Use of the Foodtexture Puff Device to Monitor Milk Coagulation

F. R. Bamelis¹ and J. G. De Baerdemaeker

Katholieke Universiteit Leuven, Faculty of Agricultural Sciences, Lab for Agromachinery and Processing,
Kasteelpark Arenberg 30, B-3001 Heverlee, Belgium

ABSTRACT

The further automation of cheese-making on an industrial level requires the development of sensor devices to monitor the gelation process and especially the firming phase. In this paper, the Foodtexture Puff Device (FPD) is tested for its ability to monitor the gelation process by comparing it with classical rheometry (G' and G'') in a series of coagulations at different initial milk pH (6.01 to 6.61). The FPD measures the deformation of the surface of the milk during coagulation after applying an air puff directed on this surface. The maximal and minimal deformation values and the deformation range were calculated. A nonlinear model of the registered characteristics with the time point from adding rennet until the end of the gelation process was fitted on the FPD data and also on the classic rheology parameters. It was concluded that the FPD monitored the coagulation process in the same way as the rheology. Moreover, the start point of the coagulation process as well as the strength of the coagulum could be estimated nondestructively. Therefore, the presented technology together with the nonlinear model may be a basis for the development of an industrial monitoring device.

Key words: rennet gelation, pH, rheology, Foodtexture Puff Device

INTRODUCTION

The first step in the production of cheese and other dairy products is the production of a coagulum by adding rennet to the standardized milk. During this process, κ -casein is hydrolyzed by rennet enzymes, which cause the protein micelles to aggregate. As a result, the milk is transformed into a gel matrix that surrounds fat globules and bacteria: the coagulum. When a certain coagulum firmness is reached, the coagulum is cut mechanically into small pieces to facilitate the expulsion of whey (syneresis). This process is further accelerated by the acidification of the mix by bacteria and an increase in temperature (Payne et al., 1993). The exact

moment of cutting the coagulum is critical for the quality of the final curd and, therefore, the cheese that is produced from this curd. Cutting too late will reduce the syneresis, and the moisture content of the cheese will increase. Cutting too early may cause the loss of fat and curd fines (Mayes and Sutherland, 1984; Riddell-Lawrence and Hicks, 1988).

Because of the subtle variations in milk properties and the wide range of standardization procedures that play a role in the coagulation process [e.g., protein and fat content, initial pH, temperature, enzyme concentrations, CaCl_2 content, and bacterial load (Lopez et al., 1998; Landfeld et al., 2002; Najera et al., 2003)], the exact starting point of the gelation process and the speed of the process are variable. Therefore, for automation of cheese-making, a measurement technique is needed for the prediction of the cutting time or to adjust the milk toward a standard product in a way in which the same cutting time can always be used (Lucey, 2002). O'Callaghan et al. (2002) lists the requirements for such a device. First, it has to monitor the curd firmness, which is not accessible to current thermal or optical sensors. Second, it has to operate on a cheese vat, instead of separate measurements on samples. Third, the measurement should not interfere with the coagulation process. Fourth, the device has to be current with dairy hygiene design requirements.

Lots of research has already been performed to develop a suitable device to monitor the formation of the coagulum and to predict the right cutting time. The status of the existing technology is reviewed by O'Callaghan et al. (2002) and Lucey (2002). They both describe different technologies that were tested as prototypes for online measurements based on mechanical, vibrational, ultrasonic, electronic conductivity, hot-wire, or optical measurements. From these, only the hot wire presented by Hori (1985), the fiber-optic reflectance (Ustunol et al., 1991), and the RheoLight sensor developed by Niro (The Netherlands) became commercially available. Recent research, however, pointed out that the hot-wire technique is able to measure the onset of the gelation process, but is not able to measure the rate of the curd firming and not able to measure the final firmness (O'Callaghan et al., 2002). The optical methods have been shown to be very powerful, but because

Received July 25, 2005.

Accepted August 29, 2005.

¹Corresponding author: flip.bamelis@biw.kuleuven.be

they need a continuous calibration process, their actual use is yet quite limited. The RheoLight sensor seems to be useful, but its price is rather high.

In the present paper, a Foodtexture Puff Device (FPD) is used to monitor the rennet-induced coagulation process of milk. The technique is based on the measurement of the dynamic deformation of the surface of the coagulating milk after excitation with an air puff, an idea presented by Prussia (1995) to test the firmness of fruits. As advised by research of Lopez et al. (1998), rheologic measurements are used as a reference technique. In the described experiments, the effect of the initial milk pH on the coagulation process is monitored using both techniques.

MATERIALS AND METHODS

Materials

To standardize the experiments, 7 L of reconstituted milk was prepared from commercial low fat–low heat-skimmed milk powder (Belgomilk, Langemark, Belgium) at 12% (wt/vol) in deionized water at room temperature. After reconstitution, the milk was stored in a refrigerator at 4°C. An hour before the beginning of a measurement, a sample of 1 L was poured into a glass beaker and equilibrated at room conditions. Subsequently, the pH of the sample was adjusted with lactic acid (88% solution, VWR International, Haasrode, Belgium) and controlled with a digital pH meter (WTW pH-meter Inolab pH level 1). The pH was adjusted to different values, such that the range between 6.61 and 6.01 was covered with 7 samples. Once the pH was stabilized, the sample was equilibrated to 33°C in a water bath. The preparation of each sample took no longer than 1 h.

After the milk was equilibrated at 33°C, 250 μ L of single-strength rennet (80% chymosin, 20% pepsin, BMS, Kuurne)/L was added, and the time to synchronize the rheology and the FPD measurements were recorded. From the 1-L sample, 100 mL was taken to be used in the rheology measurements. The remaining 900 mL remained in the water bath where the FPD measurements took place. Each sample was monitored for 1 h with the FPD and the rheometer. All measurements were performed on the same day.

FPD Measurements

The FPD generates an airpuff of 0.10 bar during 50 ms that escapes from a specially designed nozzle directed towards the surface of the coagulating milk. The end of the nozzle is placed 4 cm above the milk surface

Figure 1. Measurement head of the Foodtexture Puff Device (FPD). Distance between air nozzle and milk surface and air pressure are kept constant.

(Figure 1). From the moment that the air puff is generated, the deformation of the milk surface is recorded by a laser distance sensor during a period of 5 s after the excitation of the surface. The deformation data are sent to a personal computer via a data acquisition board (E-6024 low cost data acquisition board, National Instruments, Zaventem, Belgium) and stored on the hard disk for later analysis. The used measurement head was constructed by LET NV (Deinze, Belgium). In Figure 1, a drawing of the device is shown.

When analyzing the data, the maximum and minimum deformation and the maximum range of deformation were calculated from the deformation as a function of a wave (Figure 2), because the deformation shows up as a wave. In fact, the minimal value in the deformation curve corresponds with the maximal deformation of the milk surface under a constant force of the air puff. The maximal value in the deformation curve range corresponds with the height at which the milk bounces back after removal of this constant force. The total range is the summation of both values.

The software that was used to communicate with the measurement device was written in the graphical programming language Labview 5.3 (National Instruments). The calculation of maximal and minimal values and the range of the deformation curve were done with Matlab 6.1 (The Mathworks, Inc., Natick, MA).

The coagulation process was monitored with this device during the first hour after renneting. Four measurements were taken per minute.

Figure 2. Calculation of maximal and minimal deformation values from the registered deformation curve by the Foodtexture Puff Device (FPD). The example is taken from the coagulation process from milk with an initial pH of 6.29 just after adding the rennet (left) and 20 min later (right). The range of the FPD is the summation of maximal and minimal values.

Rheological Measurements

Gel formation was monitored using a controlled stress rheometer (TA Instruments, AR1000-N, New Castle, DE) with concentric cylinder geometry (rotor diameter: 25 mm, stator diameter: 30 mm, and gap height: 6,418 μm). The temperature of the sample was kept constant at 33°C by a controlled temperature water flow through the envelope of the outer cylinder and a Peltier temperature controller in the bottom plate on which the concentric cylinder system was placed. The storage modulus (G') and the viscous modulus (G'') were recorded at a frequency of 1 Hz under 0.015 strain amplitude during the first hour of the coagulation process. This was found to be within the linear viscoelastic region for rennet milk gels (Lopez et al., 1998; Herbert et al., 1999). A measurement was taken each 10 s.

The rheological parameters were calculated using the TA Instrument software and stored on the hard disk of a personal computer for further analysis.

Data Treatment

To illustrate the different steps in the treatment of the recorded data, the data of the coagulation process at pH = 6.29 are used as an example (Figure 3). For both the FPD and the rheological parameters, it can be observed that the recorded time signals can be split up in 2 parts: a constant value before the gelation process starts followed by a hyperbolic decrease for the total

range and the maximal value of the FPD measurements and a hyperbolic increase in the minimal value of the FPD measurements and the G' and G'' registered by the rheometer. On these data, equation 1 was fitted with the SAS software (SAS 6.12, SAS Inst., Inc., Cary, NC). This equation is a combination between a time constant value (the first term) followed by a hyperbolic change (the numerator of the second term). The denominator of the second term realizes the shift from the constant part to the hyperbolic part at the time point C/k , where k is the rate at which the shift from the first term toward the second is realized. For this work, k is chosen constant and rather high (0.5) to realize a fast shift from the constant toward the hyperbolic regimen. Therefore, the shift from the first linear phase toward the hyperbolic degree phase will be realized at the time point estimated by $C/k = C/0.5 = 2C$. The numerator of the second term $[B + 1/(Dt - E)]$ describes the hyperbolic part of the curve. As t evaluates toward infinite, it can be seen that the modeled parameter will evaluate toward B . Together with the constant part of equation 1, this becomes $A + B$. In our work, B is always chosen positive; hence, the signal will evolve toward $A - B$. When t evolves toward the start of the hyperbolic curve, the modeled parameter will evaluate asymptotically toward infinite at the time point E/D . Hence, the larger the difference between $2C$ and E/D (or the larger $2C - E/D$), the lower becomes the rate of decrease of the hyperbolic part of the process. This makes $2C - E/D$

Figure 3. The kinetics of the maximal and minimal deformation and the deformation range measured by Foodtexture Puff Device (FPD) (upper plot) and the rheological parameters G' (storage modulus) and G'' (viscous modulus) during the coagulation process of the sample with milk (pH 6.29). Measurement points and fitted model are presented.

and the gelation rate inversely related and the $(2C - E/D)^{-1}$ an estimator for the gelation process rate.

$$f(t) = A + \frac{B + \frac{1}{Dt - E}}{1 + e^{(C-kt)}} \quad [1]$$

where

A = initial value of the measured property (mm),

B = change of initial value at the end of the process of the measured property (mm),

C = estimator of the time shift at the point at which shift is made,

D and E = estimators for the asymptotes of the hyperbolic phase (mm/s and mm^{-1} , respectively),

Figure 4. The fitted model on the evolution of the total range measured by the Foodtexture Puff Device (FPD) with the physical interpretation of the fit parameters. $2C$ = start point of gelation, A = initial total range, $A - B$ = final total range, and $2C - E/D$ = estimator for the speed of the gelation process.

k = rate at which the shift is made from the first (constant) phase to the second (hyperbolic) phase of the curve (here chosen as 0.5 mm^{-1}),

t = time (s), and

$f(t)$ = registered characteristic (fitted).

The advantage of this approach is that the estimated parameters of this equation have a descriptive interpretation (Figure 4). The time point of the start of the gelation process is estimated by $2 \times C$. The initial value of the measured characteristic is given by A , whereas the final value is given by $A - B$. The rate of change of the modeled parameter during the gelation process is estimated by $(2 \times C - E/D)^{-1}$. Because the correlation coefficients of the fits on the measured data were quite high (Table 1), these parameterizations were accepted.

This fit is calculated for all 5 monitored characteristics (i.e., minimal and maximal value and total range for the FPD measurements and G' and G'' for the rheological parameters) for each of the 7 monitored gelation processes at different initial milk pH.

Statistical Analysis

For the fitting of equation 1 on the registered data, a nonlinear iteration approach (proc nlinfit) was used in the SAS software. Not more than 30 iterations were needed to find the right model parameters. Pearson correlation coefficients between the model parameters of the different measured characteristics were calcu-

Table 1. Estimated process parameters after fitting equation 1 on the evolution of the different registered characteristics for the 7 measured gelation processes. In the bottom line, the R^2 of the fit is given. At right, the test parameters for the effect of pH on the characteristics are given. 2C = start of the process, A – B = final value of the characteristic, and 2C – E/D = speed of the gelation process

G'									
pH	6.01	6.11	6.21	6.29	6.41	6.51	6.61	<i>P</i>	R^2
2C***	392	499.8	590.4	792.2	1140	1401.6	2160	<0.0001	0.984
A – B*	2.5594	2.5497	2.5668	2.5621	2.5021	2.4546	2.2842	0.0228	0.67
2C – E/D**	148.2439	117.6922	168.8848	210.3538	218.2292	355.8308	510.1786	0.0007	0.958
R^2	0.99	0.99	0.99	0.98	0.97	0.96	0.98		
G''									
pH	6.01	6.11	6.21	6.29	6.41	6.51	6.61	<i>P</i>	R^2
2C***	413.6	541.6	623.6	840.8	1282.2	1499.6	—	<0.0001	0.988
A – B	1.9876	2.0055	2.0049	2.0221	2.0024	1.9374	—	0.3546	—
2C – E/D**	189.5406	206.6562	234.3051	321.231	465.7	550.9043	—	0.0019	0.876
R^2	0.99	0.99	0.99	0.99	0.99	0.97			
FPD ¹ Minimal deformation value									
pH	6.01	6.11	6.21	6.29	6.41	6.51	6.61	<i>P</i>	R^2
2C***	385.6	470	590.6	832.6	1200	1379	2009.6	<0.0001	0.989
A – B	–0.2016	–0.1242	0.038	0.1154	–0.443	–0.6237	–0.4349	0.124	—
2C – E/D***	270.475	316.7164	402.5643	656.0286	931.1111	1018.167	2105.055	<0.0001	0.961
R^2	0.99	0.99	0.99	0.99	0.99	0.99	0.99		
FPD Maximal deformation value									
pH	6.01	6.11	6.21	6.29	6.41	6.51	6.61	<i>P</i>	R^2
2C***	409.4	500	585.8	780.4	1193.8	1369.2	2020	<0.0001	0.9850
A – B	0.0765	0.0342	0.0484	0.0321	0.0434	0.045	–0.0239	0.0679	—
2C – E/D**	9.055647	25.12667	24.27977	36.35238	67.80651	78.7	148.8517	0.0002	0.9530
R^2	0.96	0.96	0.97	0.96	0.98	0.97	0.96		
FPD Deformation range									
pH	6.01	6.11	6.21	6.29	6.41	6.51	6.61	<i>P</i>	R^2
2C***	426.6	503.8	536	802.8	1118	1300	2009.6	<0.0001	0.968
A – B*	0.3554	0.3173	0.1604	0.117	0.975	1.4084	2.0504	0.013	0.510
2C – E/D	217.9136	205.6735	199.9831	416.2091	338.5128	252.0646	359.6	0.148	—
R^2	0.98	0.98	0.99	0.99	0.99	0.98	0.98		

¹FPD = Foodtexture Puff Device.

lated with the SAS software. Finally, relationships between the calculated model parameters and initial milk pH were investigated with the GLM approach of the SAS software.

RESULTS

In Table 1, the estimated process parameters after fitting equation 1 on the evolution of the different registered characteristics are given for the 7 monitored gelation processes at the different initial milk pH. Except for the G'' measurements on the milk of pH 6.61, the R^2 of each fit was found to be as high as 0.97; hence, they were accepted. On the evolution of the G'' of the milk at pH 6.61, no good fit could be made.

A high correlation could be found between the start points (2C) of the gelation process as calculated from the 3 characteristics of the FPD measurement and those registered by the classic rheology parameters G' and G'' (Table 2). Moreover, for each characteristic separately, an exponential increase with the pH for the $2 \times$

C value (see test statistics in Table 1, right-hand side) was found. These exponential models are presented in Figure 5. From this figure, it can be concluded that all registered characteristics start to change from the same time point during the gelation process, dependent on the milk pH.

Neither for the new characteristics that are calculated from the FPD measurements, nor for the classic rheology parameters G' and G'' , a good, statistically significant relationship between their value at the end of the gelation process (i.e., the A – B value) and the initial pH of the milk could be found. This means that the gelation processes at all of the different pH evolve toward the same state at the end of the process, at least for the characteristics measured here.

The rate of the change of the measured properties during the gelation process could be estimated by $(2C - E/D)^{-1}$. Here, an exponential increase of this rate was found with the increasing pH for all characteristics except for the range of the FPD signal. This can be concluded from Table 1 as well as from the correlation

Table 2. Pearson correlation coefficients between the Foodtexture Puff Device parameters and G' (storage modulus) and G'' (viscous modulus)

	G'			G''			Physical interpretation
	Minimum	Maximum	Range	Minimum	Maximum	Range	
$2C^1$	0.996	0.998	0.999	0.998	0.999	0.997	Start of process
$A - B^1$	0.644	0.828	-0.956	0.821	-0.279	-0.820	Texture at end
$2C - E/D^1$	0.964	0.959	0.461	0.989	0.986	0.399	Speed of process

¹ $2C$ = Start of the process, $A - B$ = final value of the characteristic, and $2C - E/D$ = speed of the gelation process.

table presented in Table 2. The exponential increase is presented in Figure 6. The value of the $(2C - E/D)^{-1}$ process estimator (rate of the process) is different for

each measured characteristic, whereas the $2C$ estimator (start of the gelation process) gives an absolute value that is the same for each characteristic. However, be-

Figure 5. The effect of initial milk pH on the start of the gelation process (temperature = 33°C) as measured by G' (storage modulus; ○), G'' (viscous modulus; +), the minimal (Min.) puff value (▲), the maximal (Max.) puff value (x), and the range of the puff (●). For each data set, the exponential model is presented.

Figure 6. Relationships between the speed of the gelation process estimated by $2C - E/D$ for G' (storage modulus) and G'' (viscous modulus; left plot), for the minimal puff value (middle plot), and for the maximal puff value (right plot). For each parameter, the exponential model as well as the data points are presented.

cause the $(2C - E/D)^{-1}$ parameter of the modeled changes in maximal and minimal deformation values are well correlated with G' and G'' (Table 2), they make the estimation of the rate of the gelation process possible.

DISCUSSION

In the described experiments, the gelation process of milk at different initial pH between 6.61 and 6.01 is monitored with a newly developed technique named FPD and with a classic rheometer. From the FPD measurements, the course of the maximal and minimal deformation and the total deformation under a constant force provided by an air puff is recorded. The measurements of this novel technique were compared with the classical rheology parameters G' and G'' .

A nonlinear equation was fit to these different variables to analyze their kinetics after rennet addition to the milk. This approach is different from the classic analyses where a coagulation process may be characterized by only one value, as there are the gelation times where $G' = G''$ (Gastaldi et al., 2003), the flocculation time or rennet coagulation time (Gunasekaran and Ak, 2003), or the time point for maximal deformation of G' (Lopez et al., 1998). In other research of Landfeld et al. (2002) or by fitting the Scott-Blair and Burnett model

(Scott-Blair and Burnett, 1963; Daviau et al., 2000), an equation is presented that may be used to fit the course of G' and G'' after the start of the gelation point. In our research, a new nonlinear model was used that is able to fit the course of G' and G'' , as well as the evolution of the parameters given by the novel FPD with high precision (Figure 3; Table 1) from the moment that the rennet was added to the end point of the gelation process. This model divides the course of the registered parameters in 2 different parts. The first part is the lag phase during which the registered property stays constant. The second part is the part with a hyperbolic change of the registered property. Another advantage of the proposed model is the direct descriptive interpretation of the model parameters. The start point of the gelation process, the process speed, and the end point can be directly calculated from the estimated model parameters.

The 3 characteristics measured by the FPD (maximal and minimal deformation values and deformation range) were modeled very precisely using the proposed model, and this was observed for all gelation processes in the presented research.

The time point of the start of the gelation process was estimated by the $2C$ value in equation 1. With the decreasing pH of milk, the coagulation process started earlier. The same exponential relationship between ini-

tial milk pH and start point of gelation was found for all monitored properties (Figure 5). This exponential relationship between the rheology parameters was presented before in research carried out by Daviau et al. (2000).

In our research, the $2C - E/D$ value increased exponentially with increasing pH for the G' , G'' , the FPD minimal value, and the FPD maximal value. Because the $2C - E/D$ value can be seen as an inverse estimator for the gelation rate, it may be concluded that the gelation rate decreased exponentially with increasing pH. Again, this is consistent with previous research (Lopez et al., 1998; Daviau et al., 2000).

The values of the measured properties at the end of the coagulation process, estimated by $A - B$ in the model, was not influenced by the pH of the initial milk. No evidence is found for such a relationship in the literature.

Altogether, the newly developed technology is able to determine the time of coagulation, the firming rate, and the final firmness of the coagulum, i.e., all of the relevant characteristics of the formation of coagulum from milk in a reliable way consistent with the most rigorous rheologic approach. Whereas other sensors were shown able to estimate the start of coagulation process too, the FPD is the first device that is able to monitor properly the firming process kinetics in a nondestructive way.

The estimation of coagulation characteristics is made in a straightforward manner by plain analysis of the signal and does not require specific calibration or the building of a database such as techniques based on neural network analysis (Acuña et al., 1999). Moreover, because this novel technique is nondestructive, no sampling is needed when placed over an industrial cheese vat, and it can be constructed to conform with today's hygienic design requirements. The criteria formulated by O'Callaghan et al. (2002) for an automated measurement technique are therefore fulfilled. In addition, a model is proposed that can describe the total gelation process. This makes the FPD a technique of interest for the development of a fully automated sensor head to monitor the coagulation process in the dairy industry.

ACKNOWLEDGMENTS

The research for this manuscript was carried out in the Foodtexture project, a fifth framework project that is supported by the European Union.

REFERENCES

- Acuña, G., F. Cubillos, J. Thibault, and E. Latrille. 1999. Comparison of methods for training Grey-Box Neural Network Models. *Comp. Chem. Eng. Suppl.* 23:S561-S564.
- Daviau, C., M.-H. Famelart, A. Pierre, H. Goudédranche, and J.-L. Maubois. 2000. Rennet coagulation of skim milk and curd drainage: Effect of pH, casein concentration, ionic strength and heat treatment. *Lait* 80:397-415.
- Gastaldi, E., N. Trial, C. Guillaume, E. Bourret, N. Gontard, and J. L. Cuq. 2003. Effect of controlled κ -casein hydrolysis on rheological properties of acid milk gels. *J. Dairy Sci.* 86:704-711.
- Gunasekaran, S., and M. M. Ak. 2003. *Cheese Rheology and Texture*. CRC Press, London, UK.
- Herbert, S., A. Riaublanc, B. Bouchet, D. J. Gallant, and E. Dufour. 1999. Fluorescence spectroscopy investigation of acid- or rennet-induced coagulation of milk. *J. Dairy Sci.* 82:2056-2062.
- Hori, T. 1985. Objective measurements of the process of curd formation during rennet treatment of milks by the hot-wire method. *J. Food Sci.* 50:911-917.
- Landfeld, A., P. Novotna, and M. Houska. 2002. Influence of the amount of rennet, calcium chloride addition, temperature and high pressure treatment on the course of milk coagulation. *Czech. J. Food Sci.* 20:237-244.
- Lopez, M. B., S. B. Lomholt, and K. B. Qvist. 1998. Rheological properties and cutting time of rennet gels. Effect of pH and enzyme concentration. *Int. Dairy J.* 8:289-293.
- Lucey, J. A. 2002. Formation and physical properties of milk protein gels. *J. Dairy Sci.* 85:281-294.
- Mayes, J. J., and B. J. Sutherland. 1984. Coagulum firmness and yield in cheddar cheese manufacture. *Aust. J. Dairy Technol.* 39:69-73.
- Najera, A. I., M. de Ronabales, and L. J. R. Barron. 2003. Effects of pH, temperature, CaCl_2 and enzyme concentrations on the rennet-clotting properties of milk: A multifactorial study. *Food Chem.* 80:345-352.
- O'Callaghan, D. J., P. O. O'Donnell, and F. A. Payne. 2002. Review of systems for monitoring curd setting during cheesemaking. *Int. J. Dairy Technol.* 55:65-74.
- Payne, F. A., C. L. Hicks, S. Mandagopal, and S. A. Shearer. 1993. Fiber optic sensor for predicting the cutting time of coagulating milk for cheese production. *Trans. ASAE* 36:841-847.
- Prussia, S. 1995. Non-destructive firmness measurement device. World patent WO 095/07772.
- Riddell-Lawrence, S., and C. L. Hicks. 1988. Effect of curd firmness on stirred curd cheese yield. *J. Dairy Sci.* 72:313-321.
- Scott-Blair, G. W., and J. Burnett. 1963. An equation to describe the rate of setting of blood and milk. *Biorheology* 1:183-191.
- Ustunol, Z., C. L. Hicks, and F. Payne. 1991. Diffuse reflectance profiles of eight milk-clotting enzyme preparations. *J. Food Sci.* 56:411-415.