

# Cutting Time Prediction Methods in Cheese Making

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## INTRODUCTION

Cheese is defined as the fresh or ripened product obtained by *coagulation* of milk and subsequent *separation* of the liquid and solid phases constituting the milk coagulum called whey and curd, respectively. The curd is further processed into cheese. *Formation of a milk gel* and *cutting the gel* into curd grains to allow *whey separation* are two major unit operations in cheese making. The first step of *gel formation* consists of casein micelle colloidal destabilization owing to chemical modification of the protective  $\kappa$ -casein hairy coat by the coagulating agents. The second step consists of aggregation of the destabilized casein micelles to form the gel network. Further cross-linking of casein micelles results in the development of a firm gel. For most cheese types, *whey and curd separation* does not take place spontaneously<sup>[1]</sup> and requires cutting the gel into small cubes (curd grains). This operation increases the gel surface/volume ratio, allowing the whey to escape while curd grains contract.

## IMPORTANCE OF CUTTING TIME SELECTION

Cutting time (CT) selection depends on rheological and microstructural properties of gels, such as *coagulum firmness* and *rearrangement* capability that, in turn, depend on coagulation factors, milk composition, and milk pretreatment (Fig. 1).

For this reason, CT selection greatly affects moisture, yield, and quality of cheese and whey fat losses. As Johnston et al.<sup>[2]</sup> pointed out, cutting and stirring speeds can also exert a marked impact on curd particle size and/or fat losses to the whey at draining. At constant cutting and stirring speeds, cutting the gel too soon enhances the mechanical impact of cutting and stirring operations on curd grains, which increases curd fines and whey fat losses, decreasing *cheese yield*. By contrast, delaying CT tends to produce the opposite effect on cheese yield. But, excessive delay in cutting also produces an overly firm gel, unable to collapse, which increases *curd moisture content*. Excessive moisture content causes a “fake” increase in yield and could alter the ripening process, compromising

cheese quality. The *economical impact* in terms of yield and quality of a defective CT selection has not been rigorously reported.

## CT SELECTION PROCEDURES

In practice, gel is usually cut after a *predetermined reaction time* or upon the *operator's judgment* based on subjective evaluation of textural and visual gel properties (Fig. 1). Cutting the curd after a predetermined time is a very common practice, but it is questionable because the factors that affect curd firmness and gel microstructure could vary the optimum CT. Cutting the curd by relying on empirical inspection is accurate and acceptable if the evaluation is made properly. It has been claimed that cheese makers can select the CT with amazing consistency,<sup>[3]</sup> but in the author's opinion, it is risky to assume that curd firming and gel tendency to exhibit syneresis can be “optimized” by empirical inspection. The lack of a rigorous CT characterization and the usual changes in milk protein content are forcing modern cheese plants to standardize the protein content of milk in an attempt to control coagulation, gel firming, curd syneresis, cheese yield, and product quality. A plethora of different techniques have been proposed in the period of more than seven decades for monitoring milk coagulation and curd firming, which clearly shows that industrial requirements for CT selection have not been fully satisfied. However, during the last years, some of those instruments have been demonstrated inline, and a small number of sensors have become commercially available. Nevertheless, the use of such sensors is just starting and, definitively, more research needs to be done on the economical benefits derived from their use.

## CLASSIFICATION OF TECHNIQUES FOR MONITORING OF MILK COAGULATION AND CURD FIRMNESS

Most of the proposed devices have been developed for fundamental research of coagulation and gel

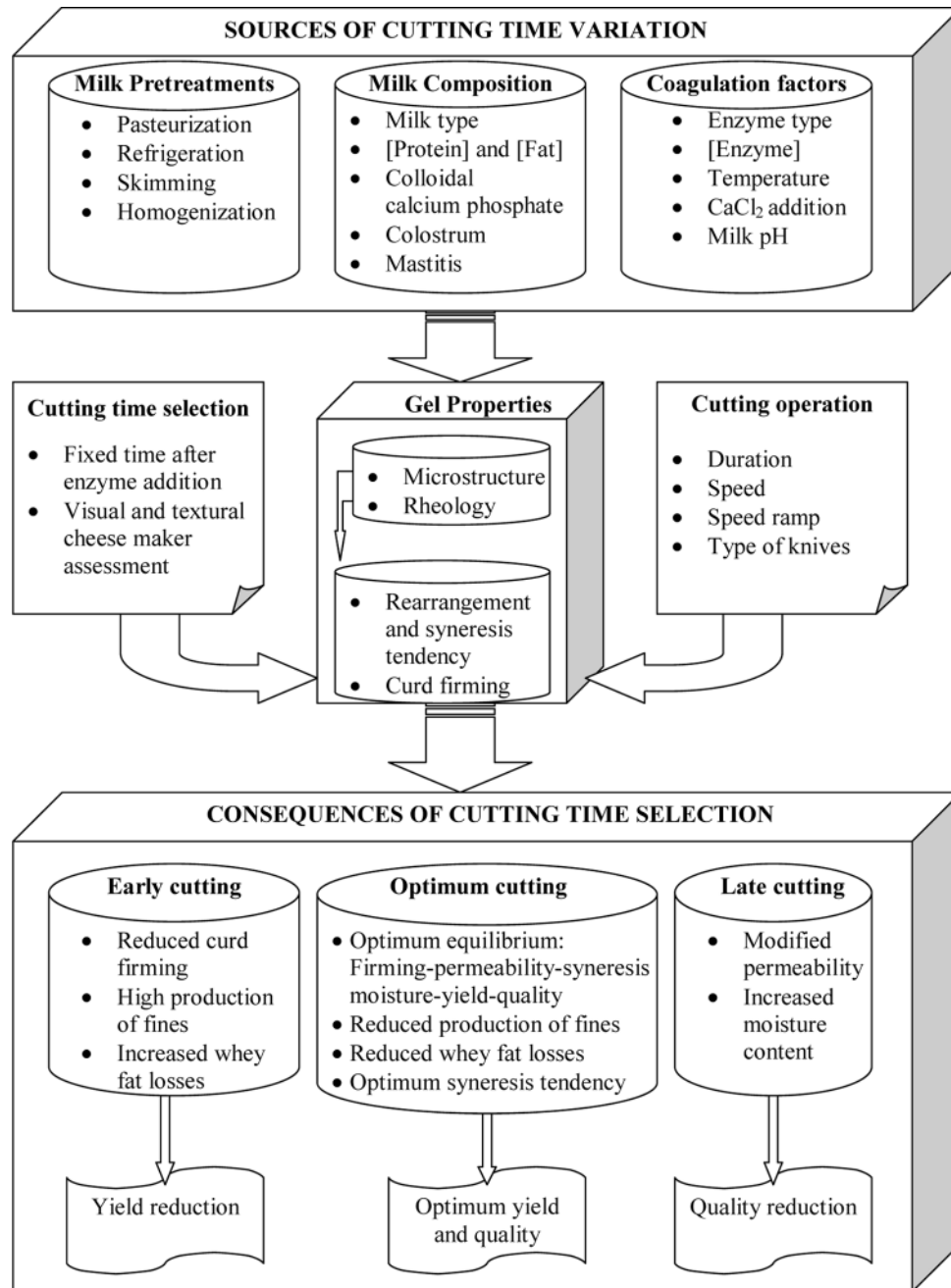


**Fig. 1** Relationship between gel properties and CT selection.

properties, evaluation and development of rennets and starter cultures, or development of inline CT sensors. Several authors have reviewed the apparatus that have been proposed for gel formation monitoring and cutting time setting.<sup>[1,4-6]</sup> Table 1 is an attempt at classifying those techniques.

We can categorize the different milk coagulation monitoring methods as nondynamic or dynamic methods depending on their suitability for carrying out continuous data acquisition during gelation.

### Nondynamic Systems

Nondynamic methods only permit single measurements, which is a limitation for kinetic studies. In general, these methods are not suitable for inline application owing to their intrusive nature. Nondynamic methods are mostly empirical and based on measurement of either rheological or optical properties. Casein micelle aggregation is visually observed when small flocks start adhering on the wall of an inclined, rotating

**Table 1** Classification of techniques that have been applied for monitoring milk coagulation and/or curd firming

|                           |                               |                     |                                                           |                      |
|---------------------------|-------------------------------|---------------------|-----------------------------------------------------------|----------------------|
| <b>Nondynamic systems</b> | <i>Destructive systems</i>    | Optical systems     | Berridge method or similar                                | [7,8]                |
|                           |                               | Rheological systems | Fingers tests                                             | Traditional practice |
|                           |                               |                     | Knife tests                                               | Traditional practice |
|                           |                               |                     | Penetrometers                                             | [9,10]               |
| <b>Dynamic systems</b>    | <i>Destructive systems</i>    | Rheological systems | Suspended bodies                                          | [11,12]              |
|                           |                               |                     | Rotational viscometers                                    | [13]                 |
|                           |                               |                     | Helipath                                                  | [14]                 |
|                           |                               |                     | Instron Universal Testing Machine: oscillatory testing    | [15]                 |
|                           |                               |                     | Vatimer <sup>a,b</sup>                                    | [16]                 |
|                           |                               |                     | Manometric methods <sup>a,b,d</sup>                       | [17–19]              |
|                           |                               |                     | Torsion viscometers                                       | [20]                 |
|                           |                               |                     | Electrical conductivity                                   | [21]                 |
|                           | <i>Nondestructive systems</i> | Electrical systems  |                                                           |                      |
|                           |                               | Thermal systems     | Hot wire <sup>a,c</sup>                                   | [22]                 |
|                           |                               | Rheological systems | Small amplitude oscillatory rheometry                     | [23]                 |
|                           |                               |                     | Vibrational systems <sup>a,c</sup>                        | [24,25]              |
|                           |                               | Ultrasonic systems  | Low- and high-amplitude pulse-echo systems <sup>a,b</sup> | [26]                 |
|                           |                               | Electroacoustics    | Alternating electric field and sound waves                | [27]                 |
|                           |                               | Optical systems     | Light reflection                                          | [28]                 |
|                           |                               |                     | Light refraction                                          | [29]                 |
|                           |                               |                     | Light scatter (turbidity) <sup>a,c</sup>                  | [30,31]              |
|                           |                               |                     | Light scatter (backscatter) <sup>a,c</sup>                | [32,33]              |
|                           |                               |                     | Dynamic light scatter                                     | [34]                 |
|                           |                               |                     | Diffusing wave spectroscopy (DWS) <sup>a,c</sup>          | NIZO Food Research   |
|                           |                               |                     | Microscopy                                                | [35,36]              |
|                           |                               |                     | Fluorescence spectroscopy                                 | [37]                 |

<sup>a</sup>The technique has been demonstrated inline.<sup>b</sup>Prototype only.<sup>c</sup>Commercial version available.<sup>d</sup>Among manometric apparatus, only Vanderheiden's Manometric Apparatus or Curd Firmness Tester and Hatfield's Apparatus or Pressure Transmission System have been demonstrated in the vat.

bottle<sup>[7]</sup> or test tube.<sup>[8]</sup> These two subjective methods allow estimating the coagulating activity of enzymes and are generically known as “*clotting time measurements*.” Most common methods representing the traditional cheese maker practice for CT selection, such as *finger and knife tests*, could be considered an empirical type of rheological measurement that provides a rough idea of gel firmness.

The cheese maker exerts a pressure on the gel surface with a finger or spatula and lifts the curd to see if there is a clean gel break and if the whey drained is clear.<sup>[1]</sup> *Penetrometers* determine the force or depth of penetration of a deformation probe at a certain gel position<sup>[9,10]</sup> and provide relative measurements owing to their dependency on the probe geometry.

## Dynamic Destructive Systems

Dynamic systems allow continuous data acquisition for studying the kinetics of milk coagulation and can be classified in destructive and nondestructive methods. Destructive systems can be subdivided in nonoscillatory and oscillatory testing. Nonoscillatory testing is frequently performed using an Instron Universal Testing Machine. A suspended body (sphere or cone) is attached to the load cell that measures the gel resistance to the body's rise during gelation.<sup>[11,12]</sup> These empirical devices exert complex and poorly defined deformations. *Rotational viscometers* use a rotating cylinder or disc that experiences a viscous drag.<sup>[13]</sup> The resulting torque depends on milk viscosity, spindle speed, and spindle characteristics. Rotational viscometers provide limited information about curd firming because the viscosity of renneted milk tends toward infinity around visual clotting time. Some devices such as Instron (in oscillatory testing mode), Vatimer, Helipath viscometer, Manometric devices, and Torsion viscometers respond to either periodic or harmonic oscillating assay principles (except for the U-tube manometric method). The *Helipath*<sup>[14]</sup> measures changes in viscosity with time while cutting the gel with a T-shaped wire following a periodical, helicoidal path that allows cutting fresh gel all the time. The *Instron*<sup>[15]</sup> and the *Vatimer*<sup>[16]</sup> measure the mechanical resistance exerted by the gel on a rectangular gauze or a metallic disc, respectively, that is vertically oscillating. Manometric methods include instruments such as the *Vanderheiden's manometric apparatus*,<sup>[17]</sup> its modified version by *Hatfield*,<sup>[18]</sup> and the *Scott-Blair U-tube*.<sup>[19]</sup> They all measure the pressure transmitted through the milk to a pressure measurement system (capillary tube, pressure sensor, etc.). In Vanderheiden's and Hatfield's apparatus, a hydraulically oscillating diaphragm or transmitter produces a pressure wave that is transmitted through the gel and measured by another oscillating diaphragm, the receiver. However, while Vanderheiden's and Hatfield's apparatus are empirical instruments, the U-tube can measure a fundamental rheological property, the elastic modulus or  $G'$ , by relating the applied pressure to the geometry and displacement of the gel. *Torsion viscometers* (*thrombelastography* or *lactodynamography*) have been also widely used to determine both rennet coagulation time and curd firming. In torsion viscometers, a suspended pendulum or a cylinder is immersed in the milk. The sample holder is oscillated or rotated, creating a drag on the pendulum in the milk, which is recorded continuously. Most popular torsion viscometers are the *Thromboelastograph*, the *Formagraph*<sup>[20]</sup> that allows 10 simultaneous measurements, and the Scott-Blair Torsionometer and its industrial version of Plint and Partners.

In general, the parameters obtained by those devices have no precise rheological significance. However, the rigidity modulus,  $G$ , has been approximated from the Formagraph signal.<sup>[1]</sup>

## Dynamic Nondestructive Systems

Most of the nondestructive systems measure changes in conductivity of certain physical properties such as electric current, heat, ultrasound, or electromagnetic radiation. *Electrical conductivity* increases 0.5–1% during milk coagulation,<sup>[21]</sup> but this monitoring technique has some significant limitations such as large temperature coefficient of conductivity and possibilities of interference between the original milk electrolytes and the measurement. A *thermal conductivity* sensor detects changes in convective heat transfer from a "hot wire" to the surrounding milk that are caused by the variation in viscosity during coagulation.<sup>[22]</sup> *Hot wire sensor* has been demonstrated to measure very accurately the gelation point that, in turn, can be used to predict CT. However, because viscosity increases exponentially between the beginning of aggregation and the onset of visual coagulation, the hot wire is not well suited for measuring gel stiffness. It should be noted that coagulation factors such as casein concentration affect the gel point independently of the curd firming rate. Some rheological nondestructive methods have been proposed for gelation and firming measurement. With *small deformation rheometry*,<sup>[23]</sup> the gelation process is not affected by the measurement because the renneted milk is subject to a harmonic low-amplitude shear strain (or stress depending on the rheometer) at a certain angular frequency within the linear viscoelastic limits of the sample. Under these conditions, the gel network recovers instantaneously when the stress is removed. This method allows continuous measurement of well-defined rheological parameters such as elastic and viscous moduli,  $G'$  and  $G''$ , complex rigidity modulus,  $G^*$ , and the loss factor or  $\tan \delta = G''/G'$ . The elastic modulus,  $G'$ , is a direct measurement of gel firmness, while  $\tan \delta$  is related to the viscoelastic properties and rearrangement capability of the gel. A relatively new generation of sensors using stainless steel probes that vibrate either in transverse (longitudinal)<sup>[24]</sup> or torsional mode<sup>[25]</sup> are much less destructive than other rheological systems and could be installed in the vats, because they use the piezoelectric principle. However, if the amplitude of the motion is too high, they expose the curd to the risk of microsyneresis. These *vibrational probes* allow measuring the increase of viscosity before gelation as well as curd elasticity after gelation (complex fluid viscosity can be measured). *Ultrasound systems* use an ultrasound emitter and receiver to measure the attenuation of

ultrasound waves through the milk during coagulation.<sup>[26]</sup> Attenuation and changes in velocity of ultrasonic waves have been tested during gel formation. However, air bubbles and fat globules might confound the measurements. Ultrasound has potential, but the technology seems not yet ready for industrial application. Recently, an *electroacoustic method* that induces casein particle oscillation, and thereby pressure disturbance, by an alternating electric field has been proposed for monitoring particle size during coagulation.<sup>[27]</sup> The last group of continuous and nondestructive methods is based on the measurement of optical properties such as reflection, absorbance, scatter, and refraction of light. Many of those optical methods are very suitable for inline measurement using optical fibers. *Reflection photometry (colorimeters)* has been applied to follow milk coagulation. The coordinates  $L^*$  and  $b^*$  (lightness and blue-yellow, respectively) rise during coagulation, which has been attributed to the increase in the average dimension of casein particles during their aggregation.<sup>[28]</sup> Changes in the *refractive index* of renneting milk have also been applied for following up of both acid and enzymatic gels. Korolczuk,<sup>[29]</sup> in 1988, fitted the refractometric profile obtained during coagulation to several theoretical equations describing the increase of the rigidity modulus during gel firming. Study of network formation has also been often realized using *light scattering*. In a particulate media, light that is not absorbed is either transmitted or scattered (Fig. 2).

*Static light scatter* can be measured in two different ways. In a nonabsorbing media, it is possible to measure directly the portion of incident light that is scattered at a certain angle (backscatter,  $0^\circ$ ; sidescatter, generally  $\leq 90^\circ$ ) or measure indirectly the portion of light that has not interacted with the media, i.e., the relative transmitted light. Measurements of light scatter at  $90^\circ$  are often referred as *nephelometry* while light scattering measured by transmission is referred as conventional *turbidity*. In milk and, especially, in the visible and near infrared ranges, light scattering predominates over absorption. Light scattering is directly related to the rate of aggregation and curd firming if total casein concentration does not vary during the measurements. Indeed, use of optical fibers allows applying different optical configurations for sensor development. Conventional turbidity measurements were one of the first light scattering techniques proposed for monitoring network growth.<sup>[30]</sup> A nondestructive optical device, the *Gelograph-NT*, which is based on conventional turbidity measurements (transmission), has been developed from the previous rheological method, *Gelograph-M* (based on an oscillating sensing needle). A 10-channel lab version of the *Gelograph-NT*, the *Optigraph*,<sup>[31]</sup> which allows estimating clotting time and CT has been developed. Direct light backscatter measurements, such as those performed at 880 nm by the inline sensor *CoAguLite* developed by Payne et al.<sup>[32]</sup> in 1990, have the advantage that the measurements do not depend on a certain

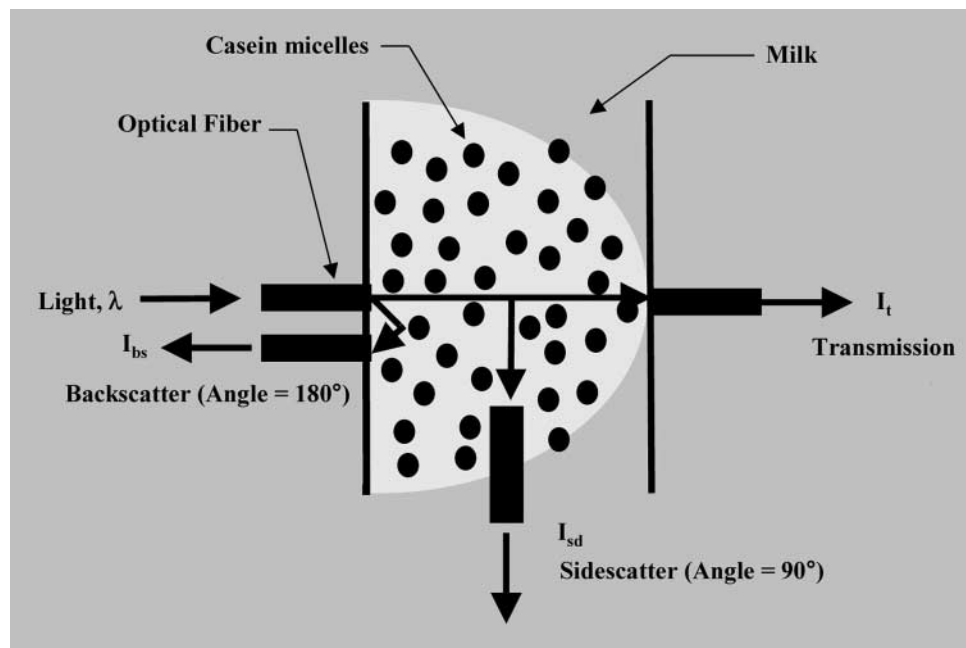


**Fig. 2** Different optical configurations that have been applied for monitoring coagulation and curd firming using light scatter measurements.

path length as compared to indirect light scatter measurements based in relative transmission (Optigraph). The light backscatter measurements after the curve inflection point have been described by combining a second-order reaction model to describe aggregation reactions and a first-order reaction model to describe firming processes reactions.<sup>[33]</sup> Horne and Davidson,<sup>[34]</sup> in 1990, applied the DWS, a measuring method based on dynamic light scattering techniques, to study particle diameter evolution during rennet curd formation. They stated that the technique was able to monitor the entire gel firming stage. DWS has been applied inline by NIZO Food Research to follow the curd firming progress during cheesemaking (*Rheo-light*). Other less practical optical and nondestructive techniques such as *electron microscopy*,<sup>[35]</sup> *dark-field microscopy*,<sup>[36]</sup> and *fluorescence spectroscopy*<sup>[37]</sup> have been also tested for describing the extent of aggregation. Table 1 shows the methods that have been demonstrated inline and those that are currently, commercially available.

### THE NEED FOR A PRECISE CT CHARACTERIZATION

Differences in milk composition and in coagulation processing conditions have an impact in curd firming and thereby in CT. Optimum selection of CT is most important for *small and less-automated cheese plants* where large differences in milk batch composition and coagulation procedures exist. Small-scale cheese factories also have more flexible process schedules that allow variation of the renneting time. In contrast, *large-scale and highly automated cheese facilities* are not willing to modify the CT because of their precise processing schedules. More likely, they *standardize the milk composition* to control CT. But, unfortunately, out-of-control variations in processing conditions and human errors could potentially result in significant economic expenses because of the large volumes of milk processed per vat. For those cases, an inline curd firming sensor could provide *real time corrections* and reduce fine and fat losses during cheese production. In addition, it is well known that longer CT tends to increase yield, but could also compromise cheese quality owing to a rise of curd moisture content. It seems reasonable to assume that there must be an *optimum CT* where gel properties optimize cheese yield, homogeneity, and quality.<sup>[1]</sup> However, the determination of an optimum CT has not been scientifically characterized. The author did not find any rigorous report on the economical impact of CT considering all the factors involved: energy cost for cutting and stirring; cheese yield; cost of defects owing to improper curd moisture content; and overall homogeneity and cheese quality.

### CONCLUSIONS

A reliable inline method to monitor curd firming and predict CT is needed to improve cheese processing automation, cheese quality, and cheese plants profits. This would require: improving our knowledge about curd firming development, gel rearrangement, and gel syneresis; characterizing rigorously CT; and finally, defining the optimum range for curd firming and gel tendency to rearrange and synerize per each type of cheese. From this point of view, an objective curd firming inline sensor would have a great impact in cheese making.

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