An Overview of Milk

Got milk?

The Webster's dictionary defines milk as "a white or yellowish liquid consisting of small fat globules suspended in a water solution, secreted by the mammary glands for the nutrition of the newborn".

" Milk is the most important determinant and regulator of the social system of mammals"

Milk and honey are the only diets whose sole function in nature is food. The role of milk is to provide nourishment and protection for the mammalian young. Milk also has been a food source for humans since the dawn of history. Milk is a very complex food with over 100,000 molecular components. Therefore, only an approximate composition of milk is usually given.

Milk components

Milk is composed of water, carbohydrate, fat, protein, minerals and vitamins. It is important to remember that milk is secreted as a complex mixture of these components. The properties and importance of milk are greater and more complex than the sum of its components.

Individual milk components can be considered from a number of perspectives:
- The biochemistry of the component
- Biosynthesis mechanism.
- The role of the component in defining the physiochemical property of milk.
- The function of the component in the mammary gland.
- The importance of the component in nursing.
- The importance of the component in milk and milk products as foods for humans.

Some terms and definition

***Solids-not-fat*:** Protein, lactose, minerals, vitamins, and enzymes.
***Total solids*:** Fat + solids-not-fat
***Skim milk (plasma)*:** milk - fat
***Whey (serum)*:** skim milk - casein micelles

Milk Fat

Fat is the most variable component in milk in both their concentration and chemical composition, whether inter- or intra-species differences are considered. It ranges from about 1% in donkey milk to more than 50% in aquatic mammals. Milk fat is the major source of lipid used by the mammalian newborn for accumulating body adipose tissue. The major lipids in milk fat are trigylcerides, which are composed of three fatty acids covalently bound to a gylcerol molecule by ester bonds. The remainder of the lipid fraction (~2% of the total in human and cow's milk) consists mainly of diacylgylcerols, cholesterol, phospholipids and free fatty acids.

Fat in milk is present as fat globules ranging from 0.1 to 15 μm in diameter. These fat globules or droplets are covered by a thin membrane whose properties are different from both milk fat and plasma. The fat globule membrane helps to stabilize the fat globules in an emulsion within the aqueous environment of the milk.

The following generalizations about milk fat are noteworthy:

- Most milks contain a much higher proportion of short- and medium-chain fatty acids than is present in the other tissues of the same species.
- Milks of ruminant species have a relatively higher concentration of short chain fatty acids (<C9) than is the case for non-ruminants. They may also contain much less of the polyunsaturated fatty acids (C18:2 and C18:3) than non-ruminant milks.
- The particular fatty acid composition of milk is dependent on the nature of the diet of the lactating animal to a greater degree than is the case for other milk constituents.

Protein

Milk protein varies considerably among species but as not as much as milk fat. Generally protein percentage is positively correlated with fat percentage. Milk protein ranges from 1% in human milk to about 14% in whale milk. Milk proteins contain more essential amino acids than any other natural food. The main milk proteins are caseins α-lactalbumin, and β-lactoglobulin. These proteins constitute more than 90% of the total protein (in cow's milk) and all of them are synthesized in the mammary secretory cell. Milk proteins are found only in milk and no where else in nature.

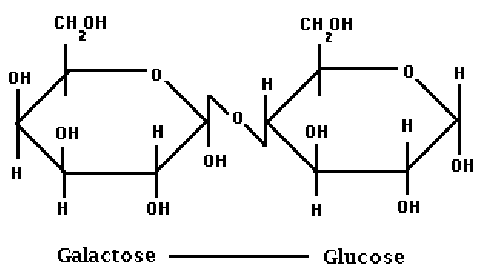
Caseins are phosphoproteins, with molecular weight > 20,000 which are precipitated at acid pH (pH 4.6 for cow's milk) or by action of gastric enzyme chymosin (rennin). In milk of most mammalian species, there are 3-4 caseins; the different caseins are distinct molecules but are similar in structure. Casein is composed of several similar proteins, which form a multi-molecular granular structure called a casein micelle. The micellar structure of milk casein is an important part in the mode of milk digestion in the stomach and the basis of many of the milk products industries such as cheese. In addition to casein molecules, the casein micelles contain water and salts.

Milk serum (whey) proteins are those which remain in solution at the pH of casein precipitation. The group includes several kinds of proteins, some of which are only synthesized in the mammary secretory cell (e.g. α-lactalbumin and β-lactoglobulin) while others (immunoglobulins and serum albumins) are identical with blood proteins. β-lactoglobulin is the principal serum protein in the milk of several species including cows, goats, and sheep, but does not occur in many others including human.

There are marked differences in the protein quantity and quality of cow's and human milks, and this has important implications for the design of milk formula for human babies. For example, the total protein content of human milk is less than one third of that in cow's milk, while the casein:whey ratio is ~82:18 in cow's milk and 30:70 in human milk. The amino acid contents of caseins as well as the type of curd formed are also different between the two species. It has been suggested that β-lactoglobulin (which is absent from human milk) may be responsible for the allergic reactions which some infants show to cow milk-based formula.

Milk Carbohydrates

Lactose (disaccharide composed of D-glucose and D-galactose) is the major milk carbohydrate in most species. Some species have very little lactose in milk (e.g. bear and kangaroo), while others (e.g. donkey, human) have a high as 7% lactose in their milk. Lactose is absent from the milk of some sea lions. In addition to lactose, milk contains other carbohydrates in small amounts, including glucose, galactose and oligosaccharides. Milks from marsupials and monotremes contain a variety of oligosaccharides, at higher concentration than that of lactose, in addition to monosaccharides



Lactose is unique to milk (i.e. does not exist anywhere else in nature) and it plays a major role in milk synthesis. It is the major osmole in milk and the process of synthesis of lactose is responsible for drawing water into the milk as it is being formed in the mammary gland. Because of the close relationship between lactose synthesis and the amount of water drawn into milk, lactose is the least variable component of milk.

Lactose is important in the manufacturing of many fermented dairy products such as yogurt. It is the preferred substrate for many lactic acid bacteria, which produce lactic acid from lactose. Because of their ability to metabolize lactose, lactic acid bacteria have a competitive advantage over many pathogenic and spoilage organisms.

Water

Water content of milk can range from about 90% in kangaroo to less than 50% in whale. Milk is a major source of water for the mammalian young and the young would dehydrate rapidly without the water component of milk. Water content of milk is greatly influenced by lactose synthesis (i.e. the more lactose synthesized, the higher the water content).
Cow milk is about 87% water, so the transportation of milk from dairy farms involves hauling of considerable amounts of water. The addition of water to cow milk can be detected by several methods. These methods are based on changes in freezing point of the milk or on changes on refraction of light of the whey component of milk after precipitation and removal of the casein and fat components.

Vitamins and Minerals

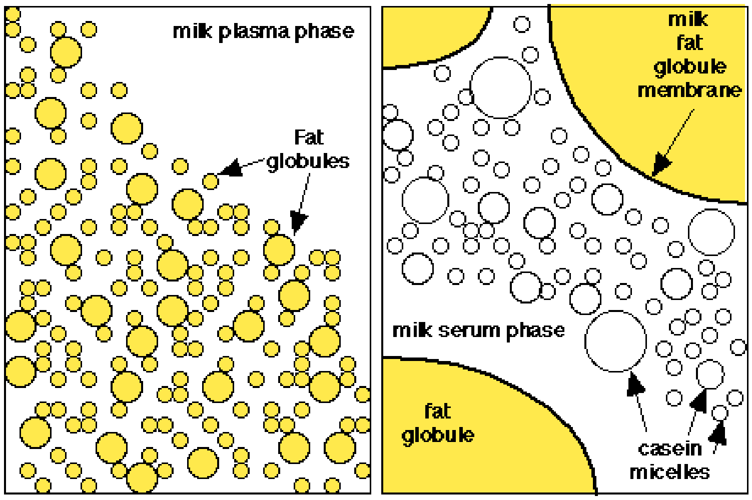
Milk contains all the major vitamins. The fat-soluble vitamins A, D, E, and K are found mainly in the milk fat. The B vitamins are found in the aqueous phase of milk. Milk in Canada and US is fortified with vitamin D. Vitamin A is also added to fat reduced milk products.

All minerals considered essential (22) to the human diet are present in cow's milk. However, the major minerals in milk are calcium and phosphorous which are associated with casein micelles. Therefor, whey has relatively little Ca and P compared with whole milk.

Minerals (salts) exist in milk in two forms: 1) as low molecular weight ions and complexes (***diffusible salts***). 2) ***Non-diffusible salts*** which are bound to protein. The most common cations in milk are K, Na, Ca, and Mg, and the most common anions are Cl, and inorganic phosphate. Of these, K, Na and Cl are almost entirely diffusible. The major ions of the non-diffusible (colloidal) phase are Ca, Mg, inorganic phosphate and citrate, which are associated with the casein micelles. There are marked species differences in both the total concentrations of salts and in their partitioning between the colloidal and diffusible phases of milk.

Physiochemical Properties of Milk

Milk at the time of secretion comprises two liquid phases. The aqueous phase contains solubilized lactose, whey proteins, some minerals, and water-soluble vitamins, which are present in simple solution, while proteins and other ions are present in a colloidal suspension. The lipid phase contains fat globules, fat-soluble vitamins and other compounds such as carotenoids. Collectively, milk is an emulsion of fat globules and a suspension of casein micelles (casein, calcium, phosphorous) all suspended in an aqueous phase.



In the diagram, milk is viewed at two magnifications; the left view is what would be seen at about 500X magnification, and the right view at about 50,000X. This illustrates that milk is an emulsion of milk fat globules (left view) in a partially stable emulsion of the plasma phase of milk (the skim milk). In the right view, the casein micelles are in a colloidal suspension in the serum phase of milk (the whey). Milk fat globules in cow milk range in size from 0.1 to 10 micrometers. Milk fat has a density of about 0.92 g/ml. Casein micelles range in size from about 10 to 300 nanometers and have a density of 1.11 g/ml.

Some other physicochemical characteristics of cow milk:
- pH of normal milk is about 6.6 - 6.9
- Osmotic pressure is about 700 kPa
- Freezing point ~ - 0.5 °C
- Ionic strength is about 0.08 molar
- Water activity is about 0.993

Pasteurization of milk is done to kill bacterial contaminants while not substantially altering the milk characteristics. Heating at 74 °C for 15 seconds (low pasteurization) results in killing most organisms and inactivates some enzymes, but does not otherwise alter the milk. Heating at 90 °C for 15 seconds (high pasteurization) results in killing all vegetative microorganisms, inactivating most enzymes, but also rendering some whey proteins insoluble. Heating at 118 °C for 20 seconds sterilizes the milk, killing all microorganisms, including spores, inactivating all enzyme activities, but also causes changes to the milk such as the browning reaction involving the proteins and sugars. Ultra-high temperature (**UHT**) pasteurization of milk at 145 °C for a few seconds sterilizes milk while minimizing the chemical changes. UHT milk, which is properly stored, has a long shelf life, even at room temperature.

General Principles of Milk Composition and Yield

Several correlations can be noted among contents of constituents when milks of various species are compared.

Relationship between milk protein and lactose: Synthesis of lactose in the Golgi body is the primary regulator of the amount of water that dilutes the protein to its final concentration. Thus, a highly negative relationship exists between the protein and lactose contents (fat-free or skim milk):

$$\textbf{\textit{Protein (\%) = 20 – 2.8 lactose (\%)}}$$

A strong negative relationship also exists between lactose and fat concentration of milk of different species.

Relationship between milk protein and fat: With the exception of few species, there is a positive correlation between milk protein and milk fat. The relationship for ungulates (hoofed mammals) is:

$$\textbf{\textit{Protein (\%) = 1.05 + 0.57 Fat (\%)}}$$

Milk isosmolarity: Milk is isosmotic with blood plasma, a feature of some importance because the maintenance of an osmotic gradient would entail energy expenditure. Osmotic pressure is chiefly determined by lactose and diffusible ions, and both within and between species there is generally an inverse relationship between lactose concentration and the sum of K and Na concentrations.

Relationship between casein, Ca and P: Calcium and P concentrations are positively correlated, presumably due to the prevalence of colloidal Ca-P in many milks. Moreover, the sum of Ca and P concentrations is positively correlated with casein concentration, suggesting that the casein-Ca-P complex has a relatively constant stoichiometry.

Aquatic, arctic and dessert mammals: Milks of aquatic, arctic and some desert species show a common feature, very high fat concentration, despite the marked differences in their habitat. In the case of aquatic and arctic species, it is likely that the high fat content is important to facilitate subcutaneous fat deposition in the suckling young and thus reducing the heat loss. Furthermore, the high-energy value of fat serves to maintain the high metabolic rates needed in low environmental temperatures. Alternative explanation, which also applies to desert animals, is that the high fat content represents a mean of conserving maternal water. The low water intake of desert mammals may be surpassed by that of phocid seals, which abstain from feeding and drinking during the several weeks of lactation, so that all water fore milk secretion must come from metabolism of body stores, mainly in the form of fats.

Frequency of suckling: There are wide variations in suckling frequency. For example, mice suckle at ~20 min intervals (although the young are attached contiguously to the teats), pigs hourly, rabbits once daily, tree shrews once every 2 days and northern fur seals about once a week. Despite the influence of other factors, there is a clear inverse relationship between the concentration of nutrients in milk and suckling frequency.

Milk composition of various mammalian species

	Fat (%)	Protein (%)	Pro/fat	Lactose (%)	Ash	Total solids
Antelope	1.3	6.9	5.3	4	1.3	25.2
Ass (donkey)	1.2	1.7	1.4	6.9	0.45	10.2
Bear, polar	31	10.2	0.3	0.5	1.2	42.9
Bison	1.7	4.8	2.8	5.7	0.96	13.2
Buffalo, Philippine	10.4	5.9	0.6	4.3	0.8	21.5
Camel	4.9	3.7	0.8	5.1	0.7	14.4
Cat	10.9	11.1	1	3.4	---	25.4
Cow:						
Ayrshire	4.1	3.6	0.9	4.7	0.7	13.1
Brown Swiss	4.0	3.6	0.9	5.0	0.7	13.3
Guernsey	5.0	3.8	0.8	4.9	0.7	14.4
Holstein	3.5	3.1	0.9	4.9	0.7	12.2
Jersey	5.5	3.9	0.7	4.9	0.7	15.0
Zebu	4.9	3.9	0.8	5.1	0.8	14.7
Deer	19.7	10.4	0.5	2.6	1.4	34.1
Dog	8.3	9.5	1.1	3.7	1.2	20.7
Dolphin	14.1	10.4	0.7	5.9	---	30.4
Elephant	15.1	4.9	0.3	3.4	0.76	26.9
Goat	3.5	3.1	0.9	4.6	0.79	12
Guinea Pig	3.9	8.1	2.1	3	0.82	15.8
Horse	1.6	2.7	1.7	6.1	0.51	11
Human	4.5	1.1	0.2	6.8	0.2	12.6
Kangaroo	2.1	6.2	3	Trace	1.2	9.5
Mink	8	7	0.9	6.9	0.7	22.6
Monkey	3.9	2.1	0.6	5.9	2.6	14.5
Opossum	6.1	9.2	1.5	3.2	1.6	24.5
Pig	8.2	5.8	0.7	4.8	0.63	19.9
Rabbit	12.2	10.4	0.8	1.8	2	26.4
Rat	14.8	11.3	0.8	2.9	1.5	31.7
Reindeer	22.5	10.3	0.5	2.5	1.4	36.7
Seal, gray	53.2	11.2	0.2	2.6	0.7	67.7
Sheep	5.3	5.5	1	4.6	0.9	16.3
Whale	34.8	13.6	0.4	1.8	1.6	51.2