The Viscosity of Milk in Relation to the Concentrations of Major Constituents, and to Seasonal Differences in the Voluminosity of Complexes of Sedimentable Nitrogen

C. H. WHITNAH

Kansas Agricultural Experiment Station, Kansas State University, Manhattan, Kan.

The objectives of this study were to determine first, correlations between the viscosity of milk and common analyses; and secondly, differences in the voluminosity of the nitrogen-containing micelles in centrifuge preparations from milks of different seasons. Both the simple and partial correlations with per cent fat and per cent protein were between 0.75 and 0.80. The lower values for total solids, solids not fat, and solids neither fat nor protein indicate an indirect inverse effect of lactose. The voluminosities differed both with the conditions under which centrifuging produced varying concentrations of colloidal nitrogen and with the season. These results suggest the need of, and possible methods of finding more information about the composition and structure of such micelles.

Commercial milk analyses are usually limited to fat, total solids, and protein. The determination of correlations of viscosity with such analyses seemed a reasonable beginning for this study. The fat globules, the casein-containing micelles, and their interaction products with each other, with water, with lactose, with mineral salts, and with other proteins are possible factors affecting the contribution of colloidal particles to the viscosity of milk. Differences in the voluminosities of nitrogen-containing micelles would indicate differences in the above interaction products. The main objective of this study is, therefore, to determine if such differences in voluminosity exist.

A simple definition of voluminosity is the volume occupied by 1 gram of a substance in its dispersed form (*3*). Ford (*2*) discussed the source and meaning of this term, and its relation to the viscosity of colloidal solutions. He extended earlier observations that plots of concentration, C_v *vs.* fluidity, ϕ/ϕ_0, are more nearly linear than C_v *vs.* viscosity, η/η_0. He selected nine equations to cover a wide range of theoretical and experimental backgrounds, and expressed each ϕ/ϕ_0 and η/η_0 as a power series in C_v. The coefficients of second and higher order terms were always respectively less in the fluidity form. He concluded that if a suitable multiplier of C_v gives a slope intercept at $\phi/\phi_0 = 0$ of 0.4, extrapolated from small values of C_v, and an actual intercept near 0.5263 (the volume fraction of spheres in cubical packing) then the multiplier is the voluminosity, V, and $V = -0.4[d(\phi/\phi_0)/(dC)]$.

There are advantages in using the viscosities of either water or the corresponding centrifuge whey for ϕ/ϕ_0, or its equivalent η_0/η, in the above equation. (The word "whey" is used in this article to describe the liquid portion obtained by intensely centrifuging milk.) Einstein's requirement for a small ratio of the diameters of solvent to solute particles favors water. This choice also avoids repeated use of any errors in measuring the viscosity of whey. The chief advantage of using the corresponding whey is that it includes all the material in which the sedimentable micelles are dispersed. Any differences in voluminosity should, therefore, be due to differences in these micelles. Regardless of any uncertainties and assumptions on which Ford's equation was based and used, voluminosity thus defined is a convenient way to condense, compare, and summarize a large collection of data on density and viscosity.

Procedures for collecting, separating, and centrifuging milk, for measuring viscosities, and for calculating voluminosities have been previously described (*9,-11*). The value 1.0019 ± 0.0003 for the viscosity of water at 20° C. (*7*), and Cragoe's equation $\log_{10}(\eta_t/\eta_{20}) = [1.2348(20-t) - 0.00146(t-20)^2]/(t+96)$ (*1*) for other temperatures are slow in receiving the recognition their careful determinations seem to deserve. The voluminosities used in this study were calculated on the university's IBM 650 digital computer.

Relations of Viscosity to Percentage of Each Major Solid Constituent of Milk

During the interval August 1 to September 15, 1956, 143 samples of milk were collected from individual cows (*5*). The viscosities were measured at 4° C. after 48 hours' storage at that temperature. Percentages of protein (*P*), fat (*F*), and total solids (*S*) were measured. *S-F* and *S-F-P* were calculated. Simple correlation coefficients were calculated for viscosity with each *P*, *F*, *S*, *S-F*, and *S-F-P*. Partials for each, except *S*, were also calculated (*6*). These correlations are shown in Table I.

The high correlations of viscosity with protein and fat are not surprising. The progressively lower values for *S*, *S-F*, and *S-F-P* are surprising, but may all be interpreted as indicating an inverse effect of lactose, the remaining major constituent. The regressions of lactose concentration on protein, fat, and ash are all negative (*4*). It is also possible that lactose concentration affects the nature or condition of micelles containing protein or fat.

Voluminosities of Centrifuge Fractions of Milk

Preliminary viscosity determinations at several temperatures were made on similar sediments resuspended in either water, a salt solution (*8*), neutralized

Table I. Correlations × 10³ between Viscosities of 143 Samples of Milk and Percentages of Major Constituents

Correlation	Protein	Fat	Solids	S-F	S-F-P
Simple	796	773	712	267	−222
Partial	726	699		220	− 80

Table II. Systems, Seasons, and Limiting Concentrations of Sedimentable Nitrogen in Milk Samples

Seasons		Systems[a] I	II	III	IV	V
		$10^4 \times$ % Sedimentable Nitrogen				
Fall, Oct. 27, 1958	Max.	3190	8729	7530	5015	5625
	Min.	0	472	397	261	1243
Winter, Jan. 22, 1959	Max.	2910	8589	8177	6506	5271
	Min.	0	1469	1439	1598	1218
Spring, June 1, 1959	Max.	5685	6430	6095	4770	6485
	Min.	0	1143	1018	938	1284
Summer, Aug. 5, 1960	Max.	3545	6971	5831	6934	5889
	Min.	0	257	221	256	223

[a] Systems I to V described in caption, Figure 1.

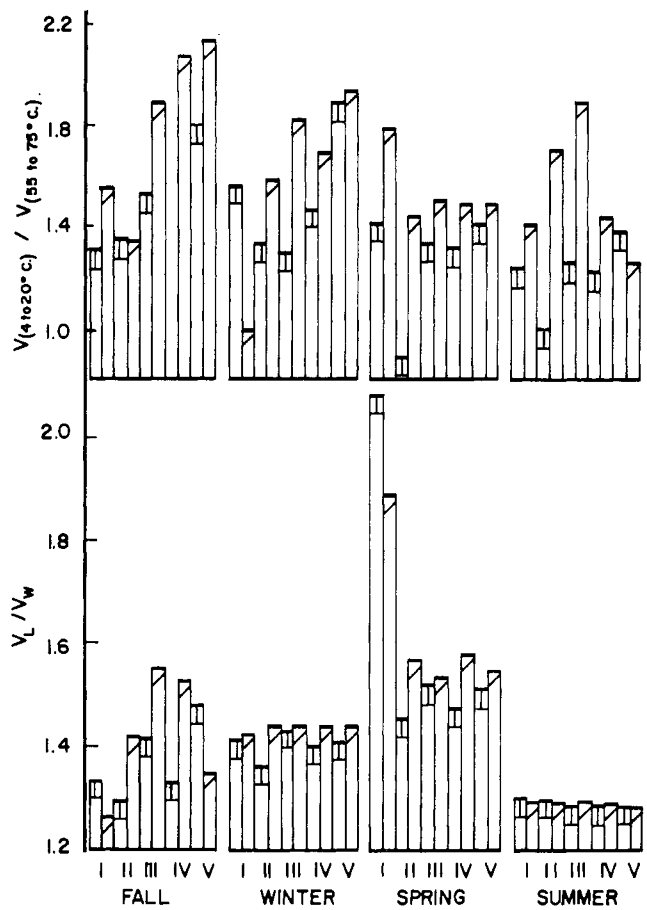

Figure 1. Comparison of the five systems ▶

Lower part: Ratios of the averages of voluminosities relative to the whey containing least nitrogen, V_L, to the averages relative to water, V_W, the ratios V_L/V_W

Upper part: Ratios of the averages of voluminosities in the range 4° to 20° C. to the averages in the range 55° to 75° C. The ratios V_{4-20}/V_{55-75}

Both parts: I. Liquids obtained by centrifuging milk
II. Bottom third of sediment from skim milk centrifuged at low speed
III. Top third of sediment from skim milk centrifuged at low speed
IV. Bottom third of sediment obtained from slow speed whey centrifuged at high speed
V. Top third of sediment obtained from slow speed whey centrifuged at high speed

acid whey, rennet whey, or centrifuge whey. Not only did the absolute value of viscosity differ for each solvent, but also the relative changes of viscosity with temperature differed. Centrifuge whey, centrifuged from the same sample of milk as the sediment, was chosen to provide nearly the same solvent for resuspended sediments as existed in liquid fractions.

Five systems for each of four milk samples were used in this study. The times for collecting samples were chosen to provide maximum differences in environmental conditions such as climate and feed. The four times of collection, the five systems prepared from each collection, and the maximum and minimum concentration of sedimentable nitrogen in each system are shown in Table II.

Vertical viscometers were used at 16 temperatures: 4°, 7°, 10°, and each 5° interval to 75° C. An inclined viscometer was used at six temperatures: 4°, 15°, and each 15° interval to 75° C. Ratios of voluminosities were selected as simple effective indicators of differences in the voluminosities of the four milk samples. Voluminosities at all temperatures and for each vertical and inclined position were averaged when comparing the two solvents as bases of calculation. Voluminosities relative to water were averaged for the lowest and highest thirds of the temperature range when studying effects of temperature. Comparisons relative to the two positions, to the five systems, to the temperature range, and to whether viscosities of whey (L) or water (W) were used to compute the voluminosities are shown in Figure 1. The significant feature of each bar is its extreme height. Each bar derived from measurements with a vertical viscometer is indicated by a vertical line near its top, while each bar derived from measurements with an inclined viscometer is indicated by an inclined line.

Even a casual glance (Figure 1) shows seasonal differences in both the relative and the absolute heights of bars. Data are not available to test the consistency with which any given difference appears at a given season, or to determine what factors in environmental conditions are responsible for any particular difference. The important conclusion to be drawn from these data is that differences exist relating to temperature of comparison, to the size of casein-containing micelles as controlled by sediment fractions in systems II to V, and to season as represented by the four samples of milk.

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