation strategies in mammals difficult. Description of the milk composition of several mammalian species is available [90–92]; however, little attention was given in these earlier reviews to critically evaluate the information presented [117]. The data in the literature on milk composition of pinnipeds are often difficult to evaluate and must be interpreted with caution [99, 117, 136]. Unfortunately, most of these studies are biased due to a few number of samples collected, poor sampling regime, incorrect analytical procedures, and methodological difficulties which consequently make interspecific comparisons difficult [117].

4.1 Milk composition and maternal characteristics

As mentioned before, during lactation, otariid mothers fast during the attendance period on land and then replenish their energy reserves by foraging at sea. In order to fast during lactation, a period of high-energy demand, there must be significant metabolic adjustments such as reduction of glucose use to lower the catabolism of amino acids and tissue proteins for other vital body functions [5].

The milk produced by otariids is low in carbohydrates concentration; therefore lipid and protein make the primary and secondary source of energy in milk (**Table 4**). Without doubt, good maternal body condition at the start of lactation will promote pup growth, and sufficient food intake to replenish energy reserves throughout lactation will enhance reproductive success of the mother [137]. Availability of food and maternal foraging success may be playing an important role in transferring energy to the pup while fasting and even regaining energy while foraging [138]. Consequently it is important to understand the relative contributions of maternal body mass, body condition, age, and foraging success to changes in milk composition and yield in lactating otariids.

Body condition indexes have been widely used in pinnipeds for many reasons: as indicators of nutritional state, to measure the response to environmental perturbations, during molting stage, to relate to reproductive success and growth [20, 48, 82, 139–143]. Two methods of estimating body condition have been used in pinnipeds; one method divides the body mass by body length [139], while the second method estimates the individual residual value of the linear regression between the body mass and body length [141]. Although these methods of body index calculation have not been standardized, making interspecies comparisons difficult, the second method has shown to be a better predictor of the body condition in otariids [82, 144–148].

In South American fur seals in the Pacific Ocean, drastic environmental perturbations such as ENSO changed the attendance and foraging patterns in the lactating females and their foraging success [149]. The low availability of food sources during ENSO resulted in longer maternal foraging trips which may have affected milk quality and volume. Not being able to replenish their body reserves may have decreased their body weight and thus body condition and reduced the benefit to foraging cost ratio [149]. Furthermore, failure in reproductive performance has been also reported in pinnipeds due to changes in body condition. Body condition in Cape fur seal (*Arctocephalus pusillus pusillus*) females influenced their ability to become pregnant or maintain pregnancy [141]. Furthermore, females with poor body condition were less likely to be pregnant than females with better body condition during pregnancy. Also, poor body condition in pregnant Steller's sea lion due to nutritional stress caused lower pup production in the subsequent season [143]. This indicates that food resources were not sufficient to support the energy demands of the reproductive strategy in this species. Similarly, when food resources were scarce for Cape fur seals resulting in low body condition, pregnancy was likely to fail through abortion [141]. In Antarctic waters, variation in food availability in any year has also been associated with low pup production in the following year for Antarctic fur seals around South Georgia [150].

On the other hand, in years when food sources are plentiful, pup production increased and also pup growth, and mothers were able to replenish and store energy body reserves to improve their body conditions for the following breeding season [4, 27]. An increased number of pups were most likely the result of an increase in the number of females in which embryos were implanted and which carried a fetus to term [150]. Lactating otariid females with low foraging success may spend more time at sea and therefore increase the chances of pup mortality due to malnutrition, hypothermia, trauma, or infection and therefore reduce their reproductive success [151, 152].

Given that in other species variation in milk composition indicates the effects of environmental and physiological factors [99, 153, 154], the relationships between these factors and their influence on milk composition in pinnipeds should be investigated. Body mass and body condition are directly linked to individual foraging success and can be used as proxy for the availability of local food resources. Milk fat has been shown to be correlated with maternal body mass in New Zealand sea lions [82] and Australian and Antarctic fur seals [3, 30], whereas no relationship was found in Australian sea lions [2, 28]. However, body mass is to some degree determined by body length and may not reflect the quantity of body reserves [141], and therefore, body mass may not be a good predictor of the quality of milk. To support this argument, terrestrial mammals such as dog [155] and dairy cows do vary in size within their species but their milk composition does not [156, 157]. Therefore, the variability in milk fat concentration in pinnipeds may have physiological basis rather than influenced by body size [158].

In mammals such as humans and dairy animals (cow and goat), body condition (e.g., cow body condition is scored) determined concentration of fat in milk [159–161]. Similarly, lactating subantarctic fur seals (body mass/body length) and lactating New Zealand sea lions (body condition index) in good body condition produced milk with a greater concentration of lipid [10, 82]. Furthermore, the relationship between BCI and lipid and energy content of milk has been reported for in Australian fur seals and subantarctic fur seals [10, 30]. It appears that individual foraging success may influence body condition and eventually the milk quality in these species.

While the mother is on land fasting and nursing the pup, the milk is initially synthesized from the nutrients that are obtained from the most recent digested food but as nutrient from the intestine is reduced, the nutrients from maternal body stores are mobilized [158]. If this is the case, then females with better body condition (measured from the relationship between body mass and body length) would secrete milk with higher concentration of fat than females with lower body condition. This has been shown in subantarctic fur seals and New Zealand sea lions [10, 82] but remains to be studied in other otariid species.

Female age could be associated with better foraging and reproductive success as older females may have more experience in finding food in years of poor food availability. In addition, full-grown mature females do not need to divert nutrient toward their own growth and thus can divert more nutrient to provide for their pup. Older Antarctic fur seal and northern fur seal females had better reproductive performance than younger females, and this was suggested by greater natality rates, heavier natal pups weights, giving birth earlier in the season, and better possibilities of giving birth the following season [162, 163]. Moreover, in New Zealand sea lion maternal age had a positive effect on the quality of milk, and this could also be attributed to better body condition of older females with more maternal foraging experience than younger females [82]. In Antarctic fur seals, there was no apparent effect of maternal age on the time budget for foraging attendance [164]; however, in years of poor food resources, the foraging time budget was adjusted [24] which increased the cost of foraging in that year by 30–50% [165]. This is consistent with the hypothesis that mothers adjust their behavior to maximize energy delivery to the pup.

Body length has been used as an indirect measurement of age [142, 146, 163, 166, 167]. Maternal age estimated from body length did not increase the concentration of fat in the milk of subantarctic fur seals [10]; however, it did in Australian sea lions [28] and Australian fur seals [30]. Estimating age from body length suffers from bias and is not reliable to assign a pinniped to a particular age [146, 166–169], because the body grows at a progressively decelerating rate with age and the changes within age class and the overlap between age classes are substantial.

Notwithstanding, maternal age may affect and determine their body condition. For instance, young primiparous lactating otariids must be able to store energy reserves and replenish energy at a sufficient rate, in order to withstand the cost of lactation and her metabolic needs and growth. The mechanisms in which maternal body condition affect the composition of milk in otariids are still unclear. Interannual variability in food sources has direct impact on maternal foraging success and consequently on body condition and thus the female's reproductive success and lactation performance. Some studies have investigated the effect of maternal age on milk composition. Maternal age may influence indirectly the milk composition via body condition, and this hypothesis may be tested in a species for which there are age data.

4.2 Milk composition and attendance pattern

The differences in milk composition among otariid species could be explained by the duration of the foraging trip, i.e., females of a species that make long foraging trip may secrete milk with higher-lipid concentration than a species making shorter foraging trips [21, 31]. In other words, the energy content of milk increases with the length of the foraging trip [135]. This in agreement with the central place foraging theory that postulates that parents that have to make long foraging trip, away from the central place (nest or breeding site), to their feeding grounds should make fewer foraging trips and gain more energy per trip. On the other hand, parents that forage near the central place would make many short foraging trips and return with lower energy per trip [170]. This theory has been tested in birds and otariids [171, 172].

The high concentration of nutrients in the milk is sufficient to sustain the pup while fasting on land during its mother's absence at sea [13, 31]. This is true for species that have among the longest foraging trips reported for any otariids such as the subantarctic fur seals, the Juan Fernandez fur seals, and the Guadalupe fur seals (**Figure 4** and **Table 6**). For females producing milk with high concentration of lipids when making long foraging trips, there must be physiological and reproductive advantages [27, 29, 35]. These advantages may include less pressure on water balance due to reduced need for water, and the capacity of the mammary gland is not a limiting factor when secreting milk with high solid content. Furthermore, the mechanisms regulating the milk secretion in which the mammary gland is able to resume lactation after long foraging trips (more than 12 days) and in the absence of the stimulus of the suckling pup and milk removal are unknown. The mechanism of milk secretion in terrestrial mammals, such as dairy animals, is controlled by autocrine factors and cell stretching [173, 174], but these are yet to be investigated in pinnipeds.

Otariid species that make long maternal foraging trips at sea may have limited capacity in their mammary gland in order to store great amount of milk.

An explanation is that the mammary glands might have a large storage capacity twosome with a slow secretion rate of high energy-rich milk while foraging at sea [5]. This argument is supported by the weak negative relationship between the foraging trip duration of lactating Antarctic fur seals and the milk secretion rate while at sea and by the positive correlation between milk secretion rate and the duration of pup attendance on land [3]. In addition due to the absence of the suckling stimulus and milk removal, which are crucial for the maintenance of mammary gland function in other species, the mammary gland may be at risk of involution [5, 29]. How otariids are able to contain the involution of the mammary gland in the absence of the suckling stimulus and milk removal is still not clear.

Mammary gland size in pinnipeds is estimated based on the mammary gland weight relative to body weight, indicating that most otariids have large mammary glands in comparison with terrestrial mammals [5, 29]. The mammary gland

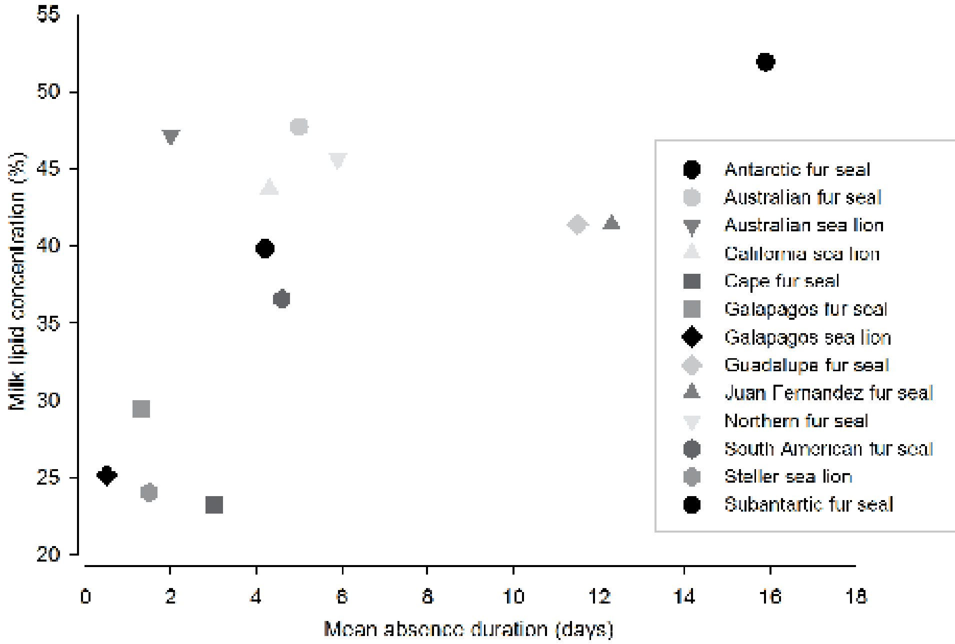

Figure 4.
*The relationship between foraging trip duration (mean absence duration in days) and milk lipid concentration in 13 species of otariids (data from sources in **Tables 4** and **6**). SL = sea lions, FS = fur seals.*

capacity of Antarctic fur seals was measured by complete manual evacuation and indicated that mammary glands were not completely full when the mother arrived ashore [31]. It is likely that the capacity of the mammary gland to store milk is not limiting the duration of foraging trips; however, it is possible that it is limited by a set point of the nutritional satiation reached by the mother [13].

The relationship between foraging trip duration and milk lipid concentration has been demonstrated between and within otariid species. The second of the two has been demonstrated in a few species. A significant relationship between milk lipid concentration and the duration of the preceding foraging trip in Australian and Antarctic fur seals was found [30, 31]. By contrast trip duration and milk fat content were not related in studies carried out on Australian [28] and New Zealand sea lions [82] and subantarctic fur seals [10]. The poor relationship found in subantarctic fur seals was thought to be a consequence of individual maternal foraging skills, and thus, the quality of the milk would have been determined by this factor [10].

Australian and New Zealand sea lions conform with the hypothesis that species that make short foraging trips secrete relatively low milk fat concentration [21, 82, 171]. Australian sea lions, as an adaptive response to inhabiting a low-energy marine environment, have prolonged the lactation period in which mothers have lowered the energy intake of their pup by secreting a low-energy milk [22]. Galapagos fur seals also produce a low-energy milk and have a foraging trip lasting 1.3 days and a prolonged lactation period (**Tables 1** and **6**). The duration of the foraging trips of lactating Galapagos fur seals appears to be regulated by short-term fluctuations of food availability [22]. Both temperate and tropical species, Australian sea lions and Galapagos fur seals, respectively, have adopted a different strategy to polar species in that they are obligated to extend their lactation period. As otariid

Species	Time to first departure (days)	Time absent (days)	Time presence (days)	Time absent (%)
Australian fur seal [30]	—	5.0 ± 0.1	—	—
South American fur seal [175]	—	4.6 ± 0.1	1.3 ± 0.1	78
Guadalupe fur seal [176]	—	11.5 ± 0.1	5.0 ± 0.1	70
Subantarctic fur seal [27]	—	15.9 ± 4.6	3.8 ± 1.1	81
Cape fur seal [43]	4.3 ± 3.3	3.0 ± 2.5	2.4 ± 1.4	56
California sea lion [19, 177]	5–8	4.3 ± 0.5	1.4 ± 0.1	75
Steller sea lion [37, 178]	5.8 ± 0.6	1.5 ± 0.1	0.86 ± 0.05	64
Galapagos sea lion [175]	6.8 ± 2.1	0.5 ± 0.1	0.6 ± 0.1	47
Antarctic fur seal [20, 23, 31]	6.9 ± 0.1	4.2 ± 0.8	1.8 ± 0.5	67
Galapagos fur seal [175]	7.4 ± 1.2	1.3 ± 0.1	1.0 ± 0.1	57
Northern fur seal [179]	7.4 ± 0.1	5.9 ± 0.1	2.2 ± 0.1	73
New Zealand sea lion* [180–182]	8.6 ± 0.2	1.7–2.7	1.2 ± 0.1	57–69
New Zealand fur seal [40, 41]	9.7 ± 0.1	4.2 ± 0.1	1.8 ± 0.1	70
Australian seal lion [1, 28, 183]	9.8 ± 1.8	2.0 ± 0.5	1.4 ± 0.3	59
Juan Fernandez fur seal [35]	11.3 ± 3.4	12.3 ± 0.1	5.3 ± 0.1	70

**Attendance pattern were recorder at early lactation.*

Table 6.
Temporal parameters of attendance pattern in otariids.

females depend upon their dietary intake to sustain lactation [135], and by regulation the duration of their foraging trips to food availability they are able to withstand a long lactation period. This strategy does not necessary occur at high latitudes in which the marine environment has dramatic rise in primary productivity during the short summer season and otariids are able forage successfully and complete lactation in a short period of time.

Subantarctic and Juan Fernandez fur seals inhabit lower latitudes, but contrary to other low-latitude otariids species, they conduct very long foraging trips (mean of 15.9 and 12.3 days, respectively) (**Figure 4**, **Table 6**). As would be expected for long forager trip species, they secrete milk with high lipid contents (38.6 and 41.4%, respectively). Moreover, these two species have one of the longest inter-suckling intervals and highest milk lipid concentration during the first month of early lactation among otariids [10, 29]. Both species leave their local low productive waters and travel long distances to waters of higher productivity [10, 35]. The similarity of the attendance patterns of Antarctic and subantarctic fur seals breeding at Macquarie island indicated that prey availability might be playing a major role influencing pattern of foraging and attendance cycles [9]. This was also shown to be true for Juan Fernandez fur seals that had a correlation between foraging trip, visit duration ashore, and primary productivity, indicating that food source location and availability were determining the foraging pattern [35].

At least for some otariid species, long foraging trips are preceded by long nursing bouts ashore. At some point, when nursing the pup ashore, the energy needed to produce milk must come from body reserves; in this scenario the rate of milk secretion and rate of energy delivered to the pup would be dependent on the maternal body lipid storage capacity. In fact, 42–79% of the milk energy transferred to Antarctic fur seals' pup comes from maternal body reserves [31]. At least for this species, the longer the duration of the foraging trip, the greater the proportion of milk energy delivered to the pup is derived from body stores [31]. Probably the most beneficial cost-efficient lactating strategy would be to maximize energy transfer to the pups, by producing and storing an energy-lipid-rich milk while foraging at sea, and store excess nutrients as body lipids and protein to be used to secrete milk while nursing the pup ashore [31]. While ashore, the rate of nutrient transfer to the pup is maximized by increasing the milk production and the concentration of milk solids. Within otariid species two distinctive strategies of energy transfer to the pup can be identified, one that makes long foraging trips and maximized their energy transfer to the pup by secreting nutrient-rich milk and those species that makes shorter foraging trips and produce a low nutrient-rich milk (**Figure 4**).

There is a strong relationship between milk composition and attendance pattern in otariids in particular for species making long foraging trip at sea; however, for otariid species making short foraging trips, this relationship is unclear. Location of breeding site (latitude), distance between breeding site and foraging ground, and availability of food source may influence the attendance pattern of lactating females. The fact that lactating otariids are absent for the longest inter-suckling period of any of the mammals makes otariids an interesting group of mammals for testing the central place foraging theory [170].

4.3 Milk composition and stage of lactation

The general effect of stage of lactation on milk composition seems to be consistent across species [117, 184–188]; however, there are differences between species in the degree of change in the milk composition as lactation progresses.

4.3.1 Seals (phocids)

The fat content of the milk of phocids increases as lactation progresses, and pup growth rate reflects the extent of this increase (**Table 3**) [189]. Phocid offspring are not different from other mammalian species, and the demands for energy by the pup increase as lactation progresses [189], but how the increase in energy demand could influence the increase in milk lipid concentration has not yet been explained. Some phocid species secrete low-fat milk in early lactation, but protein concentration remains unchanged throughout lactation (**Table 3**). The low protein content in phocid milk is a consequence relatively small to the proportion of the gain in the young's lean body mass (**Table 3**). To give an example, hooded seals and bearded seals produce the lowest protein concentration of any mammalian milk [7, 97], and in hooded seal pups, the low protein content was associated with a low gain in lean body mass [74].

In phocids the concentration of water in milk decreases, and lipid concentration increases as lactation progresses [51, 61, 94, 96, 99–101]. Similarly, in harp seal milk, the protein content remained constant, and milk fat content increased throughout lactation [94, 95, 106]. An explanation for the relatively high concentration of water in milk in early lactation is to provide the pup with water since the newborn cannot catabolize water from lipid reserves as an adequate body lipid layer (blubber) has not yet been formed. In consequence, milk provides free water to the pup when it is needed most, and the decline in water concentration in milk will coincide with the time the young is less dependent on free water [94].

Despite the short lactation duration in phocid, the pup is weaned with large weaning mass, and this is possible because the pup is nursed with very energy-rich milk and lipids are deposited rapidly in the blubber. Furthermore, in comparison with terrestrial non-fasting mammals, phocids have greater milk energy output rates [117]. Phocids are able to do so, due to the large maternal body mass that can store large quantities of energy in the form of lipids (blubber) which allow them to withstand the high cost of lactation by mobilization stored energy reserves [72]. However, some small body size phocid species such as harp seals, Weddell seals, bearded seals, and harbor seals feed at some stage during the lactation period [72, 74]. Harbor seals are known to feed from mid-lactation onward [73], most likely because energy reserves are depleted, and hence, they are unable to sustain lactation while fasting [72]. It appears that maternal size in harbor seals constrains the proportion of body fat that can be stored [73]. Furthermore, lactating harbor seals depleted 33% of their body mass during the first 80% of the nursing period and depleted their body reserves faster than other phocids [72]. A limited amount of energy stored coupled with rapid energy depletion during lactation cannot be sustained without feeding [69]. It has been suggested that it is likely that half of the phocid species may feed during lactation [6]; however, whether this occurs only in the smaller phocid species is still to be investigated.

In conclusion, lactating phocid produces great amount of energy in the form of very rich lipid milk that is transferred to the pup in a short time, and this energy is deposited as body reserves to be mobilized during the postweaning period. In addition, the pup is able to rapidly assimilate the lipid-rich milk and deposit the lipid in the blubber which is crucial for insulation and for postweaning energy reserves. The needs of the neonate seem to parallel the milk composition, and most phocids appear to follow the same trends. Some evidence has shown that not all phocid species are fast for the entire lactation period. Small body size phocids are unable to endure the cost of lactation and maternal metabolism solely with her body energy reserves and must forage to regain energy. These species of phocid have adopted an “otariid-like foraging strategy.”

4.3.2 Sea lion and fur seals (otariids)

Data on changes in milk composition throughout the whole lactation period for 6 out of 16 otariid species have been investigated [2, 3, 5, 10, 30, 190]. The general trend in these species is that milk fat concentration increases progressively, whereas protein content remains fairly constant throughout the lactation period. Less complete, but otherwise useful, data are available from northern fur seals [191], New Zealand sea lions [82], Galapagos fur seals, and Galapagos sea lions [21].

Increase in foraging trip duration related to stage of lactation and/or change in food availability [1, 163, 164] may influence variation in milk composition during lactation. It is possible that there is a combination between the effect of stage of lactation and foraging trip duration on the composition of milk. Stage of lactation was responsible for most of the changes observed in milk composition of subantarctic fur seals [10]; however, in Antarctic fur seals and Australian sea lions, stage of lactation was responsible for only a small proportion of the changes in milk composition [3, 28]. Kretzman et al. [28] and Gales et al. [2] found high variability in milk lipid concentration between and within individual Australian sea lions. However, they were unable to identify which factors contributed most to the variation in milk composition. In Antarctic fur seals, days postpartum and maternal mass contributed to the variation in milk lipid, and it was suggested that foraging trip duration also explained some of the variation [3]. These authors have recognized that extensive and systematic sampling is needed in order to describe milk composition in otariids and control for intraspecific variation in milk composition [3, 28].

The trend in changes in otariid milk composition during lactation is as follows: milk lipid and gross energy concentration increases during the first stages of lactation and peaks at mid-lactation and then decreases in the course of later stages of lactation (**Table 4**). Water content in milk changes inversely with milk lipid concentration, while milk protein concentration stays somewhat unchanged throughout the lactation period [10]. Although not all otariid species follow these trends, Galapagos fur seals, for example, produce milk that decreases in fat concentration with pup age in early lactation [21], and hence in the course of the perinatal period, they use their body fat storage to secrete lipid-rich milk. This has some advantages as the mother can conserve body water and the neonate is able to build up the layer of blubber that will act as insulation layer and energy reserve for the approaching period of fasting. The mother's water balance enhances at the start of the foraging trip, and on her return, she nurses the pup with a diluted milk that meliorate the pup's capacity to deal with the high temperatures at the Galapagos Islands [21].

Protein concentration in milk of Antarctic fur seals declined in 1 year but heightened in the following 2 years [3] but did not changed in Australian fur seals [30]. The increase of milk protein concentration during lactation may respond to the need to incorporate essential nutrient for pup growth. The proportions of the total protein in milk of whey and casein changed in the milk are produced by Galapagos fur seals at early and mid-lactation (40–25%, 60–75%, respectively) [83]. The reason and connotation for the changes in the proportions of whey and casein of the total protein in milk of Galapagos fur seals remain to be elucidated.

Increment in fat and energy concentration of milk at early lactation has been related with increment in the duration of foraging trips and/or the stage of lactation in some species of otariids [2, 3, 9, 30, 191]. However, in some species the foraging trip duration was not related to changes in milk composition; hence, it is possible that other mechanisms may be acting. After the long and energy-demanding perinatal period, the mother must replenish energy reserves and enhance body condition, in order to produce a higher-lipid concentrated milk at early lactation [18, 140]. Maternal body condition had a significant effect on milk lipid in subantarctic fur seals [10] and New Zealand sea lions [82], but it is not known whether this applies to other otariid species. The increasing demands of the growing pup may affect the maternal response and increase milk fat concentration [10].

By the last month of the lactation period, milk lipid content tends to decrease as shown in Australian sea lions and Australian fur seals and subantarctic fur seals [2, 10, 30]. In subantarctic fur seals, the data suggested that the relationship between milk lipid concentration and at the end of the lactation stage was best described by an asymptotic relationship, i.e., decrease in lipid content. The decrease in milk lipid concentration, i.e., lower rate of energy transfer to the pup, at the end of lactation could be associated with the proximity to the pup's weaning process and higher-energy demands of gestation [10, 30]. This argument was supported by a study on subantarctic fur seals that showed that the mother directed their body reserves toward gestation and not to milk production [27].

For the Antarctic fur seals, the rate of milk production decreased by the end of lactation [192, 193]; however, a concurrent decrease in milk lipid concentration has not been reported in late lactation [3]. The short lactation period (4 months) in this species and mothers not actively gestating an offspring (delayed implantation) during this period put less pressure to meet the energy demands of lactation and gestation [194]. In this context the mother is able to allocate energy resources to milk production, and the quality of milk lipid remains unaltered [30].

5. General conclusion

There are three lactation strategies adopted by pinnipeds: a fasting strategy, foraging strategy, and aquatic strategy. Phocids have shortened the duration of lactation remarkably and reduced the time the pup and mother are exposed to the conditions of the terrestrial environments. Due to the shortage of lactation duration in phocids, the daily energy output is greater than in otariids, and phocids secrete very rich energy-dense milk. Producing milk high in solid content attenuates the impact of water stress in phocids' mother that is fasting during lactation. However, some phocid species with small maternal body size have adopted a strategy similar to that seen in otariids and feed during lactation probably due to the high-energy cost to sustain the short lactation period. Walruses have evolved to nurse and feed without separating the mother from the pup in the so-called aquatic lactation strategy. The lactation duration in walruses is very prolonged (up to 3 years) which increments the chances of pup survival. Otariids also have long lactation periods, and the rate of pup growth is slower than in phocids. The concentration of milk lipid ranges greatly among pinniped species, and the absence or presence of traces of lactose in their milk may be associated with the evolution of lactation strategy in pinnipeds.

The stage of lactation, attendance pattern, and maternal body condition are factors that influence the milk composition throughout the lactation in otariids.

In order to make interspecies comparison, the milk composition values at mid-lactation should be used, since they represent the peak maximum production [117] and be limited to species for which similar data are available [2]. Researches that have collected milk samples from lactating otariids throughout the lactation period are limited. Attempting to compare the milk composition among pinnipeds is a difficult task due to the lack and poor quality of the data, small sample size, and being unrepresentative of the whole lactation period.

Lactation is a crucial part of the life history of mammals and is of particular interest in pinniped as they have adopted unique lactation strategies among mammals. In order to study lactation, the milk composition and amount of milk secreted are important parameters that need to be measured adequately.

The data reviewed in this chapter has demonstrated that data on the milk composition of pinnipeds is limited but nevertheless valuable. And that there are logistical constraints working in remote field sites, and with wild animals such as pinnipeds making the collection of milk samples difficult. In addition different analytical methods have been used, and the effect of stage of lactation among other factors is often not considered or mentioned in the literature [5, 195]. In lactation studies of pinnipeds, the lack of extensive sampling has made interspecific comparisons difficult. For otariid species, milk composition has been analyzed throughout the entire lactation period (in only three species) [2, 10, 30] and for interannual variation [3, 82, 196].

The stage of lactation influences the milk composition in pinnipeds [117], but there are factors that may also affect its composition. Maternal reproductive success in pinniped, i.e., success in rearing her pup, is directly influenced by her performance during lactation, and the survival of the offspring depends on the quality (energy content) and quantity of milk produced by the mother.

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Chapter 2

Lactation Performance of Small Ruminants in the Maghreb Region

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Abstract

Maghreb areas are characterized by rainfall seasonality and scarcity resulting in a low fodder potential. In these arid and semiarid regions areas, small ruminant production is the main source of income of farmers living where sheep (*Ovis aries*) and goats (*Capra hircus*) are generally confronted with severe nutritional deficits during feed scarcity period which exacerbate disease and health troubles and consequently low performances. Interestingly and despite the importance of the milk performance to the dairy industry, very few works studied the potentialities of the mammary gland through the lactation period both in sheep and goats elevated in the Maghreb areas. Nevertheless, understanding the different mammary gland patterns throughout lactation is essential to improve dairy production and to reduce poverty and vulnerability in rural farming systems in these developing areas. The main objective of this review is to analyse the lactate processes as well as to underline the mammary gland morphological patterns, health and physiology traits and to evaluate milk potentialities of the main breeds of goats and sheep raised in Maghreb.

Keywords: sheep—goats—milk, Maghreb areas

1. Introduction

Nowadays, dairy foods represent one of the most dietary dense food, being considerable sources of numerous nutrients, mainly calcium, riboflavin, phosphorus, protein, magnesium, vitamin B12, niacin equivalents, vitamin B6, and when fortified, vitamins A and D. Milk and dairy products are also one of the major sources of nutritional calcium which is essential both in bone development, and the maintenance of healthy teeth [73].

In the Mediterranean zones, dairy sheep and goats rural managements diverge from pastoral (showed irregular milk production, dual-purpose breeds, insignificant feed supplementation, transhumance, hand milking, absence of farm facilities, farm-made cheese) to intensive management (continuous milk production, enhanced local breeds, valorization of forage crops, feed supplementation, machine milking and farm facilities, profitable cheeses) according to the profitable impact of the production chain and the specific environment and breed [1].

The Mediterranean small ruminant dairy sector is original and very diverse. More than 46% of the dairy ewes in the world originates from the Mediterranean region. The major countries, in terms of the flock of dairy ewes and goats, are Greece, Italy, Spain, France and Turkey in Europe, and Algeria, Tunisia, Egypt and Libya in North Africa [2]. In North Africa, where there is no strong dairy tradition, ewe and above all goat milk is used mainly for family consumption likes as milk or white fresh cheese the 'Jben Arbi'. It has been considered that milk has a symbolic value of life and fertility in the Maghreb regions, as it is often used, with dates, in ceremonies to welcome guests according to the Berber and the Arabic traditions [3]. In these regions, small ruminant and camel constitute the most valuable activities in arid areas based on their resistance to dry or hot conditions. This resistance to harsh conditions evaluated in terms on adaptive traits or rusticity, is based on different abilities: mobility, physiology, feeding pattern, etc. Furthermore, sheep and goats need low investment resources and fast rate of reproduction covers short term expenditures.

In such developing countries of Maghreb, dairy production is an essential tool to overcome social and economic issues like as poverty and human malnutrition [4]. However, despite its potential contribution to sustainable economic growth and poverty drop, dairy sheep and goats sector has received restricted attention from Maghreb Nations in recent decades. Furthermore, little is known about dairy sheep and goats reared in Maghreb Nations [28, 52] and a better knowledge of these genetic resources can help promote their conservation and efficiency benefits. Therefore it is critical to understand the modifications associated with lactation in the mammary gland in order to develop strategies to improve milk yield or reduce the constraints that decrease milk production and milk quality in dairy Maghreb sheep and goats. Considering the current significance of sheep and goat milk production, this review draws a study to analyse the lactate processes as well as to underline the mammary gland morphological patterns and physiology traits and to evaluate milk potentialities of the main breeds of sheep and goats raised in the Maghreb areas. Overall, such data will be important in supporting further studies aimed at improving lactation potentialities, among other factors, with benefits for this emerging dairy sector for both the industry and the consumer.

2. Overview on Maghreb areas

Located in the Northern fringes of Africa, the Maghreb areas (Lybia, Tunisia, Algeria and Morocco) have a long tradition with dairy products' consumption. The Maghreb countries are distinguished by their typical Mediterranean climate; a long summer (May to September) with an intense drought and excessive heat and often an irregular rainfall from autumn to spring [5].

Another trait which distinguishes the Maghreb climate, the marine effect which reduces the amplitude of temperatures in zones near to the landfall: the Mediterranean in Morocco, Algeria and Tunisia and the Atlantic Ocean in Morocco. The normal annual precipitation is less than 300 mm in wide regions of the Maghreb countries, engendering arid to semi-arid climates [6].

Therefore water scarcity constitutes the main limiting factor to agriculture. Hence, the agricultural output in the Maghreb remains largely related to the level of annual rainfall in rain fed areas [9], with no opportunities of irrigation. The hydrological water stress index is respectively 29, 11 and 3 in Algeria, Morocco and Tunisia. Such index implies that at the regional level, Algeria and Tunisia face the highest level of water stress, while in Morocco water is less scarce [7]. This situation will certainly widen with the expected demographic growth and climate change, and consequently, have negative repercussions [8].

The photoperiod is another significant factor that affects sheep and goats productivity especially in breeds that originate from geographical areas at high latitudes. Thus, appropriate supervisory policies must be developed to allow milk production out of season in small ruminants [1].

3. Review on lactogenesis and mammary gland traits

Lactogenesis may be defined as the beginning of milk secretion [12]. This physiological mechanism can group two stages. The first stage occurs during pregnancy when the gland is adequately differentiated to produce little amounts of specific milk components like lactose and caseins [13]. The second stage can be defined as the start of copious milk liberation depended to parturition. Nutrition during pregnancy is the most factor that affects both colostrum yield and composition [14]. When small ruminants are kept under poor grazing conditions, there is a general mobilisation of their body reserves during the last 6 weeks of gestation owing to rapid fetal growth and colostrum yield [15, 16].

The structure and the function of the mammary gland are coordinated by the neuroendocrine control from the development of the gland via the milk ejection. The main role of the endocrine mechanism is to synchronise mammary function and development with the reproductive stage, while the main role of the nervous mechanism is to stimulate the process of milk removal. These two mechanisms are joined in the hypothalamic-pituitary axis, and manage the entire process of milk production through the release of several crops (lactose, prolactin, oxytocin, growth hormone, etc.) as well as the coordination of other hormone-releasing organs, i.e., mammary gland, placenta, ovaries [17]. The proliferation of mammary tissue may be activated by the prolactin secreted in response to the gland stimulus.

However, other factors of the normal mammogenic complex are either entirely absent during lactation (e.g., placental lactogen) or just present in small amounts or at specific moments (e.g., oestrogen) [18].

Suppression of prolactin secretion in goats and sheep [19, 20] had only partially in sheep lactation. This hormone is at least as important as growth factor in maintaining goat milk yield [21].

When it was administrated to pre-pubertal young ewe, the bromocriptine (prolactin inhibitor) had no effect on the mammary development [22]. However, a treatment with progesterone in post-pubertal ewes suppressed the epithelial proliferation [23].

The completion of tubuloalveolar development in ewes ultimately requires oestrogen and progesterone in the presence of endogenous prolactin [24]. One of the classical roles assigned to oxytocin is milk ejection from the mammary gland. Although it is mainly associated with milk ejection, treatment with exogenous oxytocin was associated with increased milk production in sheep [25]. The major amount of the milk is accumulated in voluminous cisterns of the goat gland thus it can be remote through by suction applied to the nipples. Hence, a milk discharge reflex is not necessary for the nourishing of the young, though it could help the process [25, 26]. In fact it is possible to identify goats with very high milk yield and either strong milk flow rate that have no appreciable increases in plasma oxytocin concentrations during milking [27]. Perhaps this finding is indicative of a lower dependency on oxytocin for milk removal in goats.

In small ruminant mammary gland, the glandular parenchyma is responsible for milk production and is constituted by tubule-alveolar glands relative to its anatomical organization; it has two main components, (1) the parenchyma which includes the epithelial and myoepithelial cells, (2) the stroma involving the non-cellular components, as collagen and elastin, smooth muscle cells and vessels and the ductal system [29]. However, it is important to note that anatomy and histology of the mammary gland are changed during the lactation stage, mostly led by the neuro-endocrine mechanism. There are three stages of mammary biology characterising the pregnancy/lactation periods: proliferation, secretion and involution. While the most proliferation happens throughout gestation and most of the involution occurs after lactation has finished, such processes coincide: proliferation of secretory tissue persists during early lactation and involution initiates during late lactation, simultaneously with milk secretion [30].

Concerning the lactation period, it differs between small ruminant species. In sheep lactation, it lasts for 5 months with a peak between the weeks 3 and 4 [23, 31]. In contrast, the lactation period in goats lasts for 10 months with a peak between weeks 5 and 10 [32]. These values are highly dependent on breed and nutritional status, among other factors [33].

By studying the mammary gland volume changes in goat breeds (Toggenburg, Nubian, Saanen and French Alpine) during various physiological stages [34, 35], no differences were detected in udder weights during pregnancy until day 120, when values started to increase significantly. The majority of udder growth occurred between the last 30 days of pregnancy and the first 10 days of lactation.

During gestation and lactation, an alteration of mammary gland tissue composition occurs, as well as for the first 15 days of gestation, where parenchyma fatty tissue proportion decreases and fluid-rich tissue increases [35]. Such alterations in parenchyma composition can be directly related to the increment of milk secretion and fluid accumulation in the gland [35]. Thereafter, mammary gland composition remains constant throughout late gestation and the entire lactation period. As the majority of udder growth occurs during early lactation, a reduction of mammary gland volume was detected during mid-lactation [37]. Reduction of the udder volume during the stage of lactation was reported as correlated both to parities and the mammary gland volume at the onset of lactation [37]. For example, goats with twins had more voluminous udder (+40%) than those with simples [38].

4. Review on the milk potentialities of goats and sheep raised in Maghreb and Mediterranean areas

Sheep and goats are mainly elevated for meat production in many regions of the Maghreb areas because of the harsh environments prevailing. The most of breeds have not been selected for milk yield, at the exception of the Sicilo-Sarde, where its nucleus was in Tunisia [10]. Thus, the official statistics reveal that the integrated dairy chains rely mainly on cattle milk, given that milk from non-cattle species (small ruminants and camel) represents respectively 21.3, 5.1 and 3.7% of the overall output in Algeria, Morocco and Tunisia [11] and its industrial processing remains rather weak.

After an increase by 18.7% (1997–2007), the goat population reached more than 1.5 million heads in Tunisia [66]. Such growth has been followed by the increase of production. Almost 60% of the Tunisian goats are located in the centre and in the south, reared in semi-intensive oasis systems, in small herds [70, 71]. Noting that the native goat from Tunisia is named Arbi to distinguish it from imported breeds, and it is well adapted to the natural environment of country [67]. Meat remains the major production of Arbi goats from Tunisia but also milk is produced only for home consumption. Under semi-arid conditions in the South, milk potential of the Arbi goat ranged from 1.14 to 0.69 kg/goat/day in the first 6 weeks of lactation, for females suckling singles, while those suckling twins produced 0.86–1.64 kg/goat/day [36]. Similarly, milk production ranged from 1.2 to 0.75 kg/goat/day [74] in the north where goats are reared in extensive mixed farming systems [69], together with sheep and cows. Genetic improvement schemes and biodiversity conservation strategies are currently studied in Tunisia for the native goat [68]. In some cases, the genetic capacities represent a serious restriction to improve goat production, especially for milk [72]. Failures in livestock improvement programs (national and international projects) did happen and animal productivity has remained poor.

When considering breed sheep, the only African dairy one is the Sicilo-Sarde as its milk is mostly used for cheese manufacturing. The population of Sicilo-Sarde is estimated at approximately 20,000 animals concentrated in northern Tunisia [62]. This breed was originated in the early twentieth century by crossing the Sarda and the Comisana dairy breeds, from Sardinia and Sicily (Italy), respectively, to produce sheep cheese for the Italian community.

The lactation curves have wide possibilities of applications, especially in genetic evaluation [75], ratio formulation and economic evaluation of different breeding practices [76, 77]. The prediction of yield peak is indispensable for the arrangement of feed orientation permitting and to cover the requirement of animal, reduce the cost and maintain such peak yield for as long as possible [78, 79].

A recent study taken in the Sicilo-Sarde breed [80] showed an average of daily milk production of 0.46 L with a high variation between 0.10 and 2.40 L and a milk period of 132.8 days. This study shows also a similar milking-only length (139 ± 47 days) and suckling length (104 ± 22 days) to previous reports [81]. Sicilo-Sarde ewes have a low production performances comparatively to Lacaune breed (on average 290 L of milk during 165 days) [82] and Sarda breed (on average 203 L and 162 days for milk yield and milking period) [82]. Such difference can be explained by a random crossing with other breeds which could threaten the genetic integrity and partly explains the low milking performances of Sicilo-Sarde breed [36].

Rural management farm of the Tunisian Sicilo-Sarde sheep marked a long suckling interval (3–4 months) and long lambing period (August to October) [63]. Therefore, the weaning practice applied depends on the selling price of milk. If prices are high, early weaning is practiced; if not milk is reserved only for lamb suckling. Several attempts have been undertaken during recent years in order to rehabilitate the dairy sheep sector in Tunisia [62], as well as to increase the combined member's herd size from 10,000 to 30,000 Female Units and to improve the milk yield/ewe/year from 90 to 150 L [64]. Several considerations were taken to encourage the association of breeders, control the performance and to enhance the pasture productivity throughout many programs managed by the OEP (Office of Livestock and Pastures) like as via the training and information days [65].

Udder volume evaluated for Sicilo-Sarde [52] is similar to that of Manchega dairy ewes, but smaller than that of Lacaune and Istrian dairy crossbreed ewes [50, 56]. Positive correlations were observed between estimated daily milk yield and both udder depth and udder volume in Sicilo-Sarde [45, 52]. Cisternal area also positively correlated with total milk yield, indicating that ultrasonography could be used for predicting milk yield in Sicilo-Sarde ewes. Milking lag time and total milking time reported in Sicilo-Sarde [52] were shorter than those reported in Manchega dairy ewes [61], probably due to differences between breeds in milk yield. Similarly, positive correlations were also observed between daily milk yield and both udder depth and udder volume [45, 52]. Sicilo-Sarde ewes showed adequate udder morphology for machine milking. The percentage of cisternal milk in this breed (54%) is similar to values reported in Manchega ewes [53, 54] and East Friesian crossbred dairy ewes [60], but lower than in Lacaune (74–77%) [53, 54] and Sarda ewes (82%) [58]. A medium correlation ($r = 0.69$) was reported between cisternal area and cisternal milk at 8 h after milking in Sicilo-Sarde, as a consequence of a multilocular structure, being lower than correlations reported in Manchega ewes [53, 54], dairy goats [57], and dairy cows [59]. According to previous observations on Mediterranean dairy sheep [46], Sicilo-Sarde dairy ewes are characterized by medium size udders and favourable teat position. This breed showed adequate udder morphology for machine milking [52]. Sicilo-Sarde dairy ewes are also characterized by favourable teat position [46, 52], and can be grouped as medium-cisterned ewes [52].

The seasonality of milk production characterizes the major dairy sheep industry. Nevertheless, an intensive breeding system of dairy ewes has practiced in some countries of the Mediterranean basin, for examples, those in Israel and Spain, where two breeds are mainly elevated: the Assaf and Awassi [39, 40]. In such managements based on the keeping indoors of ewes during the year and an accelerated lambing rhythm is applied with several mating/insemination season. Milking practice starts from the first day of the lactation's ewe and lambs are immediately adapted to an artificial rearing unit after their birth. Such practice of milking regime is exclusive for dairy ewe. For the Assaf ewes, few conceptions occur in early spring (February and March), which is considered an "out of season" period as it commonly results in a low conception rate and few lambs being born in summer (July and August) [41, 42].

In Italy, production of ewe milk is strongly seasonal and this seasonal production system involves most of the dairy breeds. However, under certain environmental conditions, certain breeds are able to mate during different periods. A weaning drop of milk potential is generally detected in dairy breeds [43, 44] and can be explained by the partial disappearance of the stimulus produced by the lamb when suckling. The decrease of milk production after weaning varied from 30 to 40% in the Lacaune, Préalpes du Sud, and Awassi breeds [45]. Likewise, it was observed [47] that the decrease of milk production at weaning (23–35%) may be explicated by a drop of emptying frequency (20–25%) and probably by a separation of mother-kid (3–7%). Sicilo-Sarde ewes are characterized by reduced teats in comparison with Manchega, Lacaune, Istrian dairy crossbreed and Bergamasca ewes [48–50, 55]. No significant correlations exist between teat length and milk production [48, 50]. The teat diameter of Sicilo-Sarde, measured at the medium point of the teat, was smaller than values reported in French Rouge de l'Ouest ewes [51]. Teat angle exists in of Sicilo-Sarde similarly to those in Manchega and Istrian dairy crossbreed ewes [50, 56], but with great values than those observed in French Rouge de l'Ouest ewes (26.5°) [51]. Udder volume calculated for Sicilo-Sarde is similar to that of Manchega dairy ewes, but smaller than that of Lacaune and Istrian dairy crossbreed ewes [50, 56].

5. Conclusions

The productive potential of Maghreb goats and sheep has to be considered taking into account the environmental factors and other genetic and epigenetic factors which may affect milk and lipid content.

Programs reserved to smallholder units must be urgently developed, considering their intervention as the main actors in dairy farming, and this to promote the overall farm performances, to adopt an efficiency strategy of irrigation, fodder biomass yield and its conversion to animal protein (milk and meat) and orient such farms towards dairy specialized producers.

In addition, further efforts are desirable for the promotion and diversification of income sources in dairy production chains. This will have a direct result with the development of good governance to anticipate and overcome future collective challenges: transparent appreciation and remuneration of milk quality, regular negotiations between stakeholders (smallholders, collection cooperatives and milk processors). Considering the increasing price of animal feed products on the world markets, the promotion of self-sustaining milk production chains will be indispensable.

Otherwise, preserving some small ruminant breeds of Maghreb again degradation or extinction requires an urgent establishment of breeding program simultaneously with an awareness of farmers through the action of associations that should be supported over some subsidies especially livestock feed, programming technical training for farmers, milk collectors and the creation of other industrial processing units.

Understanding the lactate processes as well as to underline the mammary gland morphological patterns and physiology traits as well as milk potentialities of the sheep and goats may improve dairy production efficiency and would be basis to better define selection indices for dairy sheep and goats breeds under a dual purpose production system in the Maghreb areas; milk and meat.

Conflict of interest

We declare that we did not have any "conflict of interest" declaration.

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Chapter 3

Nutrition for Lactation of Dairy Sheep

Houcine Selmi, Amani Bahri and Hamadi Rouissi

Abstract

The feeding of dairy sheep has to start exactly at the beginning of the last 2 months of gestation (the last third of gestation) and not after lambing. Indeed, during this critical physiological stage, the rumen is compressed by the uterus. Therefore, the ewe can no longer ingest the amount of food that can satisfy its ingestion capacity (2–2.5 kg DM/100Kg of weight/speed) which leads to a controversial situation therein the fact that on the one hand the needs are high (maintenance and gestation) and on the other hand the ingestion capacity is decreasing. To solve this issue, we should give the ewe a supplement based on good quality food that is not heavy and that favors rapid digestive transit. Thus, this supplement must be a concentrated feed distributed at a rate of 0.3 FU/ewe/day), during the last 2 months of gestation. This feeding technique makes it possible to have vigorous lambs at birth, a satisfactory colostrum production which makes it possible to give the lambs the antibodies, necessary for their passive immunity, and therefore reduce the perinatal mortality rate as well as allow for a good triggering of milk production which will be increased in the quantity produced and the peak of lactation. In general, the ration must always be balanced in energy and protein. Indeed, if the ration is surplus in energy, it can cause the infertility of ewes. If it is the other way around, the urea will be stored in the liver and transformed into the urine. However, if the excess is intolerable, it will persist in the liver and cause mortality of the animals and diseases, such as alkalosis. In addition to proteins and energy, ewes must receive the necessary minerals, mainly Ca and P, during pregnancy and lactation. A deficiency of Ca at the end of gestation will cause milk fever (hypocalcemia) which will not be recoverable later. Finally, excessive watering should be avoided after a water is cut to prevent diarrhea.

Keywords: nutritional disorders, deficiency, dairy sheep, gestation

1. Introduction

The development of ruminant livestock farming in the Mediterranean area involves different sciences (nutrition, reproduction, genetics, health) which must be conducted in parallel and in an integrated way in a breeding system. The conditions of the rearing environment (temperatures, humidity, pathologies, forage quality, etc.) are difficult and limit individual performance (production of milk and meat). Ruminant feeding in the tropics has been the subject of much work, and several approaches have been developed. The first approach focused on improving the quality of the basic ration. The low nutritional value of tropical forage is one of the main factors limiting animal performance [1]. Various works were carried out to improve the nutritional quality of the fodder, and so many varieties were distributed. Improved digestibility and ingestibility of forages, by physicochemical treatments, on the one hand, and by urea treatment, on the other hand, were also studied [2, 3]. However, the ingestibility of these forages, their protein, and energy value remained lower than those used in temperate zones and do not cover the needs of our herds. This leads to a massive reliance on imports of animal products like dairy and meat products.

Indeed, after the good period of reproduction, the feeding behavior of the ewes at the end of gestation must allow to successfully bait and ensure a good start of lactation. Reasonable dietary behavior over the last 6 weeks of gestation strongly contributes to a good birth weight of lambs, longevity, and body condition of the ewe [4].

In theory, the needs during the control period are not different from those of the maintenance, but the overfeeding practiced (flushing) during this fight influences the egg-laying and also the grouping of the calves allowing a better control of the notion of allotment.

On the other hand, many authors have reported that diet influences prolificacy. Indeed, stimulation of ovarian activity promotes ovulation rate (based on live weight and weight gain before the fight). The heaviest ewes have a higher ovulation rate. Hence, the interest of pre-estrous flushing, which improves the number of agneaus born from 10 to 20%.

In Tunisia, the Sicilo-Sarde breed is a medium-sized sheep breed with a height of 0.7–0.8 m, heterogeneous in color with the dominance of white, with a medium weight of ewes, 40 kg and 60 kg for rams. The head is slightly elongated without horns. The neck is moderately long, the members are long and thin, and the trunk is elongated with a full belly. The udder is well developed with a strong attachment and with straight nipples. Breeding performance of the Sicilo-Sarde breed depends on several factors, such as driving, feeding, housing, and genetic factors [5]. The herd is conducted in a semi-intensive system [6], characterized by rations consisting of hay, thatch, natural pastures, crop residues, and greenery (barley in green, bersim, etc.). The use of the concentrated feed takes place throughout the year in varying amounts. Figures from the Ministry of Agriculture show that the numbers of this dairy breed are in constant decline. For this, many questions have been raised about the profitability and sustainability of this breeding [6–13].

2. Physiology of lactation

2.1 Morphological and anatomical description of the mammary gland

The udder is an exocrine gland composed of two independent quarters, located on the ventral side of the animal in inguinal position. The right and left quarters of the udder are separated by a central suspension ligament composed of elastic tissue. Branches of this ligament can extend into the quarters. The udder is covered with elastic skin [14]. It can be enlarged by the accumulation of milk between two milking or between two feeding. In lactation, each quarter contains secretory tissue consisting of mammary epithelial cells, milk ducts, a gland cistern, and a teat [15, 16].

The mammary epithelial cell is a secretory cell constituting the smallest cell unit (or acini). In lactation, the epithelial cells are polarized, with the basal side on the basement membrane side and the luminal side located on the alveolar lumen side. The constituents of the milk are secreted in the alveolar lumen by the luminal side. The epithelial cells are bound together by tight junctions and are based on a basement membrane consisting of laminin, collagen, and glycosaminoglycans. Epithelial cells contain basal part of the nucleus, surrounded by granular endoplasmic reticulum.

In the direction of the apical plasma membrane, cytoplasm contains the Golgi apparatus and secretion of different units: the lipid droplets and the secretory vesicles. The apical plasma membrane forms microvillus [17]. The synthesis of milk fat takes place within the endoplasmic reticulum and is materialized by the formation of lipid droplets between the two membrane layers of the reticulum. Once formed, the lipid droplets migrate to the apical membrane according to mechanisms that have not yet been elucidated. Lactose is synthesized in the Golgi apparatus and accumulates in secretory vesicles. Proteins are synthesized by ribosomes located on the surface of the granular endoplasmic reticulum. They, then, pass through the Golgi apparatus or begin the maturation process (phosphorylation, in particular) before being included in secretory vesicles [18].

2.2 Hormonal mechanism of milk secretion

The onset of lactation or milk production is the result of the effect of two pituitary hormones, namely, prolactin and growth hormones [19]. The role of these hormones is inhibited during pregnancy by high levels of estrogen and progesterone; after lambing the sudden drop in these hormones allows the secretion of prolactin and, therefore, the onset of lactation [16]. Prolactin and GH play a pivotal role in the transition from the mammary gland proliferation phase to the milk secretion phase by acting either directly or via the mammary epithelium-secreted hormones that activate the transcription of the mammary gland. Other factors that ensure the onset of lactation [20]. Cannas et al. [21] reported that maintenance of milk synthesis and secretion is controlled by the interaction of systemic factors and local regulatory factors, whereas throughout lactation milk synthesis decreases because of increased doses of estradiol and progesterone [19].

Refs. [22, 23] have reported that GH-specific receptors are absent in the mammary gland, so this hormone exerts its positive effect on milk production, indirectly, by stimulating synthesis and secretion of insulin growth factors whose receptors have been identified in the mammary gland of the ovine species. Aside from its role in triggering lactation, this hormone (GH) increases blood circulation and increases mobilization of body reserves [24].

2.3 Mechanisms for evacuation of milk

Milk is synthesized in mammary epithelial cells lining the alveoli from the nutrients provided by the blood vessels that come in contact with them. The synthesized milk is secreted in the alveolar lumen [25]. There are two mechanisms of milk evacuation; the first is the flow of milk by contraction of smooth muscles, and the second is an ejection reflex. The first mechanism for evacuating milk is the flow of the latter after opening the sphincter under the effect of the pressure of the teat at the beginning of milking. This mechanism starts 5–10 s after teat stimulation. It involves the contraction of the smooth muscles surrounding the canals, causing the evacuation of the milk they contain [10]. This flow phase allows the evacuation of 40–50% of the milk produced. The second mechanism is the milk ejection reflex. During the first stimulation of the teat or the animal (smell, vision, hearing), nerve impulses go from the teat (or any other sensory organ) to the brain, which then releases into the blood a hormone of the hypothalamo-hypophyseal complex: oxytocin. This hormone acts on the myoepithelial cells surrounding the alveoli causing their contraction [9]. Under the contraction of the myoepithelial cells, the cells are pressed causing the ejection of the milk contained in the acini lumen toward the terminal ducts and then the intralobular, interlobular, and interlobar ducts where it reaches the cistern of the gland and then that of the teat. The milk ejection reflex usually takes place 20–30 s after the initial stimulation [26]. In this same context, [25] have shown that the level of secretion of oxytocin differs significantly depending on the season in the Lacaune race, as the level of secretion in autumn is higher than in spring (27.5 ± 1.9 µg/ml against 12 ± 1.4 µg/ml, respectively).

3. Dietary requirements of dairy sheep during gestation

3.1 Feeding gestante females

As we have reported, the feeding of pregnant females, especially during the last third of gestation, has an impact on fetal weights, vigor of newborn lambs, mortality, milk production of the mother, growth rate of lambs, the onset of pregnancy toxemia and body weight, and maturity on sale. As a result, this energy, protein, mineral, and vitamin diet can be broken down into three periods.

In early pregnancy, fetal growth is minimal, and the feeding requirements of ewes differ a little from those observed at the maintenance stage. We can therefore give the ewes a similar ration in a slightly higher quantity. Grain is rarely needed early in pregnancy unless forage is of poor quality and the body condition of the ewe is affected.

At the beginning of gestation (1 month), any sudden modification of the diet during this period can cause embryonic mortalities. The embryo settles 16 days after fertilization. In the second period, during the mid-gestation period (2nd and 3rd month), the animals' needs are still low; they are equivalent to those of a maintenance of a female (**Table 1**).

The third period, which is the end of gestation period, is the most critical period, as the needs are higher and higher because of the development of the fetus or fetuses. The volume of the uterus takes more and more place in the abdomen; it also compresses the digestive tract. The capacity of ingestion of the ewe decreases strongly; it requires a complementation with a small food (food has a fast digestive transit) which is especially rich in energy. This complementation is called steaming.

Live weight	FU	DNM
05	0.18	15
10	0.26	22
15	0.33	28
20	0.38	32
30	0.47	40
40	0.53	45
50	0.59	50
60	0.65	55
70	0.70	60
80	0.74	64

FU, fodder unit; DNM, digested nitrogenous materials.

Table 1.
Maintenance needs of sheep in FU and DNM.

In addition to lactation, this is the most nutritionally demanding stage because of fetal growth and the development of milk production potential. More than 80% of fetal growth occurs during the last 6 weeks of gestation. A deficient nutrition (especially in energy) during this period has detrimental effects on the milk production of the ewe, the birth weight, and the vigor (survival potential) of the lambs. Ewes must receive at least 335 g (0.75 lbs. of a mixture of grains, per ewe, per day, for those with a lambing percentage greater than 200%.

During calving, the ewe will experience a relatively low intake because of the loss of appetite. Thus, to cover the needs of lactation (0.6 FU and 120 g DNM/liter of milk), the diet must be based on grazing or feeding in green along with a feed-concentrated supplement, to allow the ewe to restore fat reserves lost in late gestation.

It is strongly recommended that the grass should not be young to avoid certain diseases such as grass tetany, resulting from Mg deficiency, which can lead to ewe mortality. The greenery should not be rich in legumes to avoid weathering resulting from a buildup of gas in the rumen that would cause digestive disorders.

The mineral requirements of sheep during the gestation and milking phase are summarized in **Table 2**.

A deficiency of nitrogenous materials and minerals always has regrettable consequences on the viability and the weight of the lambs. An important energy undernourishment causes an excessive mobilization of the reserves bodily, risking of a toxemia of gestation. To remedy this difficulty and ensure a good start of lactation, it is recommended to:

- Scan ewes and separate those with single lambs from those with double lambs.
- Make the batches according to the body condition.
- Avoid manipulations, especially thermal stress.

The success of the births needs a food preparation. In practice, it is necessary to provide energy intakes equal to 1.5 times that of maintenance during the last 6–8 weeks of gestation for ewes carrying multiples. Indeed, we use steaming which is an operation of providing a complement to the ewe during this critical phase. This supplementation varies according to the state of the courses at the rate of 200–400 g of concentrate, per day.

Physiological stage	Ca	P
Month of gestation		
2	05	04
3	05.5	04
4	08.5	05.5
5	08.5	05.5
Lactation month		
1	14	09
2	12	08
3	10	07
4	08	06

Table 2.
Mineral requirements according to the physiological stage.

3.2 Feeding lactating females

During the first month of lactation, the lamb is dependent on the milk production of the mother. Needs are important, but the ingestion capacity is limited for 3 weeks. The maximum milk production level is reached very quickly after the farrowing period:

- At 15 days when the ewe is nursing two lambs.
- At 3 weeks when the ewe is nursing one lamb.

During this period, the energy balance is negative, and the animal can on his bodily reserves. We accept a loss of weight of 2 kg per month (1–4 kg depending on the state of the female before the birth).

Lactating ewes typically reach maximum milk production 3–4 weeks after lambing and produce 75% of their total milk yield during the first 8 weeks of lactation [2]. The ewe that seals two lambs produces 20–40% more milk than the one that only feeds one.

As the growth of lamb is paramount and depends on the production of sheep's milk, it is essential to optimize milk production. Too often, we see herds where ewes do not receive sufficient amounts of food in relation to the number of lambs they breastfeed. In most cases, the rations do not contain a sufficient proportion of grains during the first 4–6 weeks of lactation, which results in energy deficiency and often protein. In ewes, milk production depends on the same diet as in dairy cattle.

During this period of lactation, it will be necessary to:

- Cover the nitrogen requirements of mothers (they have more reserves).
- Limit the energy deficit knowing that the animal mobilizes its reserves.
- Ensure ingestion capacity. In fact, it reaches its optimal level again 5–6 weeks after lambing.

The above information discusses production stages in the case of lambing, once a year, whether in summer or winter. To be successful, pastoralists who adopt an accelerated lambing program must ensure that the health status of their ewes is above average. Ewes should not lose too much weight during lactation if the breeder expects that they are giving birth again and is performing well in the number of lambs and their weight at weaning.

The most often overlooked step for good herd nutrition is the assessment of body condition. The farmer must measure the body condition of his flock to determine how ewes respond to feeds. If this step is neglected, forage sampling and ration evaluation will be unnecessary. The farmer must evaluate how the herd reacts to the food provided to them. In the absence of an assessment of body condition, good herd nutrition cannot be achieved.

4. Effect of diet on the production and composition of sheep's milk

Food is one of the main factors conditioning animal production. Its effects can be noted on the quantity as well as the quality of the animal products. In dairy sheep, milk production is dependent on the level of food and the quality of the constituents of the diet [27].

A study conducted by [28] on two forage species, barley in green and vetch with or without supplementation, showed that total milk production was not affected by complementation, as well as daily production was 460 and 430 ml, respectively, on barley and vetch with no significant difference, while milk produced on vetch is richer in fat and protein ($p < 0.05$).

In the same context, [6] mentioned that the amount of milk produced by Sicilo-Sarde ewes grazing oats is higher than on pasture of *Phalaris*. Milk produced with a pasture-based diet is richer in fat and protein than that produced by sheep fed with hay and silage in sheepfolds [29, 30]. These results have been confirmed by [7] who have argued that the milk of ewes fed with green fodder supplemented or not is richer in fat (77.4 vs. 69.1 g/kg) and in proteins (62.4 vs. 59.4 g/kg).

The use of legume pasture such as bersim, sulla, and medicago significantly increases the protein quality of sheep's milk and the level of production [31], leading to an intense marketing of milk and a quality of cheese. Better and with less burden because of the low use of the concentrated feed [32]. Similarly, [33] showed that the herbage was accompanied by very important changes in most milk characteristics, and in particular the urea content (+0.12 g/kg between samples taken in March and May) and mineral contents (respectively, +0.06 g/kg, +0.09 g/kg, −0.26 g/kg for calcium, phosphorus, and citrates).

Pirisi et al. [11] tested the effect of diets on the physicochemical and microbiological characteristics of milk produced by Sardinian ewes fed with hay, silage, and mixed concentrate (R1) and with ryegrass grazing. Italy (R2) showed that the level of butyric spores was higher ($p < 0.01$) in milk R1 (1140 vs. 20 germs/l) and the concentration of somatic cells was higher in milk (R1), while the fat content is higher in cheese (R1) characterized by a poor structure (**Table 3**). Similarly, [34] reported that milk production increases during winter–spring with pasture and supplementation only during the autumn (pasture alone). In the same context, the ejection of ewes previously fed with preserved fodder results in an increase in milk production, which leads to a second peak of lactation around March [29, 35].

Atti et al. [36] reported that the amount of milk produced by Sicilo-Sarde dairy sheep on green barley or fat strip grazing was significantly higher ($p < 0.05$) than that of ewes receiving milk. In sheep-fed silage (616, 618, and 363 ml/day), the fat content and the protein content are higher for sheep in sheepfold than for ewes grazing barley in green or fat ray (**Table 4**). However, there is no significant difference in either production or milk quality between the two pasture forage species ($p < 0.05$).

The milk content in urea nitrogen depends on the protein content of the ration; it is better correlated with it (R2 = 0.82) than with the amount of protein ingested (R2 = 0.56), which is in fact an effective indicator of nitrogen use [37]. The urea content of milk varied between 12 and 27 mg/dl depending on the protein level

	R1	R2
pH	6.6 ± 0.03	6.72 ± 0.03
Solide total (g/100 g)	18.54 ± 0.42	18.09 ± 0.28
MG (g/100 ml)	7.24 ± 0.37	6.98 ± 0.33
MP (g/100 g)	5.28 ± 0.12[a]	5.66 ± 0.11[a]
Casein (g/100 g)	4.26 ± 0.16	4.36 ± 0.17

[a]*The averages of the same line bearing different letters are significantly different ($p < 0.01$).*

Table 3.
Physicochemical criteria of milk from ewes fed at the trough or on pasture.

	Bergerie	Orge en vert	Ryegrass	ESM	P
Milk production	363	616	618	37.5	***
FAT	88.8	77.2	76.8	1.15	***
Protein	57.6	54.6	53	0.51	***

****p < 0.01; ESM, error standard mean [36].*

Table 4.
Average production (ml/day) and milk composition of Sicilo-Sarde sheep according to the food mode.

of the diet: these values, lower than those measured in dairy cows, are consistent with those observed on Lacaune ewes during the milking phase, when increase in the coverage rate of average needs in DINP (from 120 to 160%) causes a significant increase in the content of milk in urea (from 38 to 52 mg/dl, i.e., + 36%) which is linked (R2 = 0, 90) imbalance (DINP-PDIE)/UFL rations [38], while total dry matter intake does not affect milk urea [9, 39].

Ewes fed with a 34.1% starch concentrate produce more milk than those receiving a 12.2% concentrate (1.088 vs. 0.902 kg/d), without affecting milk fat and protein composition (TB, 8.04 vs. 8.57%; TP, 5.96 vs. 5.83%, respectively), for starchy and starchy concentrate feed [40]. On the other hand, [41] reported that a food rich in starch that is rapidly fermentable in the rumen leads to a more intense production of propionate and a drop in the milk fat content. In addition, the same authors reported that there is no systematic influence of the rate of starch degradation on protein levels and raw milk yield when comparing corn and barley. However, Sinas et al. [42] have shown that when rations comprise a large proportion of untreated sorghum which is the richest cereal in terms of slow starch, there is a decrease in milk yield compared with sorghum treated with steam under pressure. These results may reveal the existence of a maximum threshold not to exceed protected starch in the diet [43]. The relationship between volatile fatty acids and ruminal pH, on one side, and the production and composition of milk, on the other, has been studied by [44]. Thus, the proportion of propionate and butyrate is positively correlated with the amount of milk unlike acetate, while the butyrous rate evolves in the same direction as the C2 and conversely with C3 and C4.

5. Conclusion

Since there is a great deal of variation in the quality of the fodder, their analysis is paramount and must include the following nutrient content: crude protein, acid detergent fiber (FDA), calcium, phosphorus, magnesium, potassium, and possibly even micronutrients (copper, manganese, and zinc), understanding the changes in nutrient requirements according to the production cycle. To easily manage sheep farming and meet their needs, it is essential to know at all times the production cycle of sheep and each group of ewes, to be able to separate the sheep and ensure adequate management of each group. Regardless of the production system adopted by the farmer (accelerated or once a year), profitability is closely linked to a nutrition adapted to the production cycle, to know at what stage of production are the ewes you feed and to reduce feed costs by avoiding unnecessary overfeeding. The production cycle of the ewe is generally considered to have six important stages of production: maintenance, intensive feeding, early gestation, late gestation, and early lactation. Management in general, and more specifically nutrition management, should be modified at each of these stages if the farmer wants the herd to be healthy and above all to obtain a satisfactory selling price.

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Chapter 4

Probiotic Supplement Improves the Health Status and Lactation Performance in Dairy Animals

Shakira Ghazanfar, Aayesha Riaz, Muhammad Naeem Tahir, Saad Maqbool, Ghulam Muhammad Ali, Fatima Tariq and Irum Arif

Abstract

Probiotics are essential for the effective growth of beneficial bacteria present in enteric line. They help in the physiological functions of new-born calves that are highly susceptible to a variety of fatal syndromes. The criterion for the selection of strains for the design of probiotic products are based on retaining functional health characteristics. Samples from Nili-Ravi buffaloes were collected, and rumen strains are identified for probiotic product. Microscopic techniques with different biochemical tests and molecular techniques such as BLAST have performed for identification. Following species of *Weisella* has been identified based on genotypic analysis (16S rRNA) under accession number MK336765 (F2) and MK336779 (F4) in the NCBI GenBanK. The strains sharing some of the specific properties evaluated were identified genetically, and their compatibility and exopolysaccharide production were assayed. All of this will be helpful in the production of multi-stain-probiotic product for the nourishment of dairy calves.

Keywords: calves, lactic acid bacteria, probiotic, rumen, product

1. Introduction

The innovative development in the dairy industry is possible only due to scrupulous research, nutrition, genetics, and management strategies and its oriented implementation. The high risk of contagion is due to occasional bouts and improper feed of nutritional contents which become the ultimate cause of debility and economic and resource loss. To avoid the prevalence of such harms on dairy animals' proper nutritional content, management of hygiene adoption is required [1, 2]. For this, a term is defined in the 1960s which is "probiotic," which is a curious mixture of Latin (pro = for, in favor of) and Greek (bios = life). Probiotic which is discovered by Elie Metchnikoff in the early twentieth century is defined as "Live microorganisms which when administrated in an adequate amount to organism body confer a health benefit on the host and alter the gastrointestinal tract flora into the beneficial form" [3]. The nature of probiotics is on the basis of human, animals, and plants [4]. But, here we will focus on the probiotic types of animals because we are dealing with dairy animals.

Microbial infections which become the cause of mortality in dairy animals are animals scouring at early stage and perturbation in microbial GIT and the most enteric infections caused by *Escherichia coli*, *Clostridium perfringens*, *Salmonella*, and some *Streptococcus* and *Staphylococcus* species [5]. The major microbial density is present in the reticulum, rectum, and colon mostly. So, to eradicate the prevalence and outcomes of these infections and to nourish the local microbiota of the gastrointestinal tract. Due to the indiscriminate use of antibiotics, antibiotics resistance has become dominant characteristics in microorganisms [6]. Increase in the dissemination of antibiotic resistance genes is reducing the therapeutic possibilities in infectious disease. So, in order to alleviate the problems associated with the antibiotic use, a number of replacement have been proposed, and one of them is the effectiveness of probiotics [7].

Probiotic microbiota-based feed supplements are used to combat major enteric infections [8]. So, different types of probiotics strains are used for making the GIT congenial for proper health and growth. These probiotics strains are collected from a

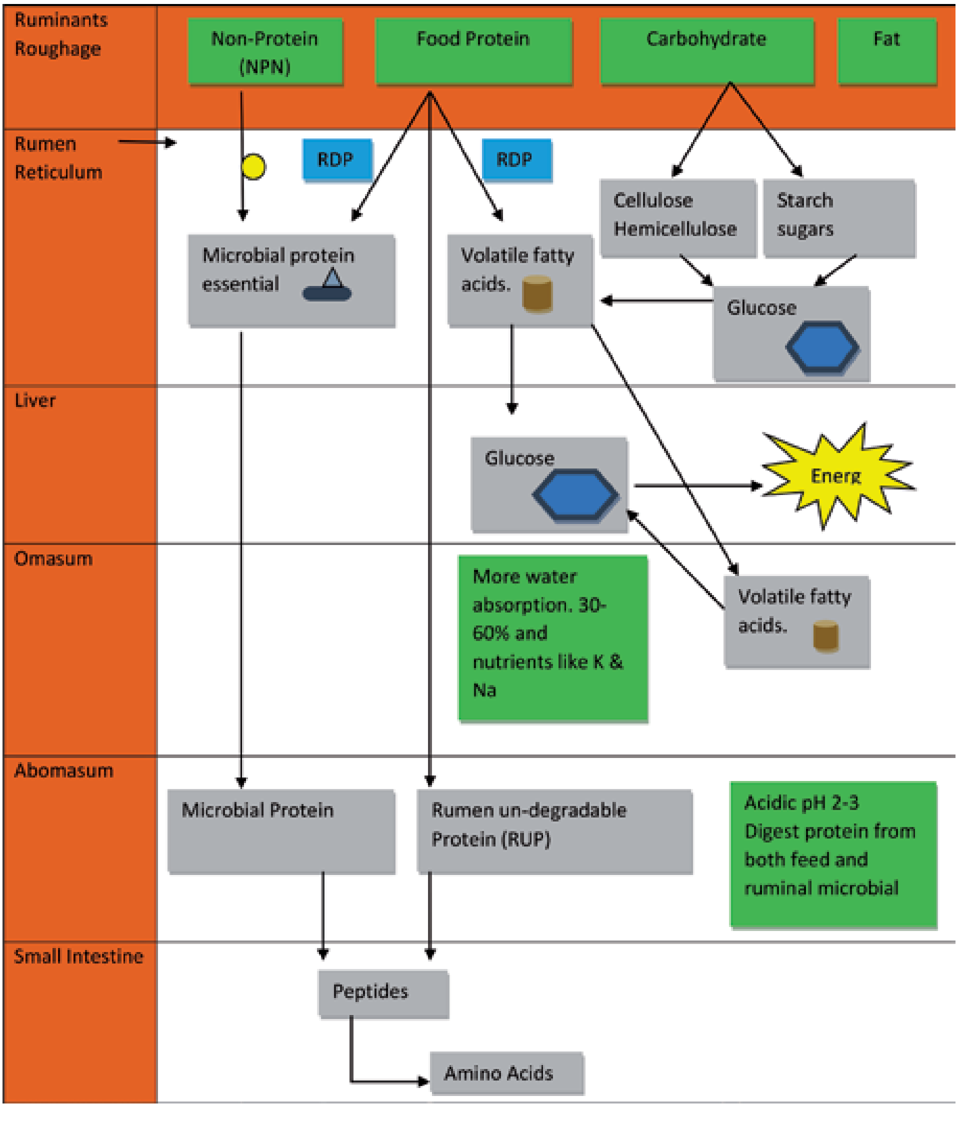

Figure 1.
Impact of the Probiotics on the GIT of dairy animal: The microbial flora degrades the feed and improve feed intake and ultimately improve milk production.

different source of host such as feces, milk, and directly from GIT. Probiotic bacteria produce protein segments or polypeptide bacteriocins which reduce the growth of harmful bacteria [9]. Probiotics help to prevent and control gastrointestinal pathogens and improve the performance and production of animals through various biochemical mechanisms. Closely related strains may differ in their mode of action [10]. Increased nutrient digestion in the diet may be due to the speed-up of enzyme activity in the intestine due to probiotics [11]. *Lactobacillus* probiotics altered the digestive enzyme activity in the GIT of dairy animals and enhanced the growth rate [12]. However, there is no change in proteolytic and lipolytic activity of the animal's digestive enzyme activity. This improvement in amylase activity is associated with a 4.6% increase in body weight gain and 5% improvement in feed use efficiency [13]. Probiotics increased the height of intestinal villi and villus height crypt ratio in dairy animals, thus increasing the surface area for nutrient absorption [14, 15].

The rumen has complex integrated microbial ecology which degrades the ingested polysaccharide and proteins resulting in short-chain fatty acids which are further used by a host as energy and protein source [16]. The probiotic concept was raised around 1900 which is hypothesized by Elin Metchnikoff, and later he was convinced that yoghurt contained the organisms which are necessary for protecting the intestine from the damaging effects of other harmful bacteria [17]. The first clinical trials were performed in the 1930s. In the 1950s, a probiotic product was licenced by the United States Department of Agriculture as a drug for the treatment of scouring (*Escherichia coli* infection) among pigs [18]. In 1994, the World Health Organization deemed probiotics to be the next most important immune defence system when the commonly prescribed antibiotics are rendered useless by antibiotic resistance, altering the natural mechanism of the body [19] (**Figure 1**).

2. Microbial composition of the GIT of dairy animals

The most common organism used in the vital preparation of probiotics in the lactic acid bacteria (LAB) is highly effective because it is also the natural flora of organism GIT system and it is regarded as safe in the words of US FDA [20]. Microorganisms other than LABs which are currently used in probiotic preparation are *Bacillus* sp. and yeasts (*Saccharomyces cerevisiae* and *S. boulardii*). Different species of *Lactobacillus*, *Bifidobacterium*, and *Enterococcus* are used for probiotic preparation with fructooligosaccharides (FOS). The probiotic products are in the form of spray, pastes, tablets, powder, and capsules [21].

3. Selection of probiotics to improve milk yield

The following abilities should be manifested by bacteria used as lactic acid bacteria:

- It should exert a beneficial effect on the host's life and metabolic activities.
- It should withstand into a foodstuff at high cell counts and remain viable throughout the shelf life of the probiotic-containing product.
- It should withstand through the GIT tract and help in colonization of beneficial bacteria.
- It should adhere to the intestinal epithelium cell lining.

Common bacterial type of probiotics			Yeast probiotics
***Lactobacillus* sp.**	***Bifidobacterium* sp.**	***Enterococcus***	***Saccharomyces***
L. acidophilus	*B. bifidum*	*E. faecalis*	*S. cerevisiae*
L. casei	*B. infantis*	*E. faecium*	*S. boulardii*
L. bulgaricus	*B. longum*		
L. fermentum	*B. animalis*		
L. lactis	*B. thermophilum*		
L. plantarum			
L. brevis			

Table 1.
Most Common species of LAB'S in animal probiotic preparation.

- It should stabilize the intestinal microflora and be associated with the health benefits.
- It should contain viable cells at the time of consumption.
- It should reduce symptoms of lactose intolerance.
- It should enhance the functionality of the immune system and enhance the bioavailability of nutrients.

These strains are used for the preparation of probiotics with or without FOS (**Table 1**).

4. Physiology of dairy animal's digestive system

The primary roles of the gastrointestinal epithelium (GE) are to shield the host from the mixture of pathogenic microorganisms, toxins, and chemicals in the lumen and to prevent unregulated movement of these compounds into the lymphatic or portal circulation [22]. The GE continuously endeavors to enhance nutrient absorption. Careful consideration of gut health—promoting the action of a particular nutrient or feeding strategy—is important. Food goes down to the reticulorumen from the esophagus, and this is like a fermentation chamber which converts plant carbohydrate to volatile fatty acids, lactate, hydrogen, and methane which are used by the ruminant host. In ruminants, process starts with the peptic digestion in the abomasum [23]. The digestive system of the rumen is composed of the first reticulum then rumen, then omasum, and finally abomasum. The rumen is a complex biological system which is like a fermentative vat where nutrients are consumed by different organisms. Energy from forages are acquired by ruminants through fermentation process which is done by microorganisms by different enzymatic activities [24]. Different factors including pH, temperature, osmotic pressure, buffering capacity, and redox potential affect the activity and growth of rumen microorganisms [25]. Different environmental and physiological conditions determined these prime factors. The normal temperature of the rumen is in the range of 39–39.5°C, but as fermentation occurs after food intake, the rumen generates heat which increases temperature up to the limit of 41°C. pH is affected by short-chain fatty acid production, feed intake level, as well as exchange and absorption of ions like phosphate and bicarbonate [25] (**Figure 2**).

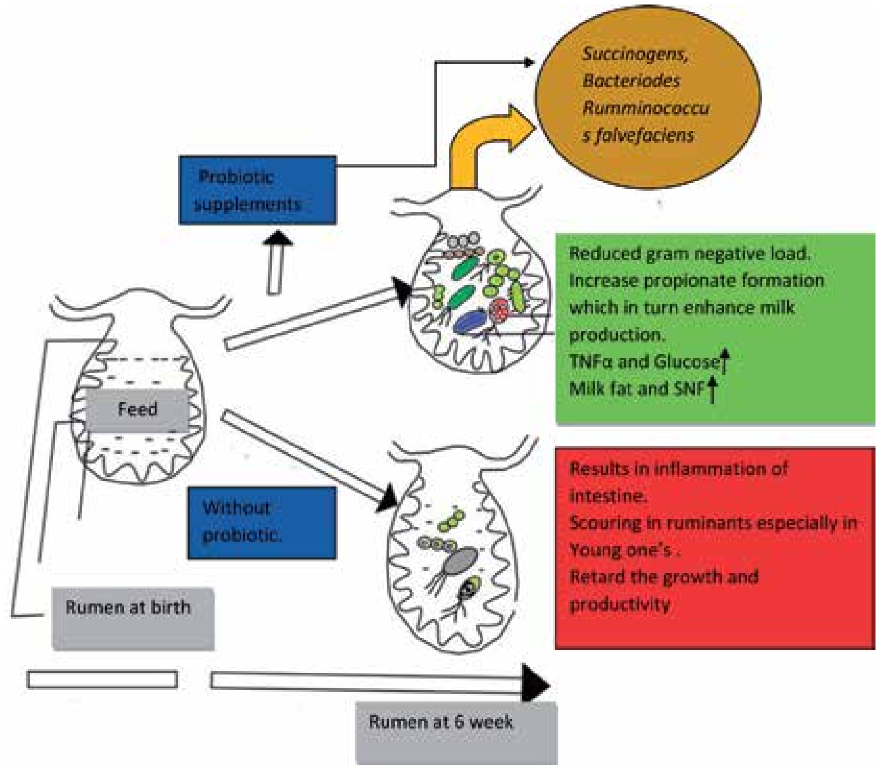

Figure 2.
Effect of probiotic on the development of the microbial flora in newborn calves.

5. Rumen microbiology

Different bacteria are present in the rumen, and they are more in ratio than other microbes which include *Megasphaera elsdenii*, *Lactobacillus ruminis*, *Streptococcus bovis*, *Fibrobacter succinogenes*, *Prevotella*, *Bacteroidaceae*, *Lachnospiraceae*, *Prevotellaceae*, *Ruminococcaceae*, *Succinivibrionaceae*, and *Veillonellaceae* [26]. There are a total of five groups of bacteria: 1, free living in liquid phase; 2, loosely attached with feed; 3, firmly attached with feed; 4, attached with rumen epithelial lining; and 5, attached with protozoa/fungi.

6. Culture-based method to develop the indigenous probiotic feed to improve milk yield in dairy animals

We have finalized the simple protocols that will guide researchers in identifying the most ideal probiotics for animal use to improve milk yield. There are two methods which have been utilized till now for the identification and characterization of the microbial flora, i.e. culture-dependent method and culture-independent method. Milk products own the major economic importance all over the globe especially in countries where agriculture and livestock cover the major area of industry. The milk we consume is derived from cattle, buffaloes, goats, sheep, and camels that come under categories of ruminants. And 99% of this milk is produced from ruminant [1].

LABs as feed supplements can help in improving the milk quality and quantity in lactating dairy buffaloes [27]. The literature showed that the species-specific probiotic can improve the host performance in a better way than the nonspecific. In our lab, we have isolated and molecularly characterized the bacterial strains that are basically animal origin probiotics. We used the culture-dependent method to isolate the animal probiotic-bacteria strains.

7. Experimental proof

7.1 Experiment no. 1: isolation, identification, and characterization of LAB from the gut of dairy lactating buffalo

Three healthy lactating *Nili-Ravi* buffaloes raised at NARC, Islamabad, Pakistan, were randomly selected for sampling. A sample was taken fresh from deep rumen with the hand using aseptic techniques. Samples were transported to the laboratory under controlled conditions for further processing. For pure isolates, 1 g of feces sample was diluted in PBS (phosphate buffer saline). Commercially available MRS (De Man, Rogosa, and Sharpe) agar media plates were inoculated with diluted fecal samples and incubated at 37°C for 24 h. Initial screening was done by using the basic microbiological methods. For that purpose, colony morphology was examined, and gram staining was done. For complete morphology scanning electron microscopy was performed. Common biochemical tests like catalase and oxidase were done. For molecular identification of the isolated strains, we used the PCR. The pure cultures were subjected to a polymerase chain reaction for amplification of DNA. Amplified products were sequenced and identified at the species level, and a phylogenetic tree was constructed. A total of 30 bacterial strains was isolated from buffalo gut. These were mostly gram-positive and catalase-negative bacterial strains. We noted that very important bacterial strains were isolated from buffalo gut (**Table 2**).

Gram staining showed that isolated strains were either gram-positive rod or gram-positive cocci, as the strains retained primary stain (crystal violet) that is one of the major characteristics of LAB (**Figure 3**). The strains appeared as a single cell or in the form of short chains or small clusters under a microscope. The colony on MRS agar was round, irregular with a smooth shiny surface, cream in color, and with entire or convex margins. If we talk about elevation and opacity, most of gram-positive colonies were raised and opaque (**Figure 4**).

The isolated strains were further subjected to biochemical characterization. We performed a catalase test. I took an isolated colony using a sterilized toothpick and mixed with a drop of hydrogen peroxide and noted the bubble formation. Many strains resulted in negative result and few were positive. I noted that the negative results were of the strains that retained crystal violet stain during gram staining, i.e. those were gram-positive rods or cocci. Selected strains were identified on a molecular level by blasting the amplified DNA using the BLAST tool at the National Centre for Biotechnology Information (NCBI) website. And the strains F2 and F4 were identified as different species of *Weisella*, on the basis of genotypic analysis. These 16S rRNA sequences were submitted to the NCBI GenBank under the accession numbers MK336765 and MK336779 assigned to strains F2 and F4, respectively (**Table 3**).

7.2 Phylogenetic analysis

Phylogenetic trees of the strains were constructed to see the closely related species of the strains (**Figure 5**). We found the following results.

Selected bacterial strains	Colony characteristics								Biochemical characteristics
	Gram staining	Shape	Form	Surface	Color	Margin	Elevation	Opacity	Catalase
F1	+ve	Rod	Round	Smooth/shiny	Cream white	Entire	Raised	Opaque	−ve
F2	+ve	Rod	Round	Smooth	Cream	Entire	Raised	Transparent	−ve
F3	+ve	Cocci	Circular	Smooth/shiny	Cream white	Convex	Slightly raised	Opaque	−ve
F4	+ve	Curved Rod	Round	Shiny	White	Entire	Raised	Moist	−ve
F5	+ve	Cocci	Circular	Smooth	Pinkish white	Entire	Raised	Opaque	−ve
F6	+ve	Cocci	Round	Smooth/shiny	Cream white	Entire	Raised	Opaque	−ve
F7	+ve	Rod	Round	Smooth	White	Entire	Convex	Translucent	−ve
F8	−ve	Rod	Round	Smooth	Cream	Convex	Raised	Opaque	+ve
F9	−ve	Rod	Circular	Shiny	Cream white	Entire	Slightly raised	Opaque	+ve
F10	+ve	Cocci	Round	Smooth/shiny	cream	Entire	raised	Opaque	−ve

Table 2.
Morphological, biochemical identification of bacterial isolates on MRS agar.

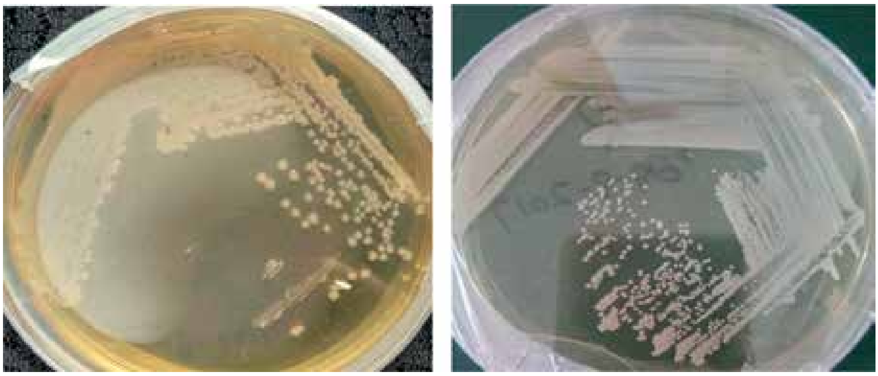

Figure 3.
Colony morphology of strain F2 and F4 isolated from animal gut.

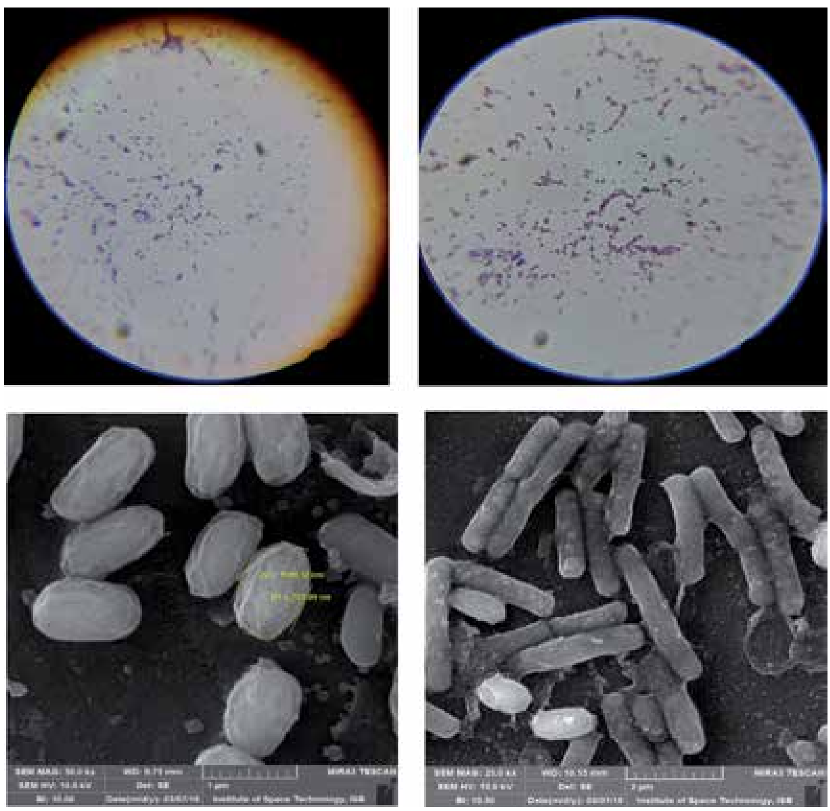

Figure 4.
Gram staining and electron microscopy of strain F2 and F4 isolated from animal gut.

7.2.1 Weisella species

The strain similarity was found using NCBI BLAST; *Weisella* MK336780 (NMCC-M14) has similarity with *Weisella* JX1880721 (AB13), and *Weisella* MK336765 (NMCC-M11) has high similarity with *Weisella* JX1880721 (AB13).

7.2.2 Staphylococcus species

The strain similarity was found using NCBI BLAST; *Staphylococcus* MK355570 (NMCC-path-2) has high similarity with *Staphylococcus aureus* strain DSTNMRM17,

Strain ID	Strain name/ genus	Accession number	Closely related valid published species	Similarity % of 16S rRNA gene sequencing
F2	*Weisella*	MK336765	*Weisella confusa* strain AB13	97%
F4	*Weisella*	MK336779	*Weisella confusa* strain AB13	96.5%
F5	*Staphylococcus*	MK355570	*Staphylococcus aureus* strain DSTNMRM17	98%
F6	*Staphylococcus*	MK355562	*Staphylococcus aureus* strain YT-3	99%

Table 3.
Phylogenetic tree of the F2 and F4 isolated from dairy animals on 16S rRNA gene sequence.

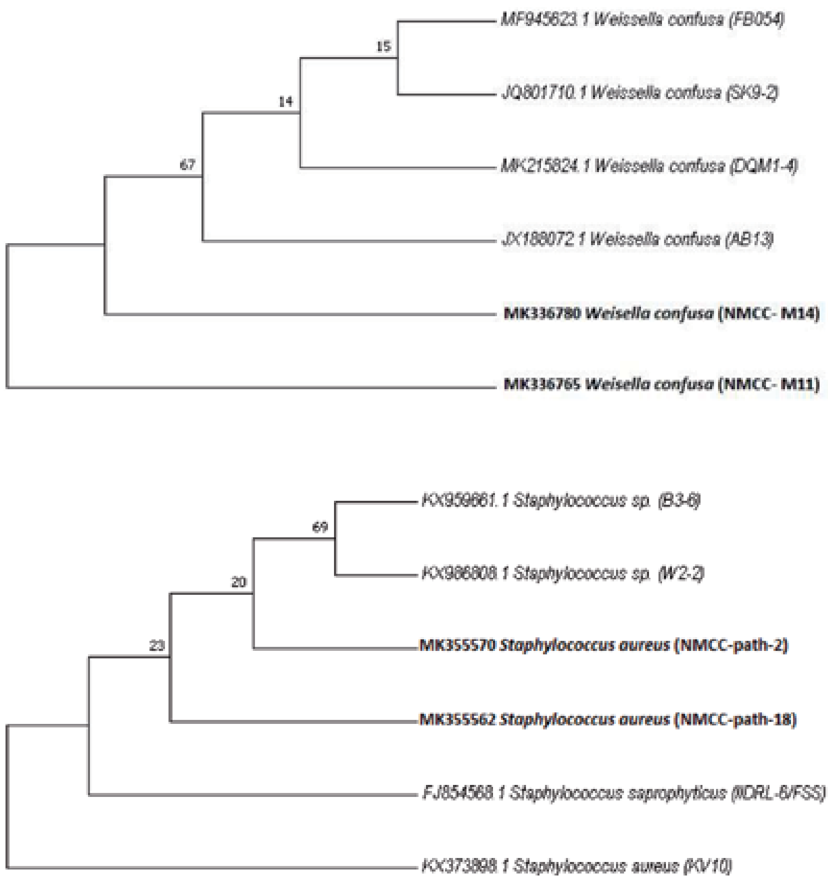

Figure 5.
Phylogenetic tree of Weisella confusa, and S. aureus isolated from animal gut.

and *Staphylococcus* MK355562 (NMCC-path-18) has high similarity with *Staphylococcus aureus* strain YT-3.

7.3 Experiment no. 2: determination of probiotic potential

Selected strains were subjected to further testing to determine the probiotic potential. Different tests like bile tolerance activity, cholesterol assimilation test, antimicrobial activity, and antibiotic susceptibility test. Bile tolerance activity was

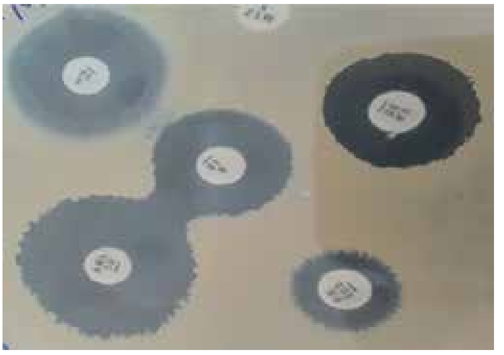

Figure 6.
Antibiotic susceptibility testing of strain F2isolated from animal gut.

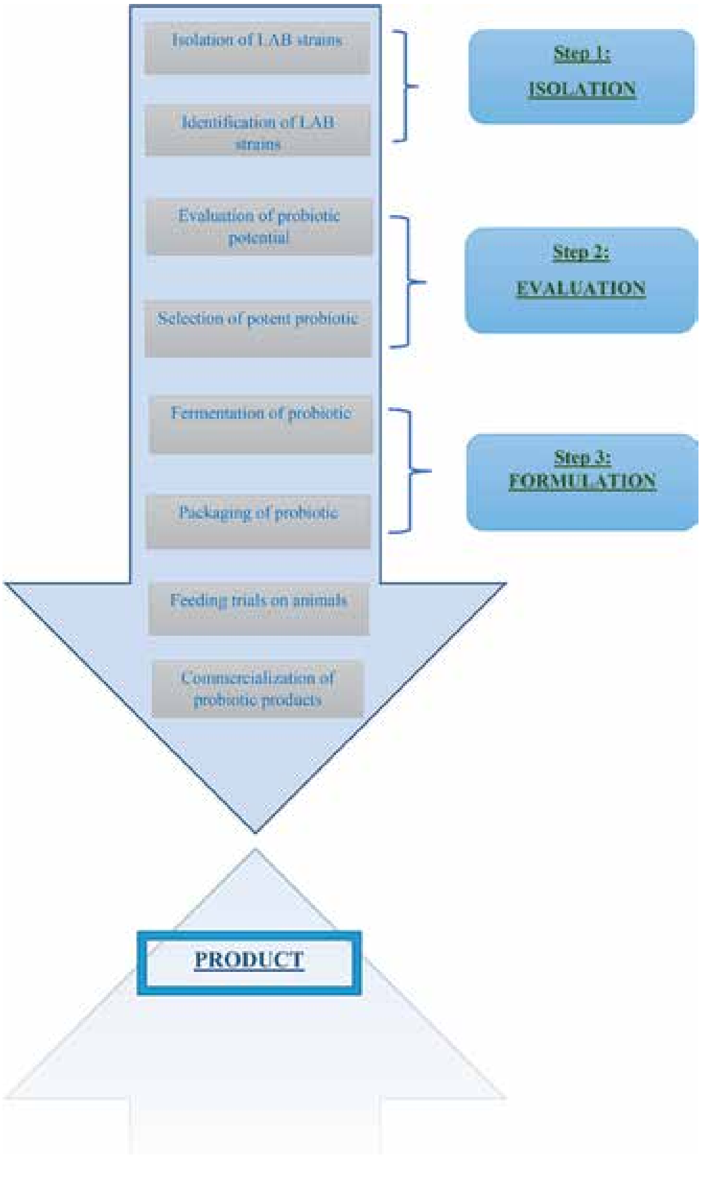

Figure 7.
Steps involved in the preparation of animal probiotic product development.

performed by inoculating the two selected strains on sterilized TSB (tryptic soy broth) in Erlenmeyer flasks incubated at 37°C in shaking incubator, 150 rpm for 24–48 h. Stock solutions of bile salts and lysozyme were added after incubation. The pH of the solution was adjusted to 3. Control was kept aside. After intervals of 30 min, samples were inoculated on TSA (tryptic soy agar) after serial dilution and incubated for 24–48 h at 37°C. After incubation, CFU was determined, and the tolerance rate was analyzed (**Figure 6**).

The livestock sector is mostly based on traditional lines which lead to unbalanced nutrition resulting in poor growth and productive performance in dairy animals. Nowadays, increasing the performance of dairy animals through the use of probiotics has become a useful and economical method to overcome the effects of malnutrition. The use of probiotic yeast enhances nutrient utilization, which may lead to improved performance and increased immunity in dairy heifers. Literature reveals that suitability and profitability of the probiotic yeast depend on many factors including animal breed, age, and probiotic strains. From this line of research, we look forward and develop a new probiotic yeast strain for our local breed, which provides a positive effect on milk yield and fat contents in lactating dairy cattle and moreover is cost-effective. At the same time, the dietary supplementation of probiotic yeast could also have an enhancing effect on the microbial balance of the GIT that leads to improved growth, health, and production performance in a dairy animal (**Figure 7**).

In the situation of a high feed cost, probiotic gives a useful nutritional strategy which allows increasing diet digestibility and consequently enhances the performance parameters of dairy animals in a cost-effective manner. Future research is needed to see the impact of the yeast cells in the GIT of the dairy animals. Future research will also need to address the behaviour of the yeast cells in the digestive environment. We look forward to the development of the new probiotic strains, which will hopefully mean that the rumen microbiologist in Pakistan instead of following the nutritious in an exploratory mood as has been the role for so long, will instead lead advances in ruminant nutrition in a year to come.

8. Recommendations

The recommendations are outlined as follows:

- For the preparation of the probiotic the sampling, the source should be indigenous/local-based.
- Internationally validated molecular methods should be used to identify the microbial strains.
- The probiotic, as well as genetic properties of the probiotic strains, should be studied. Good manufacturing practices must be applied with quality assurance, and shelf life conditions must be established, and labelling must be made clear to include minimum dosage and verifiable health claims.

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Chapter 5

Relationship between Body Condition Score, Milk Yield, Reproduction, and Biochemical Parameters in Dairy Cows

Wissal Souissi and Rachid Bouraoui

Abstract

Blood indicators are used as a tool to diagnose metabolic disorders. The present review aims to study the relationships between body condition score, milk yield, and reproduction and biochemical parameters in dairy cows. Live weight and body condition are indicators for dairy cow's health, milk productivity, and reproduction. Therefore, many authors investigated the effect of body condition score at calving and of change in body condition score on productive and reproductive performance, on lactation curve parameters, and on postpartum disease occurrence. Moreover, results showed that the cows calving at the highest body condition score lost more subcutaneous fat; condition score change did not exceed 1.05 units. Change in body condition score was positively associated with peak and total milk production. In addition, the decline in dairy reproductive performance may be due to a hampered process of metabolic adaptation. Adaptation to the negative energy balance is a gradual process. The use of risk factors is more appropriate and discussed. Among them are the body condition score and its derivatives, feed intake, the calculated negative energy balance, and metabolic parameters like the plasma concentration of insulin or the triacylglycerol content in the liver. Moreover, factors that play a role in the link between declined reproductive performance and the metabolic situation of the cow during lactating are discussed.

Keywords: dairy cow, body condition score, productivity, reproduction, metabolism

1. Introduction

High-yielding dairy cows are typically in a state of negative energy balance (NEB) during early lactation period because the amount of energy required for the maintenance of body tissue functions and milk production exceeds that the cows can consume [1]. Metabolic processes increase if milk productivity increases. It promotes an increase of metabolic stress. Milk productivity and reproduction traits decrease then. Mobilization of body energy reserves during the early lactation enables the cow to close the gap between the alimentary energy intake and its loss through the milk production [2]. Since the alterations in energy reserves have a considerable influence upon the productivity, health, and reproduction of dairy cows [3, 4], the monitorization of optimal management of energy reserves is obviously needed. Indicators, which characterize dairy cows metabolic processes, are body condition score (BCS) and live weight (LW). It is very important to evaluate the changes of these indicators. Body condition scoring has been widely recommended as a method of evaluating nutritional management of the dairy cows [5]. It is a management tool used to prove if rations meet the animal's need or not. Feeding a cow according to its needs leads to optimal performance. Over conditioned animals (especially at the end of lactation) or under conditioned animals (especially at the beginning of lactation) would have health problems. Klopčič et al. [6] have defined BCS as an indicator of how well the animal maintains energy reserves, reflective of the relationship between nutrition and milk production in a herd. However, there is also more interest in BCS from the breeding side. Generally, BCS shows the decreasing trend during early lactation due to homeorhetic response caused by negative energy balance and partitioning of energy reserves to support milk production. Excessive loss of energy during this period, generally in cows with higher/lower BCS at calving, results in productive, reproductive, and metabolic disorders in dairy cows. Once the cow recovers from negative energy balance, it starts gaining BCS during mid- and late lactation [7].

2. Body condition score

Body condition score (BCS) is a subjective assessment of energy reserves in adipose tissue of a dairy cow and is an important means for managing dairy cows [7]. According to Waltner et al. [8] and Bosio [9], it is an accepted, noninvasive, subjective, quick, and inexpensive method to estimate the degree of fatness in dairy cows. The purpose of condition scoring is to obtain a balance between diet, production, and animal welfare. This technique is mainly used to control dairy cow and pre-calving management; besides, it aims to ensure that cows calve down safely, avoid post-calving diseases (milk fever, hypocalcemia, hypomagnesemia, and ketosis) and metabolic disorders in early lactation (ketosis, fatty cow syndrome), and maximize milk production [6]. In order to determine the BCS, cows were scored on appearance and palpation of back and hindquarters [10]. A variety of scales and scoring criteria are proposed depending on the country or author, making it difficult to share data, comparisons of values, or results [11]. In the United States and Ireland, a 5-point BCS system is used for dairy cows, whereas Australia and New Zealand use 8- and 10-point scales, respectively [11]. In France, the Technical Institute of Cattle Breeding (TICB) has published a 6-point scale established by Bazin [12], where dairy cows are rated from 0 (very lean) to 5 (very fat) [13].

3. Body condition score and milk yield

The milk production of cows correlates with their body condition which is a wide and effective method to evaluate the nutritional management of dairy cows [14]. So, optimal body condition of dairy cow is essential to obtain elite herd and quantity milk production because thin or fat cows may have a greater risk of lower milk yield and higher milk somatic cell count (SCC) [15]. Agenas et al. [16] reported that, at the peak of lactation, the energy needs exceed the energy supply, which generates a negative energy balance (NEB). Then, to correct this deficit, the cow resorts to the mobilization of its body reserve and loses weight. Furthermore, Domecq et al. [17] showed that insufficient energy and protein reserves reduce milk yield. BCS has important effects through critical moment during lactation.

3.1 Body condition score during dry period and at calving

In order to support early lactation, dairy cows have to require enough body reserves. It is evident that over and under reserves have negative results on the animal's performances. Accordingly, over body reserve decreases dry matter intake and prolongs negative energy balance that causes poor production performance (lower peak yield, poor persistency) and reproductive diseases (retention of placenta, calving problems, and metabolic disorder). However, the cow with lower BCS, at calving, mobilizes less body fat, which decreases milk fat without affecting on milk yield, SNF, DMI, or nutrient utilization [7].

During dry period, the optimal body score condition is 3.0–3.25. Cows with BCS are more close to peak milk yield. The passage from BCS = 2 to 3 has a significant progress in milk productivity, but score above 3.5 at calving is deleterious for milk production [7]. According to Roche et al. [18], calving BCS is probably the most influential moment in the cow's lactation calendar, since it affects early-lactation DMI, post-calving BCS loss, milk yield, and cow immunity, and does not directly influence the pregnancy rate (it affects reproduction through nadir BCS and BCS loss). A loss in body condition score during dry period has negative impacts on the animal health, calving, and the amount of fat in ensuing lactation. However, increasing BCS in dry period may improve milk yield especially in the first 120 days [17]. Moreover, amelioration of BCS during parturition increases the milk fat percentage and reduces the anestrous interval after parturition [7]. Roche et al. [19] reported an optimum calving BCS for milk production of 3.5, whereas Berry et al. [20] reported that a total of 305-day milk yield was greatest in cows calving at a BCS of 4.25 units, and cows with 3.25 or 3 BCS units produce a further 50 and 114 kg of less milk, respectively.

3.2 BCS in early lactation

To optimize milk production, it is necessary to maximize milk production in early lactation but not necessarily during late lactation. Cows in early lactation utilize tissue reserves to support milk yield [7]. The high-producing cows cannot have their energy needs through feed intake at early lactation. There is negative energy balance with mobilization of body reserves and a loss of the BCS. Dairy cattle should not lose more than one point in their BCS during early lactation period. BCS at calving would better be around 3.5–3.75 [21]. Besides , Jilek et al. [14] showed that cows with BCS lower than 3.5 in the first month of lactation have the highest milk yield during the first 5 months of lactation. This can be explained by high mobilization of body reserves in high-yielding cows. The body condition level in the last month of drying period influenced its subsequent decrease in the first phase of lactation. Cows with the highest BCS level before parturition retained a high BCS level in the first 5 months of lactation. However, cows with the lowest BCS in the first month of lactation had the lowest BCS in the next 4 months. It is necessary that cows do not lose more than one point of body condition in early lactation: cows with excessive body condition losses will have irregular heats, have longer time to the first ovulation, and may fail to conceive. These cows will also be less persistent in milk production. Cows with a BCS over 6.5 (3.5 in a 5-point scale) at 2 weeks before calving are subject to having depressed intakes, weight loss, fatty liver, ketosis, high nonesterified fatty acid (NEFA) levels, calving, and reproductive problems [6].

3.3 BCS in mid-lactation

Scanes [21] perceived that cows need to realize a positive energy balance, so they have to recognize their BCS through undergoing a proper nutritional program.

Stage	Target body condition score
At calving	3.0
During service period	2.0–2.5
Mid-lactation	2.5–3.0
Drying-off	3.0

Table 1.
Recommended body condition score for Holstein Friesian and Jersey cows [22].

Lactation stage	DMI	BCS goal	BCS min	BCS max
Calving	0	3.5	3.25	3.75
Early lactation	1–30	3.0	2.75	3.25
Peak milk	31–100	2.75	2.5	3
Mid-lactation	101–200	3.00	2.75	3.25
Late lactation	201–300	3.25	3	3.75
Dry-off	>300	3.5	3.25	3.75
Dry	−60 to −1	3.5	3.25	3.75

Table 2.
Suggested body condition score for cows by stage of lactation [23].

BCS between 200 days of lactation and the date of dry-off should be between 2.75 and 3.50. However, the cows should be dried off when they have a BCS of 3.25–3.5. Therefore, the increase in BCS must occur during late lactation. In this period, the nutritional goals are to completely fulfill body fat reserves, without reaching an over-conditioning [7].

3.4 BCS in late lactation

Cows receive a nutritional program to maintain persistency of lactation without gaining excessive weight. Cows are dried off at a BCS of 3.5 [21]. Besides, Scanes [21] noted that nutrition is very important in late lactation and during the dry period. Both at drying-off and at calving, the BCS should be about 3.5.

As a result, Ohnstad and Jones et al. [22, 23] suggested BCS values for different stages of lactation as shown, respectively, in **Tables 1** and **2**.

4. Body condition score and reproduction

As it affects milk production, BCS affects also reproductive performance and fertility, which is negatively associated with milk production [24]. After calving, energy needs exceed energy intake of dry matter intake (DMI), which creates a negative energy balance (NEB). The NEB with some blood metabolites leads to the decline of some reproductive performance [24]. According to Froment [13], the consequences of a loss of BCS on reproduction are more obvious than those of the absolute value of BCS. Froment [13] showed a general tendency toward a deterioration of the reproduction results when this loss after calving increases. As long as this loss remains below 1 point, the influence of weight loss on reproduction remains modest. Conversely, when the loss of state exceeds 1.5 points, the degradation concerns all the reproduction parameters.

5. Negative energy balance and fertility

Negative energy balance (NEB) delays the first ovulation by limiting dominant follicle growth and estradiol production, through decreases in circulating insulin, IGF-1, and LH pulses [25, 26]. The persistence of a negative energy balance (NEB), corroborated by persistent loss of status, has a negative impact on the major sign of estrus: acceptance of overlap [13]. Butler [27] showed that greater NEB/BCS loss during the first 30 days postpartum delays first ovulation (**Figure 1**). The conception rate decreases with increased BCS loss. Cows remaining non-ovulatory after 50 days of lactation will have a higher risk of not becoming pregnant during lactation and, therefore, are more likely to be culled.

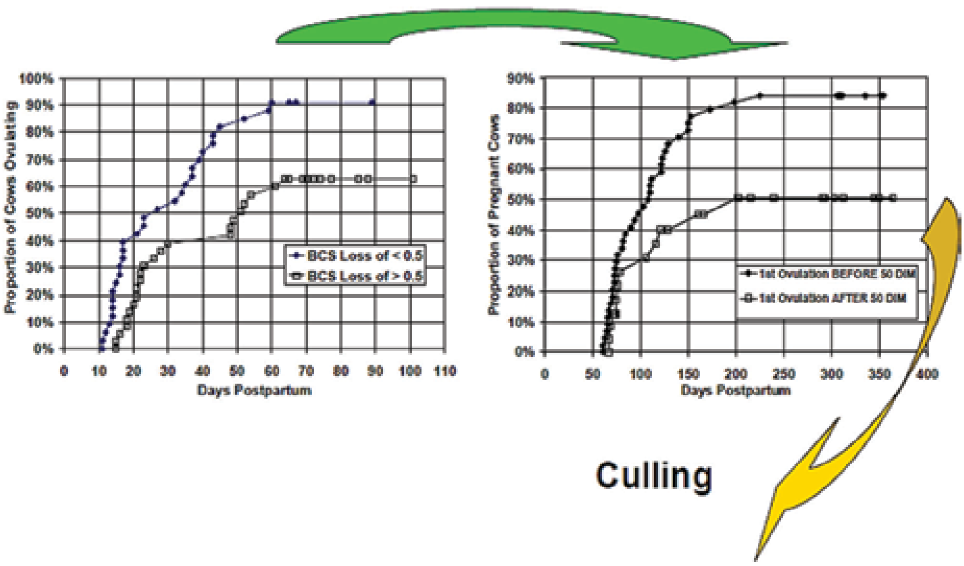

Figure 1.
Early NEB and BCS loss delays the first ovulation and relates to poor fertility/increased risk of culling [27].

6. Body condition score and cyclicity

Delayed recovery of ovarian activity is associated with poor body condition at calving. This situation appears when feed intakes in the last third of gestation are insufficient. For multiparous, practically there is no real effect of BCS at calving on the cyclicity, but a significant effect of the postpartum state loss was determined [13]. According to Freret et al. [28], cows that lost more than 1.5 points of their BCS between 0 and 60 days postpartum are characterized by no cyclicity or prolonged luteal phase.

Females with a high loss of BCS during the first month of lactation have less expression of estrus. Similarly, a loss of body condition greater than 1 point between 0 and 30 days, as well as insufficient BCS at calving, or a postpartum affection increased the average time to onset of the first estrus after calving [13]. Extreme body condition loss in the early lactation can cause irregular heats and longer time to the first ovulation and fail to conceive [29]. Butler [25] related the failure of ovulation of the first wave dominant follicle to high rates of NEFA and ketones in plasma and greater accumulation of triglycerides in the liver during the first 3 weeks of lactation.

7. Effects of BCS on pregnancy rate

López-Gatius et al. [30] reported that low BCS at parturition affects clearly pregnancy rate at the first AI. In their homogenous study, pregnancy rate at the first AI showed a significant neglect of about 10% in cows delivering in low BCS. This decrease of fertility is related to prolonged non-ovulatory intervals especially in thin cows that has a negative impact on the first service conception. In the study of López-Gatius et al. [30], the link between this loss and the success rate at the first AI is low for the category of cows losing little. The relationship becomes more obvious when the loss exceeds one point. In this same study, the loss of body condition has an impact especially on the number of days open (time interval between parturition and conception) especially for cows with a severe loss greater than 1 point. The number of days open of these animals increases by 10.6 days.

According to Hess et al. [31], cows with prolonged negative energy balance prepartum associated with reduced BCS at parturition have extended periods of anestrus [31]. López-Gatius et al. [30] suggested that BCS at parturition and at the first AI might be used as indicators of relationship between the nutritional status of the cow and the number of days open. Animals with good body condition at parturition have the reduced number of days open in comparison with cows having moderate or low body condition. Butler [25] showed that fat mobilization and loss of BCS causing a NEB are strongly associated with the length of the postpartum non-ovulatory period.

8. Body condition score, non-fertilization, early embryonic mortality, dystocia, and metabolism

In the study of Freret et al. [28], the BCS loss between 0 and 60 days postpartum had an effect on the NF-EEM rate: this rate is 41.7% for a loss greater than 1 point, against 29.8% when the loss is less than 1 point. Note that no relationship was observed between calving status score and reproductive performance after artificial insemination. According to Lopez-Gatius et al. [32], the risk of late embryonic mortality is multiplied by 2.4 for each unit of body condition lost during the first month of lactation.

The body condition score is again of interest, the animals in excessive fattening state (status score > 4 on a scale of 0–5) are more at risk of excess fat in the pelvic sector and hence a lower pelvic diameter and a higher risk of dystocia, especially for primiparous.

9. Body conditions score and metabolites

BCS change may have an effect on the biochemical level by changes in concentration of blood metabolites [33]. Malnutrition in dairy cows can influence many biochemical and physiological processes. Therefore, it perturbs the relation between the metabolic capacities of animals and causes metabolic disorders [34]. According to Bernabucci et al. [35] and Samanc et al. [36], dairy cows are exposed to several physiological challenges during the transition period, which might result in greater oxidative stress and metabolic disorders. Joźwik et al. [37] considered this period as the most critical period for dairy cows, with the highest incidence of metabolic diseases and infections caused by NEB. Consequently, during the early lactation, the liver of high-yielding dairy cows aims to correct the negative effect of NEB through undergoing extensive physiological and biochemical changes.

Duchacek et al. [38] showed the changes in milk fat and protein contents as well as the development of the BCS in the post-parturition period (**Figure 2**). The content of milk fat decreased from 4.89% at the beginning of lactation to 3.27% in week 7, and then it increased to 4.06% in weeks 14 and 16 of lactation. The protein content tended to decrease slightly until week 7, and then it increased until the end of the period observed.

Indeed, Duchacek et al. [38] demonstrated (**Figure 3**) the development of the fat to protein ratio used as an indicator of NEB. Cows with a more extensive loss of BCS produced more milk with a higher fat to protein ratio [20]. The maximum value of this ratio (1.62) was observed in the first week of lactation. Later, it decreased to 1.08 in week 7, and then it slightly increased and became stabilized around the value of 1.2.

Fat and labile protein reserves are mobilized during early lactation, but the ability to use body protein is limited in quantity and duration. For instance, estimates have ranged from 10 to 90 kg of fat and up to 24 kg of protein [39]. No further protein mobilization occurred after 5 weeks of lactation, whereas utilization of body fat continued until at least 12 weeks postpartum [40].

Cincovic et al. [41] showed that NEB in early lactation is associated with typical changes such as lower concentrations of glucose, insulin, and IGF-I but with higher concentrations of nonesterified-fatty acid (NEFA) and β-hydroxybutyrate (BHBA) resulted mainly from adipose tissue mobilization.

Furthermore, Van Dorland et al. [42] reported that typical changes during early lactation, associated with negative energy balance, are lower concentrations of glucose, insulin, IGF-I, and higher NEFA and BHBA concentrations. In this period, dairy cows experience several metabolic challenges characterized by the decrease in responsiveness of tissues to insulin [43] and increase in liver gluconeogenesis [44].

Locher et al. [45] recorded that cows with BCS > 3.5 in transition period are exposed to important fat mobilization which leads to elevated plasma NEFA in order to support the energy need. Circulating NEFA can be oxidized in the hepatocytes or exported as constituents of very-low-density lipoproteins (VLDL). Nevertheless, generally postpartum discharge of NEFA exceeds energy requirements and oxidation capabilities of the liver and leads to production of ketone bodies including BHBA and reesterification to triglycerides (TG) [45].

Akbar et al. [46] indicated that these triglycerides are stored in hepatocytes and involve fatty liver development, reduced metabolic function, health status, production and reproductive performance, as well as the incidence and severity

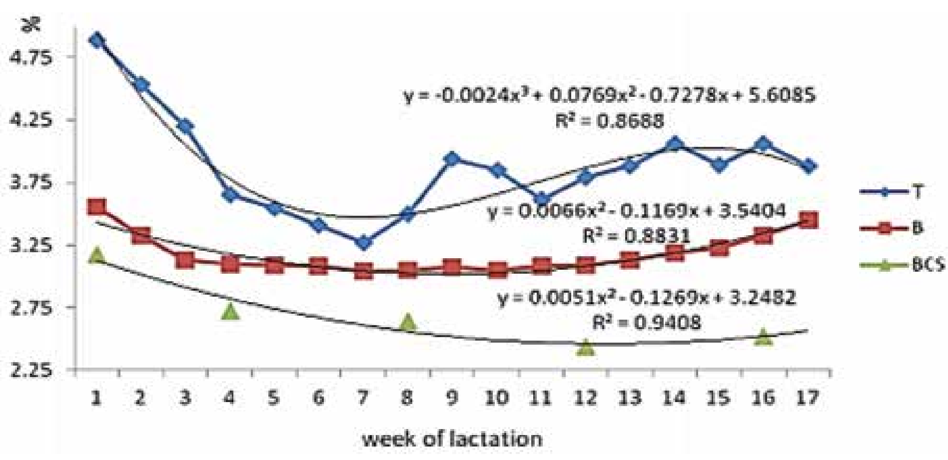

Figure 2.
Development of fat (B) and protein (T) content in milk and the BCS of cows during the first 17 weeks after calving [38].

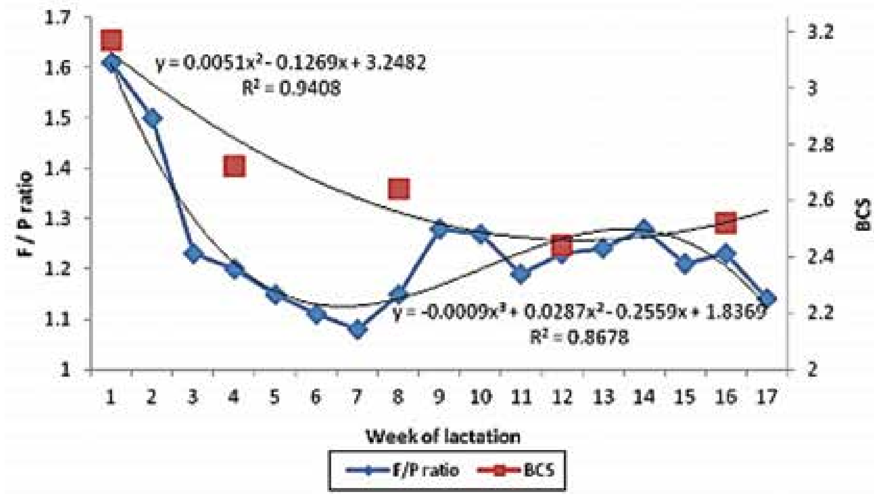

Figure 3.
Development of fat to protein ratio and BCS after calving [38].

of metabolic and infectious disorders. Gillund et al. [5] disclosed that high BCS at calving usually leads to an increased risk of ketosis. Both BCS at calving and BCS in early lactation could be generators of metabolic disorders [18].

10. Conclusions

The body condition scoring (BCS) is a practical and effective tool of management in dairy herds; it affects the productivity, reproduction, and health of the animal. Each stage of lactation has its recommended BCS; thereby, over and under conditioned cows may undergo a verity of risks. BCS has clear effects around calving and early lactation where energy intake exceeds energy needs which leads to NEB. Thus, most of researchers agree about a BCS around 3–3.5 at calving to limit undesirable results on lactation; cows with BCS out of this range are exposed to a decrease in milk production, changes in milk components such as milk fat and proteins, and even a decrease in persistence of lactation.

According to previous studies of BCS, certain complications such as reduced milk yield, increase in metabolic diseases, and delay in the postpartum estrus cycle of thin cows may occur due to a lack of usable body reserves in the early period of lactation. In addition, the risk of dystocia, early embryonic mortality, no cyclicity or prolonged luteal phase, increase in the number of days open, increase in metabolic diseases, and decrease in milk yield of fat cows could occur due to a loss of BCS more than 1 point.

Other studies investigated the effect of changes in BCS and BCS loss on metabolism and showed that NEB in early lactation is associated with typical changes such as lower plasma glucose due to the high demand for this substrate to synthesis lactose and decrease in concentrations of insulin and IGF-I. However, higher concentration of NEFA and BHBA is determined, which are related to body reserve mobilization in order to support early lactation demands.

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Conflict of interest

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Acronyms and abbreviations

TICB	Technical Institute of Cattle Breeding
NEB	negative energy balance
BCS	body condition score
LW	live weight
SCC	somatic cell count
SNF	solids-not-fat
DMI	dry matter intake
IGF-1	insulin growth factor-1
LH	luteinizing hormone
AI	artificial insemination
NF	non-fertilization
EEM	early embryonic mortality
BHBA	β-hydroxybutyrate
VLDL	very-low-density lipoproteins
TG	triglycerides

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Section 2

Modeling Lactation and Optimizing Milking

Chapter 6

Mathematical Modeling of Lactation Curves: A Review of Parametric Models

Mahdi Bouallegue and Naceur M'Hamdi

Abstract

The mathematical representation of milk production against time represents one of the most successful applications of mathematical modeling in agriculture. Models provide summary information, which is useful in making management and breeding decisions. Several empirical mathematical functions have been proposed to describe the lactation curve of dairy cattle differing in mathematical properties, in the number of parameters and in their degree of relationships with the main features of a typical lactation pattern, such as peak yield, time at peak and persistency. This review gives an overview of the parametric models used to fit of lactation curves in dairy cattle. Parametric models are those that found large application to fit the lactation curves, basically due to their limited mathematical complexity, and their abilities to fit a large kind of curves. Models to describe the lactation curve have been classified into two main groups: linear and nonlinear models. Nonlinear parametric functions have represented the preferred tools for modeling lactation curves with the main aim of predicting yields and parameters describing the shape of the curve in addition to important parameters such as peak yield and persistency. Nonlinear models need iterative techniques to be solved. Different iterative methods frequently employed in nonlinear regression models are Marquardt, Newton, Gauss and Dud. Wood model was the most popular parametric model with the largest application can be found in the immediate and easy understanding of relationships between its parameters and main curvatures of the lactation pattern.

Keywords: mathematical modeling, parametric models, nonlinear regression, goodness of fit, shape of lactation curve

1. Introduction

The lactation curves provide useful information for selection programs and for developing suitable management decisions and production strategies at the farm level. So, the modeling of the lactation curve is not a new research topic, the first reference of a model of lactation curve is attributed to Brody et al. [1]. Because of computational difficulties, and the limitations of computer means, early models of lactation curves based on simple logarithmic transformations of exponentials, polynomials, and other linear functions were developed [2]. Mathematical models are able to predict milk yields. The application of these models on the first lactations data can provide important predictive information. Indeed, predicting the evolution of milk production at the individual or herd level is a powerful tool for managing herd performance. Linear and nonlinear methods were used to estimate the parameters of production peak and inclining and declining phases of milk production during lactation [3]. The incomplete gamma function or Wood function proved relatively powerful in fitting the observed daily milk yield [4]. According to Wood [5], knowledge of the parameters of lactation curves can predict total production from a single control, regarding the number of controls available for prediction. In recent years lactation curve fitting functions have been implemented in dairy farm management software [6]. Moreover, lactation curve modeling is a tool for monitoring individual yields, feeding planning, early detection of diseases before clinical signs appear, and selecting animals for breeding [7]. Another frequently advanced interest in curve production modeling is the measure of persistency. The selection of animals with higher persistency (low decrease of production during the second phase of lactation) is interesting. Thus, cows showing higher yield at the peak of production followed by rapid decline are undesirable and will be easily detected and identified using the adjusted lactation curve. The cost of milk production depends largely on the lactation persistency. The unexpected drop in production after the peak increases the cost of production, because of production inequitably along the lactation [8]. Economically, cows with flat lactation curves are more persistent and produce milk at lower cost [9]. Indeed, the incidence of metabolic and reproductive disorders, arising from the physiological stress of high milk production, would be lowered. The animal may have a more stable diet, favoring in particular the proportion of fodder in the ration and thus reducing production costs [8]. Thanks to these interests and utilities of the lactation curve, the choice of one or more appropriate mathematical functions capable of effectively describing the evolution of milk production throughout lactation is a crucial point. Thus, the interest of the study of the lactation curve is reflected by a multiplicity of mathematical models. Really, the mathematical representation of milk production during the lactation period is one of the most successful applications of mathematical modeling in agriculture [10]. The choice of a model as well as the quantity and the quality of the information necessary for its estimation must, therefore, be reasoned according to the desired use. For example, for studies of the effect of environmental factors on the shape of the lactation curve and the estimation of the classical parameters of the curve by adjusting the data sets classified by groups of animals according to a well-defined factor, a simple model with fewer parameters can meet these objectives. The selection of a mathematical function must, therefore, be based on the ease of parameter estimation, its versatility (possible modeling of the different constituents of the milk and not just the quantity of milk), and the quality of the adjustment. Guo and Swalve [11] recommend the use of the model with the lowest possible number of parameters. The availability of data collected through individual lactation and the development of genetic evaluation methods based on elementary controls, as well as the evolution of the specific requirements of the dairy cattle industry, have oriented the interest of modelers toward more linear functions flexible and general, such as polynomials or splines [12].

2. Description of the standard lactation curve

Milk production evolves during lactation following a cycle that is similar in all dairy females and usually characterized by two different phases: an ascending phase from parturition to peak production (the maximum production) and a downward phase, from this peak to the dry period. The slope of this phase represents the persistency of lactation [13]. Knight and Wilde [14] explain that this phenomenon is related to the exponential increase in the volume of secretory cells, during gestation due to the phenomenon of hyperplasia (proliferation of cells) and between calving and the peak of lactation by hypertrophy (intensification of their activity). The descending phase of lactation is the longest during which the milk secretion gradually decreases until dry up. This second phase is explained by the involution of secretory cells but especially by the fall of their numbers. The phenotypic expression of these biological processes is represented by standard or typical form (**Figure 1**) of the lactation curve, obtained by plotting on the abscissa the time elapsed since calving and on the ordinate the corresponding daily production [15, 16].

The general appearance of this curve is relatively constant between many domestic species. The lactation curve can be characterized by a number of parameters [13]:

The length of lactation defined by the subscale interval. In most studies concerning lactation curve modeling, this duration is standardized at an interval of 5–305 days. Animals with lactation times greater than 305 days are considered lactations of 305 days [12]. Currently in most countries, several cows have prolonged lactations beyond 305 days.

Total production obtained by combining daily milk production. Total milk yield is considered to be of high economic importance [18]. Total production is also the area under the lactation curve, which mathematically translates as the integral of a mathematical function over the interval of lactation duration.

Initial production (y 0) estimated by the average of the productions of the 4th, 5th, and 6th postpartum days [13].

The growth rate in the ascending phase. This phase ranges from calving to maximum production. Masselin et al. [13] expresses the growth rate of the increasing phase by the difference between the maximum (ym) and the initial production (y0).

The maximum daily production (ym) and the date at which this maximum (tp) is observed.

The peak of production is the highest yield of lactation, and its date is expressed in week (Wood, 1967) or in day. When a mathematical model of adjustment of the lactation curve is available, parameters y_m and t_p are obtained, respectively, as ordinate and abscissa of the point where the derivative of the function of adjustment of the curve $\left(\frac{dy\,(t)}{dt}\right)$ is equal to 0.

The persistency of production in decreasing phase. It is most often identified with a measure of decay of production in a period of time. It is defined as the ability of a cow to maintain milk production after the peak. Assuming uniform nutrition and

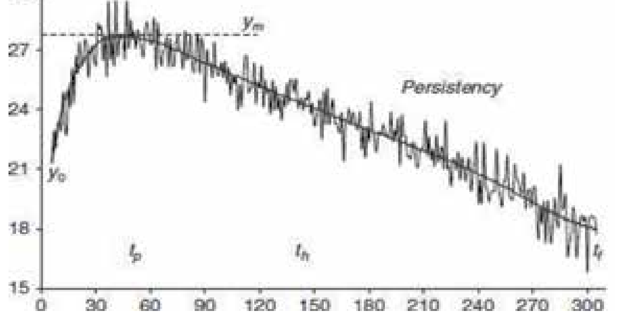

Figure 1.
Lactation curve for dairy cattle (observed and adjusted yields) [17]. With y0 = initial yield; ym = yield at the peak of production; tp = peak time; th = time of mid-lactation; and tf = time of end of lactation.

management conditions, the post-peak decline rate is calculated as the proportion of the decline in milk yield from the previous month, usually ranging from 4 to 9% [14].

3. Mathematical modeling of lactation curve

The interest of the lactation curve is reflected by a variety of mathematical models proposed to describe or predict it. These models are appreciated and used because they have a simple biological or economic interpretation [19].

3.1 Empirical models

An empirical model has a theory that refers only to the level of reality for which the phenomenon being considered is expressed. These so-called empirical models (models based exclusively on experience and observation and not on theory), whether linear or not linear, represent the huge majority of studies published in the bibliography [12]. In fact, empirical models have found great application in different fields of animal science, mainly because of their limited mathematical complexity. Most of them permit to estimate certain classic characteristics of the curve (date and level of the peak of production, persistency, and total production). Many empirical mathematical functions have been proposed to describe the lactation curve of dairy cattle [16, 20]. These functions differ in their mathematical properties, the number of parameters, and their degree of relationship to the main characteristics of a typical lactation structure, such as yield at peak time, persistency, and total yield. Nonlinear parametric models have been a preferred tool for modeling mean curves of homogeneous animal groups [12].

3.2 Parametric curves

To describe the temporal evolution of milk secretion (lactation curve), scientists generally use parametric curves where the variation over time is modeled using linear or nonlinear functions. Most of the mathematical functions proposed to fit lactation curves in dairy cattle are primarily aimed at describing the phenomenon of milk secretion. Their basic assumption is that lactation is characterized by a continuous and deterministic component with an increasing phase to a maximum, followed by a decreasing slope [12]. The mathematical tool used in this approach can be represented by an analytic function of general time:

$$Y = f(t) + \varepsilon \tag{1}$$

where Y is often the daily output obtained on the day of control t; $f(t)$ is a continuous function, differentiable over the interval represented by the duration of lactation; and ε is the random residual.

The use of parametric models has several advantages. Indeed, these models allow algebraically to calculate characteristic parameters of the curve. For example, the yield and the date of the peak of production are obtained, respectively, as ordinate and abscissa of the point where the first derivative of the function $\left(\frac{df(t)}{dt}\right)$ is equal to 0.

Production between two dates is obtained by calculating the integral of $f(t)$ over this time interval. The total production also corresponds to the integral of the lactation curve over the duration of the lactation.

Another advantage of parametric models is that they summarize distribution characteristics through a small number of parameters (in the majority of cases, three parameters). Rekaya et al. [21] highlighted that a function with a minimum number of parameters and a significant biological interpretation is the most desirable. Although increasing the number of parameters in the model improves the quality of fit for some functions, interpreting the parameters of the most complex models is difficult, and, in many cases, it is impossible to connect them with the classic characteristics of the lactation curve [13].

3.3 Exponential functions

Among the parametric models, lactation curves adjusted by exponential functions or integrating an exponential component into the model formula were widely used. The first attempt to develop a mathematical model to describe the lactation curve dates back to 1923. Brody et al. [1] used an exponential function in the following form:

$$Y_t = a \exp(-ct) \tag{2}$$

This model has been adjusted to monthly lactation yields. Its expression highlights the scaling factor for adjusting production to initial level a and the c parameter associated with the descending phase of the lactation curve and highlighted as a measure of persistency. Although this model is a good attempt to describe the descending phase of the lactation curve, it does not model the growth rate in the ascending phase to reach the peak of lactation. In order to overcome this limitation, Brody et al. [22] presented an improved version of their model, which takes into account the increase in milk yield until production maximum by incorporating an exponential decline function into the model:

$$Y_t = a \exp(-bt) - a \exp(-ct) \tag{3}$$

While this is a great improvement over the first model, Cobby and Le Du [23] reported that this model underestimates milk yield in the middle of lactation and overestimates milk yield at the end of lactation. This model was followed by an exponential parabolic function introduced by Sikka [24] for modeling milk yield:

$$Y_t = a \exp\left(bt - ct^2\right) \tag{4}$$

This model provided a good fit for lactation curves of primiparous cows, but it was less effective for multiparous cows, resulting in a bell-shaped curve that does not respect the regularity of the lactation curve around peak production. Then, numerous proposals were made to improve these aspects. Fischer [25] attempted to improve model 3 by replacing the exponential decline integrated in this model by means of a linear decline:

$$Y_t = a - bt - a \exp(-ct) \tag{5}$$

This model underestimated the maximum milk yield and also resulted in a relatively early estimate of the peak date [26]. The individuality of this model is that the ratio *a/b* estimates the duration of lactation. Vujicic and Bacic [27] attempted to modify model 2:

$$Y_t = t\, c^{-a} \exp(-ct) \tag{6}$$

This model seems to be the first attempt to develop a model that varies both directly and exponentially over time. The disadvantage of this model is that it does not consider the initial evolution to the peak of production. Since the abovementioned exponential models do not correctly translate the ascendant phase of the lactation curve, Wood [28] proposed to adjust the entire curve by an incomplete gamma-type function:

$$Y_t = at^b \exp(-ct) \tag{7}$$

The incomplete gamma function is probably the most popular parametric model of the lactation curve. It generates the standard form of the lactation curve as the product of a constant, a power function, and an exponential decline function [12]. The disjunction of the Wood equation in its components emphasizes the direct relation of its parameters with the main elements of the shape of the lactation curve. In this expression, the power function *tb* permits to integrate the ascending phase of the lactation curve, whereas the exponential term accounts for the downward phase. For these reasons, Wood [28] interpreted parameters *b* and *c* as indices of growth intensity and output decline, respectively; the function *tb exp (−ct)* thus appears as the form factor of the curve [13]. Parameter *a* is then the scale factor of the level of production, which Wood [28] associates with the average production level of the beginning of lactation. Wood [29] tried to justify the use of model 7 from a physiological point of view, but does not interpret parameters *b* and *c* from a practical biological point of view. Parameter *b* is an index of a cow's capacity for the relevant use of energy to produce milk, but mathematically according to Wood [29], parameter *b* represents the rate of growth of production to yield maximal, and parameter *c* alternatively represents the rate of decline after the peak of lactation. Cobby and Le Du [23] argued that these interpretations of parameters *b* and *c* are fairly simplified and may be erroneous. Wood [30, 31] sought to interpret parameters *a*, *b*, and *c* as a function of the energy flows in the body. According to its approach, the parameter would translate a potential of production which is the function of the intrinsic capacity of secretion of the udder, the level of the mobilizable reserves, and the capacities of ingestion and digestion of the animal. On the other hand, the expression *tb* is explained by the fact that all the secretory cells would not be functional immediately after calving. According to Masselin et al. [13], the last aspect should rather be interpreted as the growth of the body's ability to ensure gluconeogenesis to synthesize lactose, which is the main element determining the exit of water from milk. Finally, parameter *c* would integrate the progressive reduction of the contribution of body reserves to the milk secretion and the exponential decline of the number of secretory cells. Several critics have been reported in Model 7. Cobby and Le Du [23] reported an overestimation of early lactation production and underestimation of peak lactation. Dhanoa [32] reported problems of strong correlations between the estimated parameters. Another reproach has been given to the Wood model that by construction, calving day production is constrained to be zero. This is not real in most mammal species. However, Tozer, and Huffaker [33] have indicated that a cow produces colostrum just after calving, which has no economic value, so considering zero milk yield after calving is not a significant problem. Rowlands et al. [26] reported that the Wood curve does not provide good consistency with the data collected on higher dairy cows at the peak of lactation. According to Macciotta et al. [12], Wood's model limitations are an overestimation of milk production per day in the first part of the curve and an underestimation around and after the peak of lactation. These weaknesses have been reported by some authors [34, 35] primarily because of the multiplicative structure, and the model is characterized by higher correlation between its parameters (ranging from 0.70 to 0.90, [12]) which results in higher sensitivity to data distribution [2].

Despite the limits reported, the Wood model remains the most used function for modeling lactation curves [35]. In addition, it has been used to describe traits other than milk yield, such as fatty acids [37], and it has also been used for adjustment of extended lactations [34, 36]. Many other models have been reported in the literature especially after the appearance of critics of Wood's model. To anticipate these restrictions, many authors have proposed improvements to Wood's model in order to increase its flexibility. As a result, several derivatives of Wood's function have appeared while noting improvements in the modeling of the lactation curve. Beever et al. [20] summarizes the improvements made by these derivatives in greater flexibility in modeling curve shapes and in improving the mathematical properties of the model by decreasing the correlation between model parameters [32]. Cobby and Le Du [23] reported that milk yield after the peak of production declines at a constant rate and proposed a modification of Wood's gamma function, substituting the power function (tb) for an asymptotic function of the type exp. (t^b) and replacing the first exponential function of the equation obtained by the function of Gaines resulting in a model of the form:

$$Y_t = a - bt - a\exp(-ct) \tag{8}$$

The advantage of this model over that of Wood [28] is that declines in milk production are modeled exponentially [16]. This model allows a better adjustment of the initial phase of the lactation curve with a good estimate of peak production [26]. Rowlands et al. [26] compared models 3, 7, and 8 and concluded that model 8 describes the initial evolution of milk yield up to 5 weeks better than model 7. They also observed that models 7 and 8 slightly underestimated the initial yield and model 3 slightly overestimated the peak of lactation. Model 7 provided the best position of the peak yield date. According to Olori et al. [38], this model has a parameter that cannot be estimated by linear regression, and this limits its use in practice. Dhanoa [32] proposed a slightly different writing of Wood's model:

$$Y_t = at^{bc}\exp(-ct) \tag{9}$$

Such model reduces the correlations between the parameters of the curve in many cases. In addition, this model provides, with parameter b, a direct estimate of the peak lactation date. In an attempt to include a season effect in the Wood model, Goodall [39] proposed the introduction of a categorical variable D which takes the value 0 from the period October to March and the value 1 from April to September, resulting in the following model:

$$Y_t = at^b\exp(-ct + dD) \tag{10}$$

where D estimates the effect of season. This change takes into account the quantitative estimation of the effect of seasonal changes.

Another modification of Wood's function was attempted by Jenkins and Ferrell [40] (1984) through placing the exponent of t, which is the value of b in Wood's model equal to 1:

$$Y_t = at\exp(-ct) \tag{11}$$

This model has its limits since curve fitting results have shown that evolution to maximum yield is relatively slow [41]. Based on the model of Cobby and Le Du [23], Wilmink [42] proposed a linear model to describe the lactation curve:

$$Y_t = a + b\ \exp(-kt) + ct \tag{12}$$

According to Wilmink [42], parameter *k* is related to the peak of lactation time and usually constitutes a fixed value, derived from a preliminary analysis of average production, implying that the model has only three parameters to estimate. Brotherstone et al. [4] emphasized the importance of parameter *k* in the ability of the Wilmink model to model daily production in early lactation. In an attempt to overcome underestimation of peak yield and overestimation of yield in the decreasing phase of lactation that results from the use of the Wood model, Cappio-Borlino et al. [43] proposed a nonlinear modification of the Wood model in the following form:

$$Y_t = \mathrm{a}\ \mathrm{t}^{\mathrm{b}\ \exp(-\mathrm{ct})} \tag{13}$$

while this proposal is more complex than Wood's equation, this model reduces the extent of underestimation at the beginning of lactation and overestimation at the final stage of lactation. Franci et al. [44] have successfully used to adjust the lactation curves of dairy ewes, characterized by a rapid increase in milk yield to the peak of lactation.

4. Linear adjustment models

Dairy production can be considered as a linear combination of the time since calving [13]. Gaines [18] developed a simple linear first-degree model to measure the persistency:

$$Y_t = a - bt \tag{14}$$

In this model, parameter *a* is an estimator of initial production, and *b* was proposed as a direct measure of absolute persistency and assumed to be constant during lactation. This model has been compared to other proposals [45], and it has been used to compare feeding strategies of dairy cows with their performance [46].

After the application of this simple linear model, several researchers have attempted to adapt the parabolic or quadratic model whose general form is as follows:

$$y_t = a + bt + ct^2 \tag{15}$$

Dave [47] used a quadratic form for modeling the lactation curve of water buffalo in first lactations:

$$y_t = a + bt - ct^2 \tag{16}$$

Sauvant and Fehr [48] sought to adjust lactation curves of dairy goats by a third-degree polynomial:

$$y_t = a + bt + ct^2 + dt^3 \tag{17}$$

In this model, the interest of the presence of the term of degree 3 with respect to the parabolic model is the introduction of an asymmetry in the curve. The limits of this model are at the level of its parameters *b*, *c*, and *d* which have no biological or zootechnical sense [13]. Dag et al. [49] reported that the cubic model best matched the data collected in Awassi ewes and allowed for an appropriate description of the shape of the lactation curve. These authors also indicated that the total milk yield estimated by the cubic model was similar to that obtained by the Fleischmann method.

Other higher-degree polynomials have been used to model milk production. With these models, the parameters remain simple to estimate. However, interpretation and biological significance remain a major difficulty. In addition, the adjustments obtained by some authors are satisfactory, but as indicated by Masselin et al. [13], they cover a portion of the lactation curve. Nelder [50] suggested that if biological responses over time were to be modeled with quadratic regression, then it was better to first perform an inverse data transformation. However, a polynomial of the second order is unbounded and tends to be symmetrical with respect to its stationary point, while the characteristic lactation curve is not symmetrical with respect to the asymptote. To obtain an asymmetry, it will be necessary to estimate more parameters. An inverse quadratic polynomial is bounded and generally non-negative and has no integrated symmetry. As a result of these suggestions, Nelder [50] proposed a polynomial function (called the inverse function) to adjust the response curves in multifactorial experiments, particularly in the context of modeling lactation curves. Day t production is described as follows:

$$Y_t = t/a + bt + ct^2 \tag{18}$$

Yadav et al. [51] were the first to value this design to model the lactation curve of dairy cattle and found it appropriate. According to Batra [52], this model gave a good fit for low-yielding lactations with an early lactation peak. Based on the coefficient R^2, the same author observed that the function 18 gives a better fit than the gamma function when weekly milk control data were used. This function was also greater to parabolic and exponential Wood models for modeling average lactation curves using weekly data from Hariana cows [53]. Olori et al. [38] showed that model 18 underestimates the milk yield around the peak and overestimates it immediately afterwards. An inverse transformation of data as proposed by Nelder [50] to obtain the properties will allow to model the lactation curve with a quadratic polynomial. Singh and Gopal [54] increased the number of parameters by including the term *Log (t)* as an additional co-variable. The introduction of the logarithm breaks the symmetry of the parabolic model [13]. Therefore, these authors have proposed two new models: linear cum log model:

$$Y_t = a - b\,t + c\,Log(t) \tag{19}$$

and quadratic cum log model:

$$Y_t = a + b\,t + c\,t^2 + d\,Log(t) \tag{20}$$

These authors indicated that these models were superior to the Wood models and the inverse polynomial when fitted to the bi-weekly controlled performance data. At the same time as one of the limits, these models are undefined at $t = 0$, because $Log\ (t) = \infty$ [16], although these models have not been widely applied. They have contributed as support for the development of other models. Ali and Schaeffer [55] added the term $e\ (Log(t))^2$ to the second model of Singh and Gopal [54] and proposed the use of a five-variable linear model:

$$y_t = a + bX + cX^2 + f\log(1/X) + e(\log(1/X))^2 \tag{21}$$

where $X = t$ / *length of lactation*, a is a parameter associated with the peak of production, and f and e are associated with the upward part of the production curve and b and c with the descending part.

Linear model has a greater number of coefficients that allow the adjustment of large forms, while its parameters do not have a technical and biological meaning [12]. Two mathematical models (Ali and Schaeffer and Wilmink) have been used successfully to adjust individual curves [2, 56]. Both models have also been implemented in earlier versions of random regression models [57–59]. A potential problem is raised by the author authors of model 21, and it is that the parameters of the regression model are strongly correlated, which can strongly limit its use. However, the results reported in several studies using this model are contradictory. According to Jamrozik et al. [60], this model gives results very similar to those obtained with the Wilmink model, despite the fact that the Ali and Schaeffer model includes additional parameters. Guo and Swalve [11, 61] have found that this model is less efficient than others, notably that of Wilmink. Concerning the limits of this model, Macciotta et al. [56] found very strong correlations in absolute values (from 0.85 to 0.99) of lactation curve coefficients with a standard form [62]. The correlations obtained by these authors are much higher than those reported by Ali and Schaeffer [55]. Olori et al. [38] compared different functions and showed that the function of Ali and Schaeffer was slightly better than that of Wilmink. Quinn et al. [63] reported that this model is inappropriate for the description of milk component lactation curve (percentages of fat and protein). Schaeffer and Dekkers [64] proposed to adjust the lactation curves by a logarithmic model:

$$Y_t = a + b \log(305/t) + ct \tag{22}$$

Guo and Swalve [11] introduced the mixed logarithmic model:

$$y_t = a + bt^{1/2} + c \ \ log(t) \tag{23}$$

This model can be considered as inspired by model 19 suggested by Singh and Gopal [54], substituting time t for the square root of t in the second term of the model. However, this model tends to underestimate peak yield, while overestimating post-peak yield [38]. Catillo et al. [65] reported that this model was effective in estimating lactation curves and milk production characteristics of Italian water buffaloes.

5. Other models

For a competitive model, Papajcsik and Bodero [66] have introduced trigonometric functions and combined functions with increasing variation such as t^b,$1 - \exp(-t)$, $Log(t)$, and $\arctan(t)$ and decreasing functions such as, and, where *arc-tan* and *cosh*, respectively, refer to the *arc-tangent* trigonometric function and the hyperbolic cosine function. These reflections gave birth to the following six models:

$$Y_t = at^b / \cosh(ct) \tag{24}$$

$$Y_t = a(1 - \exp(-bt) / \cosh(ct) \tag{25}$$

$$Y_t = a \arctan(bt) / \cosh(ct) \tag{26}$$

$$Y_t = a\,Log(b\,t)\exp(-c\,t) \tag{27}$$

$$Y_t = a\;Log(b\,t)/\cosh(c\,t) \tag{28}$$

$$Y_t = a\arctan(b\,t)\exp(-ct) \tag{29}$$

The authors compared the effectiveness of 20 different mathematical models, including these six models, and concluded that model 24 and the Wood model better fit the data of the Holstein cows. Although, this study is cited in most of the following studies as an advantage for Wood's function over the model proposed, but we note that this work directs the thinking of modelers to the possibility of the use of complex mathematical models and particularly of trigonometric mathematical functions. An approach was introduced by Grossman and Koops [67] who proposed that lactation could be visualized as a multiphase biological process, that is, visualizing lactation as a two-step process divided in a slant until the peak of lactation is established as the first phase and the progressive decrease in production after the peak as a second phase. The suggested multiphasic logistic function determines the total milk yield by obtaining the sum of the yield resulting from each phase of lactation:

$$Y_t = \sum_{i=1}^{n}\left\{a_i b_i\left[1 - \tanh^2(b_i(t - c_i))\right]\right\} \tag{30}$$

where n is the number of lactation phases considered and *tanh* is the hyperbolic tangent function. For each phase i, the maximum yield is equal to ai and bi and occurs at time ci. The duration of each phase is associated with $2b_i^{-1}$ which represents the time required to obtain 75% of the total asymptotic production during this phase. This model has been applied in two-phase or three-phase model, with better adjustment resulting from the three-phase model with a low correlation between residues. For a two-phase model, the first phase could be considered the peak phase because of its proximity to the general spike and its short duration. Likewise, the second phase must be studied because it corresponds to the phase of "persistency." This model has been criticized by Rook et al. [68] who reported lack of justification for lactation to be visualized as a multiphase process. Despite the wide range of models available to adjust lactation curves, the situation cannot be considered satisfactory because of the importance of the remarks that can be made to most of the proposed models. In this regard, an almost general reproach of the comparison of the adjustment quality of these models is the insufficiency of the evaluation of the adjustment's quality. Indeed, the coefficient of determination, which is only a very partial element of this evaluation, is one of the main parameters used for this purpose. Recent studies incorporate residue variation, and the diversification of the results in this respect according to the data used prevents the publication of standard criteria for comparing the quality of the residues of fit models. Olori et al. [38] adjusted data from a single, uniformly managed herd to five mathematical models. They concluded that the relevance of the empirical models of the lactation curve does not depend on the mathematical form of function but on the biological nature of lactation. We notice that the adjusted character remains in most cases the raw milk production. So, it seemed logical to compare the quality of the models for the quantitative level of production.

5.1 Methods applied for adjusting the lactation curve

Nonlinear and linear estimation methods have been used to adjust lactation curves, where the method employed is determined by the nature of the model to be used. Some models can be developed using a nonlinear and linear estimation at the same time, such as the polynomial regression model of Ali and Schaeffer [55]. Others can be transformed into linear models. Wood [28] has already noted that the gamma function can be converted into a simple linear regression model by performing a logarithmic transformation to determine the initial values of the parameters *a*, *b*, and *c* by means of a least square's estimation. Congleton and Everett [69] reported that the adjustment of the incomplete gamma function with linear regression after a logarithmic transformation has the advantage of requiring a minimum of computational machine time. Due to the large number of lactations analyzed, parameter estimation is obtained by linear regression rather than an iterative nonlinear technique. In linear models the parameters are linear functions of the lactation day, and the least square estimates of the parameters can always be obtained analytically by a simple linear regression. On the other hand, nonlinear models such as the Wilmink function can only be solved by numerical methods following iterative optimization procedures. Adjusting data with a nonlinear regression model has specific advantages. Indeed, nonlinear models are often derived on the basis of biological and/or physical considerations. Thus, the parameters of a nonlinear model usually have direct interpretation in terms of the processes studied. In addition, the main advantage of nonlinear regression compared to other curve fitting procedures is the wide range of functions that can be adjusted. The objective in nonlinear regression is to obtain estimates of the parameters that minimize the residual effects, measured as the sum of the squares of the distances of the data points on the curve [17].

To estimate the parameters following an iterative procedure, it is necessary to have those initial values, which will be subjected to successive iterations. These initial values are adjusted, and the sum of the squares of the residues is reduced significantly to each iteration. The process of estimating the parameters continues until a convergence criterion is met, accepting that from this point on, a negligible or no improvement in data fit is possible [17]. A major difficulty of this procedure is to enter the initial values of the model parameters. If the pre-estimates are not correct, the process may not converge to the minimum of the sum of error squares. Moreover, it is not always possible to know if the process converges toward the best estimate of the minimum of the sum of error squares [70]. The initial values should be reasonably close to the estimates of parameters that are still unknown if the optimization procedure cannot converge. The consequence of a bad choice of the initial parameters is the obtaining of low values of the coefficient of determination, the standard errors that are high [71], and consequently a poor quality of adjustment of the model to data. Fadel [71] discussed a technique for identifying appropriate estimates of initial parameter values using the nonlinear procedure of the statistical analysis system (SAS, PROC NLIN). This technique was illustrated via a segmented nonlinear model with four parameters to estimate (*b1*, *b2*, *b3*, and *b4*), frequently used for the modeling of fiber digestion as a function of fermentation time (*t*):

$$\begin{cases} f_1(t) = b1 + b4, \text{si } t \leq b3 \\ f_2(t) = b1 \exp\left[-b2\,(t\text{-}b3)\right] + b4, \text{si } t > b3 \end{cases} \tag{31}$$

The principle of this technique consists in using a network of values for *b3* (example of 2 to 6 per unit of 0.1) with fixed estimates of the parameters *b1*, *b2*, and *b4*. The SAS program generates a set of data sets for each proposed value. Then *b1*, *b2*, and *b4* will be calculated for each estimate of *b3* of the proposed network. The combination of the parameters estimated from the solution with the smallest value of the sum of the squares of the residuals will be used as initial values for the final analysis [71].

Different iterative methods such as Marquardt, Gauss-Newton, and Does not Use Derivatives (DUD) are frequently used in nonlinear regression models. The simplest method, known as the DUD, does not require the specification of the partial derivatives with respect to the parameters of the mathematical model. It is an algorithm that brings the derivatives closer by differences. However, it is important to note that this algorithm does not give good estimates especially when the parameters are strongly correlated. Another method commonly used in nonlinear regression is the iterative Gauss-Newton method also available in SAS. The algorithm of this technique is based on Taylor series development near the initial parameter values [67]. Generally, Marquardt's nonlinear regression was the most commonly used method to adjust lactation curves using nonlinear models [34]. The Marquardt method, which follows an intermediate path between the Gauss-Newton (Taylor series method) and Newton (second derivative) methods, was often considered better to achieve convergence when the parameter estimates were strongly correlated [34].

6. Lactation curve of milk constituents

Lactation curves relating milk yield and milk constituents would be considered for influencing different of lactation curves. However, it is necessary to consider factors that influence milk yield and milk constituents, for example, different genetic, effect of climate, and nutrition. These factors will cause changes in milk compositions and milk yield which may be the data for prediction of the lactation curve and lactation persistency [72]. This link has already been studied at the phenotypic and genetic level. The genetic correlations of milk yield with negative percent of fat and protein were negative (0.25 and 0.27, respectively), and the same sign was observed at the phenotypic level (0.28 and 0.39, respectively) [72]. The ordinary description of milk secretion refers to the appearance of changes in milk composition during lactation, i.e., the decrease in milk yield is accompanied by an increase in fat and protein contents. Milk composition can be used as a diagnostic and monitoring tool in nutritional assessment [73]. Several studies have shown a correlation between energy levels and milk composition using different traits such

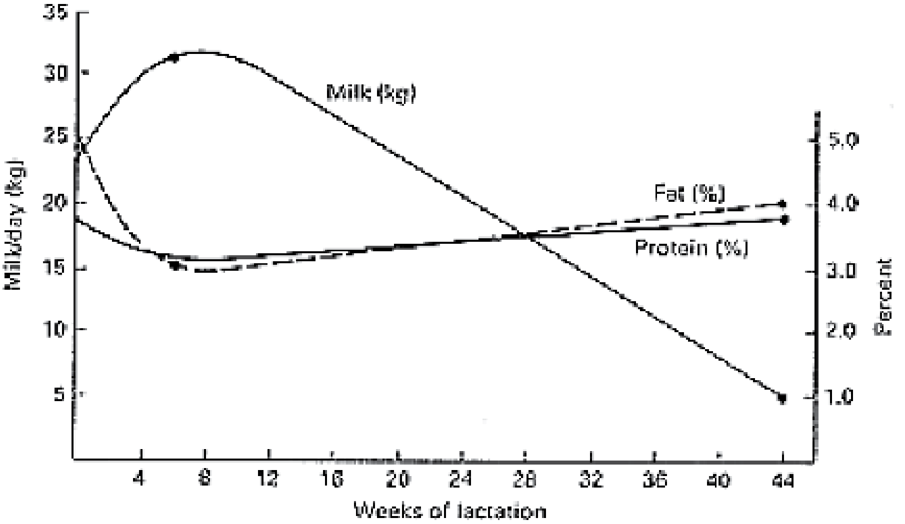

Figure 2.
Lactation curves for milk production, percent fat, and percent milk protein (Wood, 1976).

as fat/protein ratio (FPR), protein/fat ratio, fat/lactose ratio [74]. Higher FPR values are associated with a decrease in dry matter intake and an increase in fat mobilization on the negative energy balance phase after calving [73]. Thus, FPR changes in milk may be an indication of a cow's ability to adapt to the requirements of milk production and postpartum reproductive efficiency [75]. The richness of the milk (fat and protein contents) follows an inverse curve to that of the milk secretion, mainly because of the effect of the dilution. It decreases rapidly during the first weeks, stabilizes at a minimal level (nadir point), and rises again due to less dilution. The relative composition of milk constituents changes profoundly during the first days after parturition. The concentration of immunoglobulins decreases rapidly after parturition in favor of caseins. The nadir point of the fat concentration curve is reached approximately 3 weeks after peak lactation of milk yield, while that of protein is established near the peak of lactation [15]. As a result, milk fat and protein are often modeled with the same functions as those used to model milk production, provided that they can take a convex form. Most of the models generated for the description of the lactation curve focused only on milk yield, although the first reference found on the adjustment of lactation curve adapted to milk composition was that of Wood [28] who studied its seasonal variation. **Figure 2** illustrates the shape of the lactation curve of milk yield and its fat and protein composition, expressed as a percentage and adjusted by the incomplete gamma function of Wood.

7. Conclusion

Mathematical models allow the lactation curve to be represented in terms of a set of parameters to be estimated. Various models have been used to study the lactation in dairy cattle. Each function has advantages and disadvantages. Parametric models such as Wood and Wilmink models have several advantages. Indeed, parametric models offer the possibility to calculate primary and secondary parameters, which have a biological meaning and are therefore easy to interpret. These parameters are key elements to study the effect of the environment factors on the shape of the lactation curves. Recently the increased availability of records per individual lactations and the genetic evaluation based on test day records has oriented the interest of modelers toward general linear functions, as polynomials or splines. But these functions present some computational difficulties especially at the level of the lactation curves parameters.

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Chapter 7

Optimization of Milking Frequency in Dairy Ruminants

Moez Ayadi

Abstract

To make a decision on the number of milkings per day for each ruminant is a key factor to optimize the use of a machine milking. Currently, this decision is mainly taken from yield and stage of lactation data, but no udder capacity is taken into account. Milk is stored in the udder in the alveolar and cisternal compartments. Milk partitioning in the udder varied widely according to species, breed, lactation stage, parity, and milking interval. The increase in milking frequency has improved milk production in dairy ruminants. However, this practice reduces the milk composition, fertility, and productive life. To avoid increasing the number of milkings per day and reducing milk losses, a strategy based on the selection of ruminants with large udder cistern to store a large quantity of milk was adopted. Animals with great cisterns tolerate extended milking intervals and are milked faster with simplified routines. Ultrasonography will be a useful tool to measure udder cistern and to predict high-yielding animals. In practice, we propose to use the evaluation of udder cistern area, as helping criteria of udder milk storage capacity, establishing the optimal milking frequencies for each ruminant according to the production system.

Keywords: udder morphology, milking frequency, cisternal capacity, ultrasound, profitability

1. Introduction

The problems faced by farmers vary according to the region of production, the breed, the breeding, the feeding system, and the environmental conditions. Indeed, data in Europe show that milk production is surplus, but it is in deficit in Africa and South America [1]. The breeding programs for dairy animals have led to an increase in the quantity of milk. The reasons of this increase in milk yield include udder size, connective tissue mass, and secretory tissue. In fact, a hypertrophy of the secretory tissue of the udder is accompanied by a large milk production that can only be expressed phenotypically when the volume of the udder cistern is important to facilitate the storage of the milk produced [2–7].

In practice, because of the selection pressure exerted on the morphology of the udder, for example, cows with a high milk production must be milked at least three times a day. So, the increase in milking frequency has improved milk production in cows (15–20%, [8]). However, this practice reduces the fat matter, protein, fertility, and productive life of dairy cows [9]. It should be noted that the increase in the number of milkings per day is not accepted by farmers who are looking for farming practices to reduce the number of milkings per week and improve the quality of life on the farm [6].

To avoid increasing the number of milkings per day and reducing milk losses, a strategy based on the selection of ruminants with large udder cistern to store a large quantity of milk was adopted [2, 3]. Therefore, noninvasive in vivo imaging techniques to measure udder storage capacity have been developed [10–14, 5].

Indeed, the study of the internal morphology of the udder in ruminants will know an important development soon. Scientific advances such as embryo transplantation and cloning can contribute to increased uniformity of livestock. Therefore, with this new orientation, it is interesting to take into account, in addition to the external volume of the udder, the internal size of the udder, the capacity of distension of the cells, and the kinetics of udder filling to ensure better adaptation of the udders to the number of milkings (conventional mechanical milking and robotic) and the different milk production systems (extensive, intensive) to maximize farmer's income.

2. Morphology of the mammary gland in dairy ruminants

2.1 Udder morphology and milk production

The purpose of the use of morphological traits in a dairy breeding scheme is to improve the functional longevity of animals by reducing the frequency of reforms and facilitate the adaptation of animals to milking, mechanics, as well as the work of the breeder. In fact, the study of mammary morphometry in dairy animals permits identifying correlations between some morphological traits and milk production as well as the possibility of mechanical milking.

Several authors have studied the external morphological characteristics of the udder in ruminants for performance evaluation and mechanical milking skills [15–18]. The importance of these morphological measurements of the cow's udder has been accentuated by the interest in the application of the system of mechanical milking by robot [19]. In dairy cows, the large udders are usually the ones that give the most milk. Moreover, the correlations between the estimated volume of the udder and the milk production can vary from 0.60 to 0.82 depending on the breed [20]. According to the same authors, the teats must be implanted vertically, and the distance between them must never be less than 6 cm. Wide teats are associated with udder health risks and with the quality of produced milk [21]. In cattle, positive correlations have been confirmed between the distances of the teats and the teat diameter and milk yield of cows [15]. The same researchers have shown that some features of cows' mammary morphology may be associated with a risk of higher mastitis such as low teats and wide teats, as they may increase the risk of injury and the entry of pathogens inside the udder.

In ewes, the criteria of the size and shape of the udder and teats are positively correlated with milk production [21] and milk flow [22]. The presence of developed udder implies a good ability to withstand long intervals between milking and even the practice of single milking (one milking per day). Indeed, the removal of one milking per day indicates a greater loss of milk in breeds with smaller cistern udders [4]. In addition, the udders with rather horizontal teats and inserted high relative to the base of the cisterns are associated with the increase in the fraction of milk drip, requiring a manual intervention of massage and udder movement to collect the milk not extracted by the machine.

In Murciano-Granadina goats, positive correlations between teat length and milk flow ($r = 0.55$) and between teat surface ($r = 0.47–0.58$) and residual milk were reported [23]. In the Saanen goats, a positive correlation ($r = 0.65$) was found between the circumference of the udder and daily milk production.

Unlike other dairy animals, there has been little work on the study of mammary morphology in camels [24–29]. A good udder in camels is characterized by well-developed and symmetrical neighborhoods with vertically implanted, uniform, and well-spaced teats [30]. In the same context, [28] reported that the length and depth of the udder in camels are of the same order of magnitude as those indicated for cows [6] and for buffalos [31]. In camels, the teats placed very close to each other and sometimes fused are frequent. Juhasz and Nagy [32] showed a great heterogeneity in the morphology of the udder and teats in camels. They defined at least five different forms of teats. Ayadi et al. [28] found that daily milk production is positively correlated with teat distance ($r = 0.61$), udder depth ($r = 0.29$), and breast vein diameter ($r = 0.34$). The conformation of the udder in camels varies considerably according to the breed, the age, and the stage of lactation. Indeed, [25] reported that camels' teat length varies with parity with shorter teats in primiparous (3.40 cm) than multiparous (6.10 cm).

Recently, for the development of a dromedary selection program according to the udder and teat typology adapted to mechanical milking, [33] proposed a 5-point linear scoring template for evaluating the udder of dairy camels based on five main traits.

2.2 Storage of milk in the udder

A functional mammary gland is an exocrine gland consisting of a tubuloalveolar epithelial tissue and a stroma. In order to fulfill its production function, the udder is richly vascularized and innervated. There are two main categories of udders: the so-called udders composed without cistern (case of rodents and primates) and the so-called udder simple cistern (case of ruminants).

In the ruminant udder, it is possible to distinguish an alveolar compartment (alveoli and fine channels) from an interconnected cistern compartment (large canals and cistern). The volumes of milk accumulated in each of these anatomical compartments can be measured accurately. Milk was first evaluated by draining the milk accumulated in the cistern by insertion of a cannula into the teat canal; the alveolar milk is then recovered by milking followed or not by an injection of oxytocin [2]. The use of a cannula to drain milk has been widely used. By using this technique, the volume of milk may be overestimated (in addition to milk, a fraction of alveolar milk can be recovered by endogenous oxytocin secretion conditioned or linked to stimulation of the udder when introducing the cannula).

Intravenous injection of oxytocin receptor blocking agent (Atosiban), which inhibits milk ejection, has been developed [34, 35]. Milking after injection of Atosiban permits to collect the cistern milk; then oxytocin injection reverses the effect and the alveolar milk can be collected. The use of Atosiban is therefore recommended in ruminants [36]. Moreover, noninvasive in vivo imaging techniques (ultrasonography) have been used to measure cistern udder storage capacity [10, 11, 5, 13]. Certainly, whatever the measurement method, knowledge of the distribution of milk in the udder, as well as the kinetics of its filling according to the species, is particularly important to determine the appropriate intervals between milkings.

In cows, the volume of milk contained in the alveolar compartment is preponderant since it represents between 70 and 80% of the total quantity of milk 12 hours after milking [2, 3, 5]. This fraction is about 50–75% in ewes [37, 38, 4] and reaches even 80–90% in goats [39]. The cisternal milk represented 3–19% of total milk in camels [28, 12, 26] and 5% in buffaloes [40]. These proportions may vary depending on the breed of animals but also on the stage of lactation. In addition, the volume of milk stored in the cistern increases during lactation because of the decrease in secretory tissue during lactation [41]. Likewise, the volume of milk is higher in multiparas [41]. This is due to the immaturity of the development of cisterns in primiparas [42]. Studies on milk accumulation in the udder after milking have been conducted in dairy ruminants.

Recently, [43] proposed a 6-point linear scoring template for evaluating the cisternal size of the udder of dairy cows (0 = absent cistern; 6 = very large cistern), evaluated by ultrasound according to the methodology of [5]. This classification optimizes the milking frequency according to the stage of lactation and the production system.

3. Milking frequency

Milk production (quantity and quality of milk) is regulated at different levels: by genetic factors, diet, various endocrines, and environmental controls. One of the levers for acting on the metabolic and secretory activity of the udder is the frequency of milking. Generally, cows are milked twice a day with milking intervals ranging from 8 to 16 hours, though studies have been conducted to determine animal milking management systems that combine maximization of quantitative and qualitative production with reduced work constraints. Research showed that for a frequency of two milkings per day, a 12–12 interval would be beneficial for high-producing cows (3–5% gain over a 10–14 interval) [37], suggesting the appearance of a brake on secretion beyond a certain time limit. To determine this limit, several studies place it between 10 and 18 hours depending on the animals [44]. These differences could be due to inter-individual variations and could also be related to anatomical features of the udder.

In fact, animals with large udder cistern produce more milk and withstand relatively longer intervals between milkings than animals with a small udder cistern, which cannot transfer their alveolar milk and in which a brake on the secretion is set up faster. Such an observation has been verified in cows [2, 5], ewes [37, 13], goats [39], and camels [45, 12]. Therefore, it has been shown that when milk can flow continuously from the udder, milk production increases [44].

3.1 Decrease in milking frequency

The consequences of reducing the number of milkings on ruminant milk production have been studied by many authors. Certainly, the passage from two milkings to a single milking per day leads to a loss of milk production from 10 to 50% in cows [42].

Short-term (1 week) trials of mid-lactation Friesian and Jersey cows from two milkings to one daily milking reported milk yield decreases ranging from 10 to 25% [2]. The responses would depend on the stage of lactation since the loss of production would be more pronounced for animals in early lactation than for animals at the end of lactation (−38 vs. −28%) [44]. This can be related to the anatomy of the gland since it is known that the proportion of milk stored in the cistern varies with relation to the stage of lactation in cows [46, 41]. In ewes, switching to one milking per day causes a decrease in production from 15 to 35% [47–49]. The lowest losses are reported in Sardi ewes, known for their high capacity for storage and high production capacity, while the largest losses are observed in pre-Alpine ewes with small tanks and low production.

In goats, one milking per day leads to production decrease from 6 to 35% compared to two milkings per day [50]. As in cows and sheep, race and stage of lactation have an effect, which can be related to the storage capacity of the udder. Undeniably, the largest losses are recorded at the beginning of lactation [39], and the lowest losses are observed in Canary goats, with very large cisterns. Overall, a decrease in milking frequency causes production losses depending on the animal's storage capacity. Finally, it seems that this milking practice increases the concentration of somatic cells in milk [44], the increase being more marked as the number of cells in the milk at the beginning of the experiment is important. In dairy sheep, switching to one milking per day does not significantly modify the composition of milk [47], whereas in goats, an increase in fat matter and casein concentrations is reported [39].

In dairy ruminants, as time after milking increased, there is (i) an increase in alveolar distension, (ii) a decrease in udder blood flow, (iii) an increase in tight junction's permeability, and (vi) an accumulation of putative feedback inhibitor of lactation [50, 51].

3.1.1 Alveolar distension

The first signals of local regulation of mammary gland activity are probably the degree and duration of alveolar distension. Studies by [52] have shown that the amount of alveolar milk in goats is low compared to animals with a high volume of residual milk. Despite the size of the alveolar compartment of the udder of cows reaches its maximum around 16 hours after milking, the longer the interval increases beyond 16 hours, the more the cells are filled with milk. In fact, the increase in pressure following the accumulation of milk throughout the mammary ducts generally leads to an inhibition of the secretion of milk [44]. According to [53], the dilation of the mammary alveoli is accompanied by a decrease in prolactin concentrations when the milking frequency is reduced. Furthermore, the increase of the intra-alveolar pressure causes the compression of the mammary epithelial cells (CEMs) altering the activity of their cytoskeletons and thus the intracellular traffic of the constituents of milk.

3.1.2 Decrease in udder blood flow

Dairy production and mammary blood flow are positively correlated throughout lactation, with the synthesis of 1 L of milk requiring the passage of approximately 300–500 L of blood regardless of the ruminant species [54]. The increase in intra-mammary pressure (IMP) related to milk accumulation decreases the mammary blood flow (−10% after 24 hours in cows) [55] and −50% after 36 hours in goats [56]. The availability of hormones and nutrients would be reduced in the gland, thus decreasing the rate of secretion. This decrease in mammary blood flow could also be related to the activation of the sympathetic nervous system by the accumulation of milk [57]. Draining more frequently would therefore avoid a decline in blood flow, which could be a limiting factor for milk production, although the latter hypothesis has not been confirmed in goats [58].

3.1.3 Increase of tight junction's permeability

A regulating mechanism involved in the practice of a single milking per day acts on the tight junctions, leading to an increase in the alveolar permeability. Really, the change in the chemical composition of milk during the practice of daily milking can be attributed to an increase in the serum in milk, as a result of changing the permeability of tight junctions. Furthermore, the increased permeability of the tight junction is achieved at around 17–18 hours of milking in cows [51], 19–20 hours in sheep [13], beyond 21 hours in goats [39], and 16 hours in camels [45]. Indeed, the change of the permeability of the mammary epithelium membrane during the practice of a single daily milking suggests a rapid increase in the concentration of lactose in the blood plasma and increased serum protein in milk and content of milk in Cl and Na and a reduction in lactose and K [59].

3.1.4 Accumulation of the feedback inhibitor of lactation

The causes of the decrease in milk production for daily single milking are not well known. Indeed, in dairy cows, it has been shown, reduction of the milking frequency in one quarter of the mammary gland and not in the other quarters, that the quantity of milk in the treated unit only once a day decreased [60]. The same results were observed in sheep and goats [61]. In addition, incomplete emptying of the udder causes a decrease in production [62]. In order to prevent engorgement, the mammary gland has a feedback mechanism on milk synthesis; it produces a glycoprotein that inhibits its synthesis. Therefore, frequent emptying reduces the amount of this inhibiting factor in contact with the CEMs. This local chemical factor with inhibitory activity on milk secretion, called feedback inhibitor of lactation (FIL) or lactation inhibitor factor (LIF), is a low-molecular-weight protein (7.6 kDa), which has been shown in goats [63]. The FIL reduces the secretion rate of milk in vitro [62] and in vivo [63] when in contact with the alveolar epithelium. It works by inhibiting the constitutive secretion of proteins by CEMs by reversible blocking of the early stages of the biosynthesis-secretion pathway. In addition, the FIL would also inhibit lactose synthesis. Finally, FIL would regulate the number of cell tissue by triggering apoptosis [54]. Indeed, incomplete milking or milking removals would allow an accumulation of the FIL in contact with the CEMs, which would explain the reductions in milk production described above.

Recently, serotonin (5-HT) has been proposed to be an autocrine/paracrine regulator of lactation in the mouse, humans, and more recently in the bovine. The enzymatic machinery necessary for 5-HT biosynthesis has been detected in the mammary epithelium [64]. Other researches support the concept that serotonin (5-HT) is a feedback inhibitor of lactation in the bovine [65].

3.2 Increase in milking frequency

Increasing milking frequency in dairy cattle to more than two milkings per day has resulted in an increase in milk production without any negative effect on the health of the animal. There are various reasons for the practice of three milkings a day, namely, increase in the time of use of the milking machine, the size of the herd, and milk production. In fact, milking three times a day results in an increase in milk production from 3 to 39% compared to two times in dairy cows [66], 15–35% in ewes [47], 10–20% in goats [67, 62, 39], and 4–13% in camels [68, 45]. The response to increased milking frequency would be greater in high-producing, primiparous, and late-lactating cows [66, 69]. Erdman and Varner [70] in their review of 40 comparative studies of increased milking frequency reported that switching from 2 to 3 milkings per day resulted in a stable increase in milk production in terms of quantity (3.5 kg/day) and not by a proportional increase.

In studies on the milking robot, it has been shown that cows, when given free time, are milked on average between 2.7 and 3.9 times a day [71]. In addition, when a rate of four milkings per day is applied for 4 weeks, a production increase of 14% is observed [2]. However, switching to six milkings per day for 2 days only increases production by 10–15% [8]. Such observations suggest that an interval between milkings of 6–8 hours is physiologically ideal for the animal and that there would be no advantage in increasing the rate of milking above four milkings per day in cows [53], as in ewes [47]. An increase in milking frequency would therefore allow improved persistence of production in goats and cows [2, 51].

There are contradictions in the literature regarding the effects of switching to three milkings per day. For some, changes in milk composition at three milkings per day would be insignificant, while others report a decrease in milk fat compared with cows milked twice a day [8]. For some, this decrease would be greater for primiparous cows, while for others, the decrease would be greater for multiparous cows [66]. At the lactation scale, [69] noted a slight decrease in protein and casein concentrations in milk, enough to reduce cheese yield by 1.5%. Somatic cell milk content is used as an indicator of the microbiological quality of milk. Indeed, the number of somatic cells decreases when milking frequency increases [71]. On the other hand, [66] report that switching from two to three milkings per day in dairy cows increases the California mastitis test (CMT) score.

The increase of milking frequency could lead to an increased release of lactogenic hormones which will stimulate the synthetic activities of the CEMs and allow a better persistence of the lactation. These hormones may, in addition to their metabolic effects, increase the number of secretory cells and thus increase the volume of milk secreted [72]. Indeed, even if it is admitted in ruminants that the CEMs deteriorate and that their number decreases progressively with the advancement of lactation, by triggering apoptosis [54], the activity of synthesis of remaining cells is unchanged [72]. This decrease in the number of cells would be modulated by the frequency of milking. The increase of milking frequency causes cellular hypertrophy followed by an increase in the number of CEMs by proliferation of new cells. In addition, an increase in enzyme activities, reflecting their potential for synthesis, is observed in response to an increase in milking frequency in goats [62], cows [2], and camels [45].

4. Conclusions

Deciding about the number of milkings per day for each ruminant is a key factor in optimizing the use of mechanical milking. Currently, this decision is primarily based on the production level and stage of lactation data, but no udder capacity is taken into account. Therefore, it is recommended to use ruminants with large cisterns in order to minimize the effect of hydrostatic pressure on the cells and consequently reduce production losses. In practice, we propose to use the evaluation of udder cistern area by ultrasonography as a criterion to estimate milk storage capacity in the udder in order to establish the appropriate milking frequency for each ruminant according to the production system.

Research opportunities are open to broaden and consolidate this study. Indeed, the work on the heritability and the repeatability of this character "glandular cistern" is essential in order to incorporate it into the breeding programs for dairy ruminants.

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Greater knowledge of lactation allows us to alter environmental, nutritional, and milking procedures, or general management to maximize production. This book, focusing on lactation in farm animals (biology, physiological basis, nutritional requirements, and modelization), presents invited papers from internationally recognized scientists. This volume contains seven chapters covering the key topics related to milk production and lactation biology and physiology. The authors show that animals raised on a well-controlled nutrition regimen may have significant enhancement of succeeding lactations. Furthermore, the usefulness of a milk yield prediction system depends upon how accurately it can predict daily milking patterns and its ability to adjust to factors affecting supply. Milk yield prediction models have proven helpful for genetic analysis and for bio-economic modeling. On the whole, this book serves as an inspirational basis for both scientists and farmers.

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