

Impedimetric Biosensor for the Assessment of the Clotting Activity of Rennet

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Cheese production is relied upon the action of rennet (a mixture of chymosin and pepsin) onto casein micelles of milk. For the first time, the monitoring of this interaction with electrochemical impedance spectroscopy (EIS) was used to develop a faradic impedimetric biosensor for the assessment of the clotting activity of rennet, using hexacyanoferrate(II)/(III) couple as a redox probe. Gold electrodes were modified with self-assembled monolayers of different thiols (thioctic acid, dithiobis-*N*-succinimidyl propionate, and cysteamine), and (artificial) casein micelles were immobilized on the modified gold surfaces. The proposed method is based on the measurement of charge-transfer resistance (R_{ct}) changes attributed to the degradation of the negatively charged immobilized casein micelles by rennet to neutral biostructures. This action results in the increase of the flux of the redox probe, which exists in the bulk solution, to the surface of the electrode and, consequently, in the decrease of R_{ct} . Experimental parameters such as the micelle loading, the reaction time, the concentration of rennet, and the working pH, were optimized. Besides EIS measurements, cyclic voltammetry, FT-IR, and atomic force microscopy (AFM) experiments were also performed before and after the interaction of the immobilized micelles with rennet. Finally, the proposed biosensors were successfully tried for various commercial samples.

The casein content of milk represents about 80% of milk proteins. The principle casein fractions are α_{s1} -, α_{s2} -, β -, and κ appa-casein (κ -CN), and their distribution in cow's milk is 38, 10, 40 and 12%, respectively.¹ In combination with appreciable quantities of colloidal calcium phosphate (CCP) nanoclusters, they appear in the form of not-quite spherical colloids, 50–500 nm in diameter, called casein micelles.² The distinguishing property of all caseins is their low solubility at pH 4.6.

Rennet is a natural complex of enzymes produced in any mammalian stomach, and it is widely used in the cheese making

industry as the major milk coagulant.³ The milk-clotting activity of rennet relies on its ability to degrade casein micelles, and this action depends on the chymosin (pI $\approx$ 4.6) content of the complex. Chymosin proportion may differ by source (cow, lamb, goat, chicken, camel, or nonanimal sources) and age, accompanied by a concomitant alteration of pepsin content.⁴ The proportions normally present in commercial rennets are 70% chymosin and 30% pepsin.⁵

Rennet coagulation of milk may be divided into primary (enzymic hydrolysis) and secondary (aggregation) stages, although these stages normally overlap to some extent during cheese making. During the primary stage, chymosin hydrolyses the outer “hairy layer” of κ -CN (Figure 1A). More specifically, κ -CN is cleaved by rennet at the Phe105–Met106 bond, producing the soluble glycomacropeptide (GMP, residue 106–169), which diffuses away from the micelle into the serum phase, and the positively charged (pI > 7)⁶ insoluble para- κ -casein molecules, which remain attached to the casein micelle.^{1–3} This results in a reduction of the net negative charge of micelles, as well as of the electrostatic repulsion among them. As a consequence, rennet-altered micelles become susceptible to aggregation⁷ (Figure 1B). The nature of the attractive forces during the aggregation of casein micelles is still not completely clear, although calcium bridges, van der Waals forces, and hydrophobic interactions appear to be involved.^{3,8}

The evaluation of the clotting power of rennet has always been a parameter of great importance from scientific, technological, and commercial viewpoints. The importance of this parameter has raised the scientific interest since the end of the 19th century when the first method, based on visual observation of the formation of a clot, was published.⁹ Since then, numerous methods, which also depend upon visual observations of the coagulation point of the milk, have been used to measure rennet activity.^{10–12} Even though they are still in routine use, they suffer from the subjective nature of the observation, especially when

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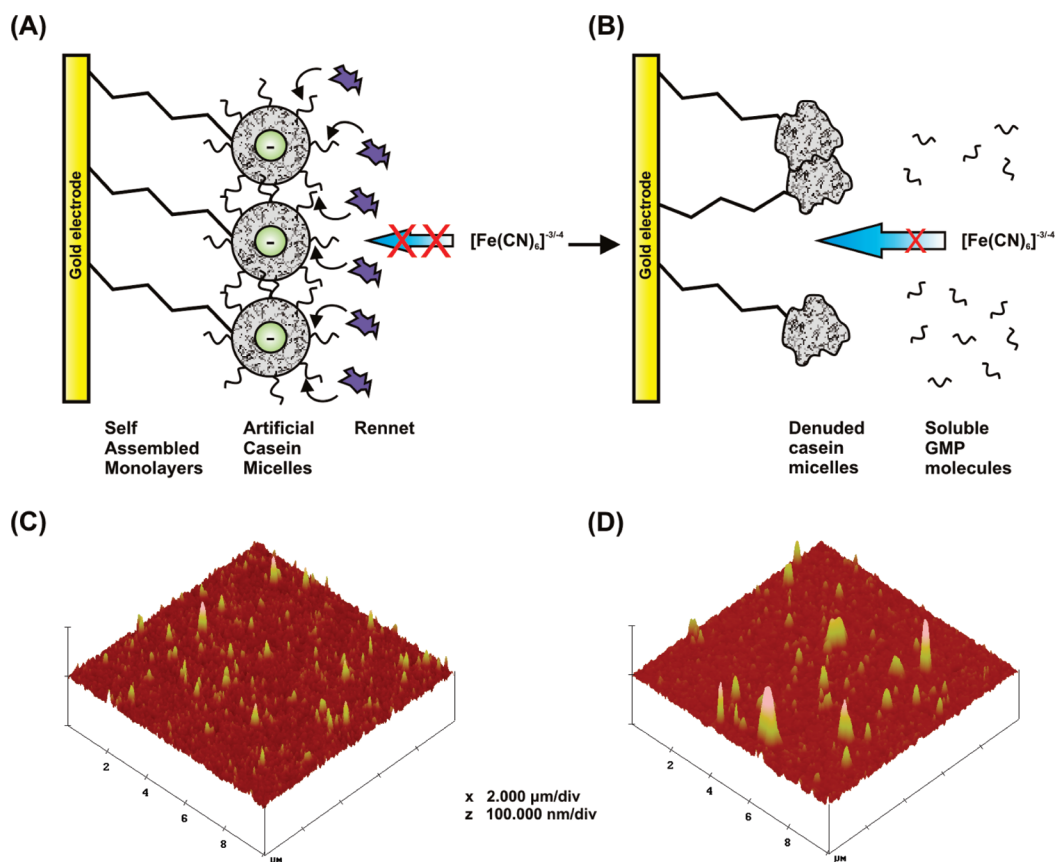


Figure 1. Idealized view of Au/SAM/ACM electrodes (A) before and (B) after their interaction with rennet. AFM micrographs obtained from Au/DTSP/ACM surfaces (C) before and (D) after incubation in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5.0, for 2 h at 37 °C. Drawings A and B are not to scale.

different persons in different laboratories are involved. Some of these drawbacks have been adequately overcome by the joint IDF/ISO Standard - ISO 11815/IDF 157:2007 method, which uses reference rennet powder with an overall milk-clotting activity of 1000 IMCU g^{-1} (IMCU = international milk-clotting units).¹³

Other methods based on blood clot timers¹⁴ or on viscosity measurements of renneted milk^{15–17} have also been proposed. In addition, spectrophotometric measurements of milk-rennet reaction products at 290 nm,¹⁸ measurements of the electric conductivity,¹⁹ and a turbidity method²⁰ have also been proposed. The first instrument proposed for measuring milk clotting, the Formagraph, was developed in 1980.^{21,22} Its operation is based on the movement of a small pendulum immersed in oscillating samples of renneted milk and a light flash for recording the position of the pendulum, as it alters due to the milk clotting, on a photographic paper. Formagraph was then replaced by the

Optigraph (Ysebaert, France),²³ an also bench-type instrument, which employs measurements of near infra red attenuation through a milk sample during its coagulation. According to a recently published comparative study, results received by both instruments correlate well.²⁴

Aiming to develop an inexpensive and easy-to-perform method, compatible with the modern sensor technology, artificial casein micelles (ACM), made by commercially available sodium caseinate, were immobilized onto self-assembled monolayers (SAMs) of thiol-modified gold electrodes (Au/SAMs). Employing faradic impedimetric measurements before and after the immersion of the electrodes (Au/SAMs/ACM) in rennet samples, clotting power is expressed by the relative decrease of the charge-transfer resistance, R_{ct} .

EXPERIMENTAL SECTION

Chemicals and Solutions. Sodium caseinate, thioctic acid (TA), dithiobis-*N*-succinimidyl propionate (DTSP), cysteamine (CYS), lysine, and glutaraldehyde (GA; ~25% in water; kept in sealed vials under argon at +4 °C) were purchased from Sigma. 1-Ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC), *N*-hydroxysuccinimide (NHS), imidazole, D-(+)-gluconic acid δ -lactone, absolute ethanol, potassium ferrocyanide, and potassium ferricyanide were from Merck. All other chemicals were from Merck and Sigma and double distilled water (DDW) was used through-

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out. Rennet solutions were prepared before use by dissolving appropriate amounts of dry powder of calf and/or bovine rennet (Ipirotopoula, Greece; Chr. Hansen, Denmark) in a 20 mM solution of imidazole pH 5–6.5. Rennet samples in liquid form (Chr. Hansen; Danisco, Denmark) were mixed with an equal volume of 40 mM imidazole, and the pH of the mixture was adjusted to 5 with 0.1 N HCl. A 20 mM imidazole solution, pH 6.5, was used in various washing steps throughout the buildup and storage of the biosensors. A 50 mM phosphate buffer (PB) solution, pH 7, was used for the activation of amine groups at Au/CYS electrodes with glutaraldehyde.

Preparation of Artificial Casein Micelles. Suspensions of artificial casein micelles (ACM) were weekly prepared by a modified Patent method.²⁵ Powdered sodium caseinate (6.3 g) was carefully added into 50 mL of hot DDW (~55 °C) and mixed under stirring for about 6 to 7 h to achieve a homogeneous opaque solution. The solution was left to reach a temperature of 37 °C, and then, 4.56 mL of an aqueous solution of 0.87 mM CaCl₂ was added dropwise into the caseinate solution with a constant mixing over a 20 min period of time under stirring. Then, 2.98 mL of an aqueous mixture of 17.1% (*w/v*) K₂HPO₄ and 1.8% (*w/v*) NaOH was introduced dropwise into the stirred reaction medium, with a constant mixing over a period of 6 min. Afterward, the mixture was kept under stirring for 3 h at room temperature and remained for at least 12 h at 4 °C before use. The size of ACM depends on the addition order of the reagents in the mixture and the mixing rate.²⁶ The as-produced ACMs have a mean diameter of 250 nm.²⁵

Apparatus. Electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV) experiments were performed with the electrochemical analyzer PGSTAT12/FRA2 (Metrohm Autolab) in a one-compartment three-electrode cell. Gold electrodes and a platinum wire were served as the working and auxiliary electrodes, respectively. The reference electrode was a Ag/AgCl/3 M KCl (IJ Cambria) electrode, and all potentials reported hereafter refer to the potential of this electrode. The impedance spectra were recorded over the frequency range of 10⁻¹–10⁵ Hz, using a sinusoidal excitation signal, superimposed on a DC potential of +0.200 V. Excitation amplitude of 10 mV (rms) was used throughout. All measurements were performed in a solution of 5 mM hexacyanoferrate (II)/(III) (1 + 1 mixture) in a 50 mM imidazole buffer solution, pH 6.5, containing 100 mM KCl, at room temperature.

FT-IR studies were conducted with an FT-IR optical spectrometer (Thermo-Electron) over gold surfaces, which had been functionalized according to the procedures described below. The surface topography of ACM-modified gold surfaces, before and after their immersion in rennet solutions, was studied by atomic force microscopy (AFM), at tapping mode, using a Nanoscope IIIA instrument (Digital Instruments).

Formation of SAMs and Immobilization of ACM. Gold electrodes were constructed using the commercial kit EasyCon (EasyCon Hellas, provided by Metrohm Autolab). Before use, gold electrodes of 2 mm active surface were polished with Al₂O₃ (0.01 μm grain size) and sonicated for 3 min in DDW. After polishing, gold surfaces were cleaned by dipping into a solution of 1 + 1

+ 5 (*v/v*), NH₄OH + 30% H₂O₂ + H₂O for 10 min, washed thoroughly with DDW, and dried under argon. Immobilization of ACM onto the three different modified gold electrodes was made as follows.

Au/TA Electrodes. Gold electrodes were immersed in a solution of 1 mM TA in ethanol for 20 h, rinsed thoroughly in fresh baths of absolute ethanol, and dried under argon. Activation of the terminal carboxyl groups was done in a freshly prepared mixture of 0.2 M EDC and 0.05 M NHS in DDW for 30 min under stirring. Activated surfaces were thoroughly washed with the same solvent, and finally, 1 mL of the ACM suspension [undiluted, 1 + 1, 1 + 2, 1 + 4, 1 + 8 (*v/v*) mixtures of it with 0.2 M NaCl, all at pH 6.5, and 1 + 4 (*v/v*) mixture with 0.2 M NaCl at pH 5.6] was placed, with the aid of a plastic cup, over the electrode surface for at least 12 h in a humidified glass chamber. Adjustment to pH 5.6 was made by adding appropriate amounts of a 0.2 M solution of gluconic acid δ-lactone in the ACM/NaCl mixture.

Au/CYS Electrodes. Gold electrodes were immersed in a solution of (10 or 20) mM CYS in ethanol for 20 h, rinsed thoroughly in fresh baths of absolute ethanol, and dried under argon, and then, they were immediately immersed in a degassed solution of 2.5% glutaraldehyde in PB solution for 1 h under mild stirring. After thoroughly rinsing with the same buffer solution, to remove the physically absorbed glutaraldehyde, 1 mL of the ACM suspension [undiluted and as an 1 + 4 (*v/v*) mixture with 0.2 M NaCl, pH 6.5] was placed, with the aid of a plastic cup, over the electrode surface for at least 12 h in a humidified glass chamber.

Au/DTSP Electrodes. Gold electrodes were immersed in a solution of 2 or 5 mM DTSP in acetone for 4 h, rinsed thoroughly in fresh baths of acetone, and dried under argon. Then, 1 mL of the ACM suspension [undiluted and as an 1 + 4 (*v/v*) mixture with 0.2 M NaCl, pH 6.5] was placed, with the aid of a plastic cup, over the electrode surface for at least 12 h in a humidified glass chamber.

Before use, all the above Au/thiol/ACM electrodes were immersed in a 0.1 M solution of lysine to deactivate the remaining amine-active groups, washed thoroughly with 20 mM imidazole solution, pH 6.5, and stored in the same buffer until use.

Fixation of immobilized ACM (if it is stated) was made by incubating the fully functionalized (Au/TA/ACM) electrodes in a solution of 2.5% glutaraldehyde in 20 mM imidazole, pH 6.5, for 30 min under mild stirring. Before use, glutaraldehyde-fixed biosensors were extensively washed (4 × 10 min) in 20 mM imidazole, pH 6.5.

Procedure. Fully functionalized (Au/thiol/ACM) electrodes were incubated in rennet solutions in 20 mM imidazole, pH 5–6.5, for a specified time interval at 37 °C, rinsed thoroughly with a 20 mM imidazole solution, pH 6.5, and transferred to the measuring cell. All the optimization studies were made with the product “Ipirotopoula”.

Calculations. Throughout this study, the relative change of the signal of the Au/thiol/ACM electrodes, before and after their immersion to the rennet solution, Δ*S* (%), which is expressed as Δ*S* (%) = {[*R*_{ct} (after the immersion to rennet) – *R*_{ct} (before the immersion to rennet)]/*R*_{ct} (before the immersion to rennet)} × 100, was taken as a measure of the clotting power of the tested samples. Relative signal changes (*R*_{ct}^{Au/thiol/ACM/}

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$R_{\text{ct}}^{\text{Au/thiol}} \times 100$ were used as a measure of the efficiency of immobilization of ACMs onto the different Au/TA, Au/DTSP, and Au/CYS electrodes. At Au/TA/ACM electrodes, R_{ct} values correspond to the real impedance component at 0.1 Hz, since attempts to model the impedimetric data as Randles circuit or different two-time constant equivalent circuits showed a poor fit to the model, indicating that the circuit was considerably more complex. On the other hand, in both Au/CYS/ACM and Au/DTSP/ACM biosensors, R_{ct} values were calculated by fitting the impedance data to a Randles equivalent circuit $R_s(Q_{\text{dl}}[R_{\text{ct}}W])$.²⁷

RESULTS AND DISCUSSION

Rennet action results in the degradation of the negatively charged immobilized ACM and the formation of denuded, neutral biostructures (Figure 1A). This action has a dual effect, namely, (i) elimination of the negative charge, which repulses the negatively charged redox probe and (ii) partial aggregation of ACM (Figure 1B), which increases the part of nonblocked electrode surface. Both effects result in the increase of the flux of the redox probe, which exists in the bulk solution, to the surface of the electrode and, consequently, in the decrease of R_{ct} . Referring to immobilized ACM, the stage of aggregation is expected only among adjacent casein micelles. On the basis of the atomic force micrographs of the ACM-modified gold surfaces taken before (Figure 1C) and after (Figure 1D) their incubation in rennet solutions, an idealized view of this process is illustrated in Figure 1A,B.

A determining factor in the performance of the proposed biosensors is the design of the immobilization platform in order to achieve functional surfaces. For this reason, our study includes modification of the gold surfaces with SAMs bearing negatively (TA), neutrally (DTSP), or positively (CYS) charged terminal groups. A detailed description of the performance of the corresponding biosensors is given below.

Au/TA/ACM Biosensors. Immobilization of ACM. Protein immobilization via carbodiimide chemistry is favored when the pH of immobilization lies between the isoelectric point of the protein and the pK_a of the surface. Activation with EDC/NHS roughly results in a 30–40% transformation of the carboxyl groups to amine-active succinimide esters, and thus, the immobilization platform carries negative charge. At pH values lower than the isoelectric point, proteins carry a net positive charge and, due to electrostatic interactions, are effectively preconcentrated on the immobilization carrier. Thus, the pH of the immobilization solution is a crucial parameter to receive high yields of immobilization, and actually, this is a conflicting point between previous published works referring to the immobilization of casein micelles onto gold surfaces modified with SAMs of 11-mercaptopundecanoic acid.^{28,29} However, the low solubility of caseins at pH values near their isoelectric point does not allow them to efficiently preconcentrate near the surface of the electrode. To overcome this problem, immobilization experiments were performed with solutions of high ionic strength.

Table 1. Evaluation of Coupling Yields of ACMs onto Au/TA Electrodes Taken as a Measure of Values of R_{ct} before and after the Immobilization Step^a

electrode assemblies at different modification steps	$(R_{\text{ct}}^{\text{Au/thiol/ACM}}/R_{\text{ct}}^{\text{Au/thiol}}) \times 100$
Au/TA electrodes	100
Au/TA electrodes after activation with EDC/NHS	32 ^b

Au/TA electrodes after immobilization using	$(R_{\text{ct}}^{\text{Au/thiol/ACM}}/R_{\text{ct}}^{\text{Au/thiol}}) \times 100$
undiluted ACMs suspension	120
1 + 1 v/v ACM + DDW, pH 6.5, 24 h	150
1 + 1 v/v ACM + 0.2 M NaCl, pH 6.5, 24 h	175
1 + 2 v/v ACM + 0.2 M NaCl, pH 6.5, 24 h	400
1 + 4 v/v ACM + 0.2 M NaCl, pH 6.5, 24 h	450
1 + 2 v/v ACM + 0.2 M NaCl, pH 5.6, 24 h	470
1 + 4 v/v ACM + 0.2 M NaCl, pH 5.6, 24 h	550

^a R_{ct} value at Au/TA electrodes was taken as 100%. ^b $(R_{\text{ct}}^{\text{Au/thiol/after activation}}/R_{\text{ct}}^{\text{Au/thiol}}) \times 100$.

In a series of comparative experiments, immobilization of ACM was tested from the original suspension and 1 + 1, 1 + 2, and 1 + 4 (v/v) mixtures of it with a solution of 0.2 M NaCl or DDW. From the results tabulated in Table 1, we can assume that diluted mixtures of ACM, especially those containing NaCl, serve as the most suitable immobilization solutions. Sodium chloride at a dilution ratio of 1 + 4 seems to provide an effective shield to the negative charge of ACM and an increased concentration of ACMs close to the immobilization surface, resulting in higher coupling yields. Dilution ratios and the concentration of NaCl were selected to preserve the 3D-structure of ACMs. Higher dilution ratios (1 + 8) or higher concentrations of NaCl result in unstable mixtures (precipitation of ACMs over time) due to an ion exchange process with the calcium cations present in the micelles.^{30,31} On the other hand, mixtures up to 1 + 4 v/v with 0.2 M NaCl are quite stable over time (see IR studies below).

Moreover, in both 1 + 2 and 1 + 4 mixtures, lowering of the pH of the immobilization solution from 6.5 to 5.6 leads to higher coupling yields, as at more acidic regimes the repulsing electrostatic forces between ACMs and the immobilization surface become weaker.^{28,29}

CV and EIS Studies. CV and EIS spectra during the various modification and interaction steps are illustrated in Figure 2A,B, respectively. Figure 2A shows superimposed CVs of the redox couple using a scan rate of 100 mVs⁻¹ at (a) bare, (b) Au/TA, and (c) Au/TA/ACM electrodes before and after (d) their immersion to a 0.2% solution of rennet in 20 mM imidazole solution, pH 5, at 37 °C for 2 h. Formation of the SAM of thioctic acid inhibits the electrochemical reaction, thus both oxidation and reduction peaks disappear. Immobilization of bulky ACM results in further decrease of the current due to the effect of the ACM on blocking interfacial electron transfer. It is, also, important to note that both layers (SAMs of TA and ACM) generate a negatively charged interface that repels negatively charged $[\text{Fe}(\text{CN})_6]^{4-/3-}$ anions. This repulsion is anticipated to retard the interfacial electron-transfer kinetics of the redox

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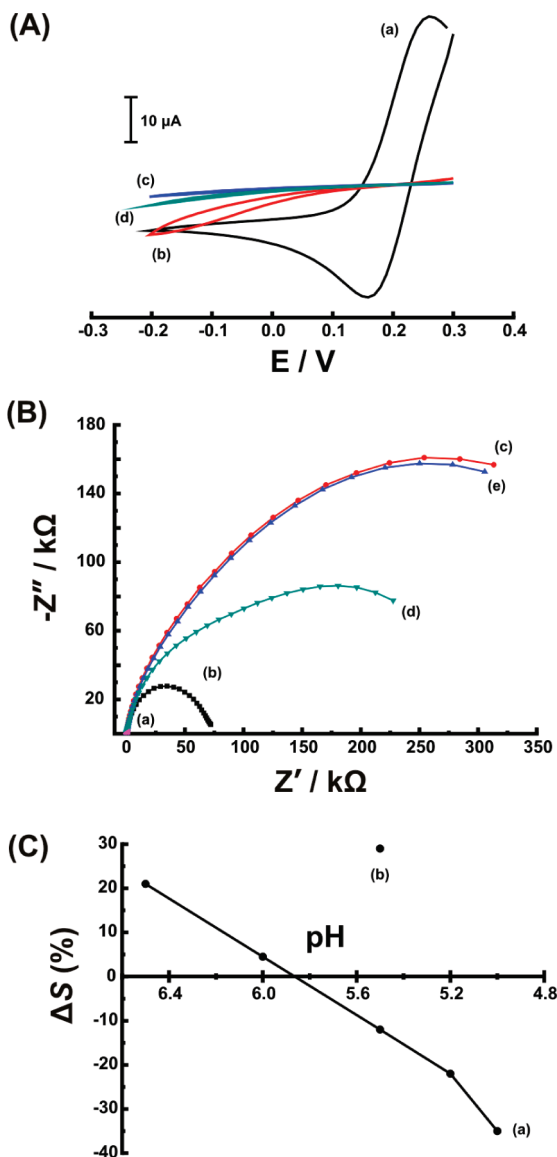


Figure 2. (A) CVs and (B) Nyquist plots of Au/TA/ACM biosensors at various modification and interaction steps: (a) bare gold electrodes, (b) Au/TA electrodes, (c) Au/TA/ACM biosensors, and (d) the biosensors after incubation for 2 h at 37 °C in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5, and (e) in a solution of 20 mM imidazole, pH 5, which was used as a blank. (C) pH profile of Au/TA/ACM biosensors after (a) incubation in 0.2% w/v solutions of rennet in 20 mM imidazole for 2 h at 37 °C and (b) as in (a) in the presence of 5 mM CaCl₂.

probe at the electrode surface. On the other hand, interaction of the Au/TA/ACM biosensors with rennet leads to neutral biostructures, thus enhancing the diffusion of the redox probe at the electrode surface and, consequently, the observed current intensity, which lies between the values corresponding to Au/TA and Au/TA/ACM electrodes.

An analogous behavior is observed at EIS studies. The bare gold electrode shows a very small semicircle domain implying a very fast electron-transfer process with a diffusional limiting step (spectrum in Figure 2Ba). Gradual blocking of the gold surface with the negatively charged layers of TA and ACM results in the increase of the R_{ct} values (spectra in Figure 2Bb,c, respectively). Similar to CV studies, interaction of the Au/TA/ACM biosensors

with rennet enhances the interfacial electron-transfer kinetics of the redox probe at the electrode surface, thereby decreasing R_{ct} (spectrum in Figure 2Bd), that is $R_{ct}(b) < R_{ct}(d) < R_{ct}(c)$. The spectrum in Figure 2Be corresponds to Au/TA/ACM biosensors after their incubation in a solution of 20 mM imidazole, pH 5 (blank), at 37 °C for 2 h.

Performance of Au/TA/ACM Biosensors. On the basis of the results tabulated in Table 1, the action of rennet onto immobilized ACM was investigated at Au/TA/ACM electrodes made from a 1 + 4 v/v ACM + 0.2 M NaCl mixture at pH 6.5. Electrodes made from the same mixture at pH 5.6 showed a similar performance, and thus, results are not included. According to the literature, the formation of casein micelle aggregates is favored in low pH values and in the presence of calcium cations.^{3,32,33} Both parameters reduce the net negative charge of the reacting biomolecules (casein micelles and chymosin), thus facilitating chymosin to approach κ -CN fraction and, consequently, the cleavage of the bond Phe(105)–Met(106).² In cheese manufacturing, this process is initiated at the natural pH of milk, that is, 6.4. At immobilized ACM, however, and under the specific experimental conditions, this process become obvious in the absence of calcium cations and only at pH < 5.8 (Figure 2C). Within the pH range 6.5–5.8, no obvious discrimination between the action of imidazole (blank) and rennet solutions on the impedimetric behavior of Au/TA/ACM electrodes is observed. Regarding the effect of calcium ions, their presence in both the blank and the rennet solutions results in the increase of R_{ct} . It is well-known that calcium cations are introduced into the lattice of ACM,^{2,3,30} however, the exact mechanism leading to the increase of the observed signal is not clear. On the other hand, signal changes of –22 and –34%, which were obtained at pH 5.2 and 5, respectively, indicate the suitability of the proposed biosensors for the evaluation of the clotting power of rennet.

The impedimetric behavior of the Au/TA/ACM electrodes at different concentrations of rennet (0.1, 0.2, and 0.4%), incubation times (30, 60, and 120 min), buffer solutions (imidazole, 3-(*N*-morpholino)propanesulfonic acid (MOPS), and *N*-2-hydroxyethylpiperazine-*N'*-2-ethanesulfonic acid (HEPES)), and after fixation of the immobilized ACMs with glutaraldehyde was also studied, and the results are collectively presented in Figure 3. The drop of the response at concentrated (>0.2% w/v) solutions of rennet might be attributed to (physical) adsorption of rennet's enzymes over Au/TA/ACM electrodes, and thus, for applications at such concentrated protein solutions, postblocking of the nonspecific binding sites seems to be necessary. On the other hand, the performance of Au/TA/ACM biosensors, at different incubation times, indicates that the kinetics of the reaction is rather slow. The measuring parameter reaches a maximum value after, at least, 120 min, while at shorter incubation times (30 min), where the applicability of the proposed biosensors is more attractive, the observed signal change is –15%. Finally, in accordance with previous works,^{28,29} imidazole buffer solution seems to be the optimum choice for the stabilization of immobilized casein micelles. Substantially lower signal changes were observed when experiments were performed in MOPS or HEPES buffer solutions.

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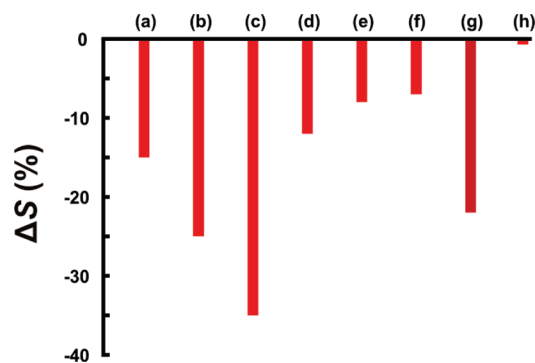


Figure 3. Signal changes, ΔS (%), of Au/TA/ACM biosensors after (a), (b), and (c) incubation in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5.0, at 37 °C for 30, 60, and 120 min, respectively; (c), (d), and (e) incubation in 0.2, 0.1, and 0.4% w/v solutions of rennet in 20 mM imidazole, pH 5.0, for 2 h at 37 °C, respectively; (c), (f), (g) incubation for 2 h at 37 °C in 0.2% w/v solutions of rennet, pH 5, in 20 mM imidazole, 20 mM HEPES, and 20 mM MOPS, respectively; and (h) fixation of the immobilized ACM with glutaraldehyde.

A control experiment, which was designed to support our assumptions regarding the nature of ACM–rennet interaction and, consequently, the mechanism of the signal production was performed after fixation of immobilized casein micelles with glutaraldehyde.³⁴ This treatment stabilizes the immobilized ACM²⁸ and leads to the formation of a compact layer due to the interconnection of immobilized ACM through Schiff bonds between the aldehyde groups of glutaraldehyde and the primary amines in casein micelles. The remarkable increase of R_{ct} at glutaraldehyde-fixed Au/TA/ACM electrodes [1.2 MOhm (data not shown) compared with that of 325 kOhm (Figure 2Bc)], as well as the nil effect of rennet on them (Figure 3), is probably attributable to an extended blocking effect to redox species in solution and to a limited access of chymosin to κ -CN fractions, respectively, due to the formation of the aforementioned compact layer of immobilized ACMs.

Performance of Au/CYS/ACM Biosensors. Au/CYS/ACM biosensors, based on SAMs developed from 10 or 20 mM cysteamine, were also examined in their efficiency to probe the action of rennet toward immobilized ACM. Both biosensors, after their immersion in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5, for 2 h at 37 °C, gave almost the same response [ΔS (%) = −45%] (data not shown), which is higher compared with that observed using Au/TA/ACM biosensors [ΔS (%) = −35%]. In contrast with the TA-modified based electrodes, Nyquist plots of CYS-modified based electrodes (Figure 4) include a semicircle (charge-transfer controlled behavior at high frequency region) followed by a straight line (diffusion-controlled behavior at low frequency region), thus allowing R_{ct} values to be calculated by fitting the impedance data to the Randles equivalent circuit $R_s(Q_{dl}[R_{ct}W])$ illustrated in side panel of Figure 4. Observed alterations of the R_{ct} values in various modification and interaction steps are attributable to similar phenomena, which are described above for Au/TA/ACM electrodes. The most noticeable difference is the magnitude of recorded R_{ct} values (in the range of a few hundred Ohm) due to the electrostatic attraction between the oppositely charged redox anions and the CYS-modified gold surface.

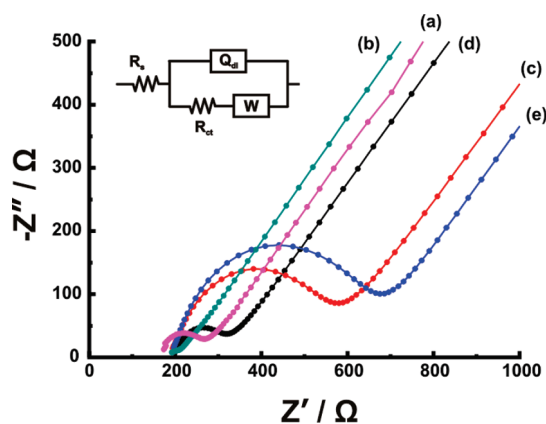


Figure 4. Nyquist plots of Au/(10 mM)CYS/ACM biosensors at various modification and interaction steps: (a) bare gold electrodes, (b) Au/CYS electrodes, (c) Au/CYS/ACM biosensors, and (d) the biosensors after incubation for 2 h at 37 °C in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5, and (e) in a solution of 20 mM imidazole, pH 5, which was used as a blank. Inset panel, Randles equivalent circuit $R_s(Q_{dl}[R_{ct}W])$.

Performance of Au/DTSP/ACM Biosensors. The use of DTSP-SAMs as immobilization platforms offers certain advantages, as such monolayers provide interfaces with specific hydrophilicity and desired chemical reactivity to amino-group containing biomolecules.³⁵ In addition, there is no need to use coupling agents or activators, simplifying, in this way, the experimental procedure for the construction of the biosensors. Preliminary experiments were conducted with gold electrodes modified with 2 or 5 mM DTSP, while the immobilization of casein micelles was tried using the undiluted suspension of ACM or an 1 + 4 v/v mixture of ACM with 0.2 M NaCl. The impedimetric profile of Au/(2 mM)DTSP/ACM electrodes, made from the original suspension of ACM, at the different modification and interaction steps, is illustrated in Figure 5A. These electrodes showed the best performance (comparative data not shown), and thus, they were further used to investigate the behavior of the biosensors to different concentrations of rennet and incubations times. The data shown in Figure 5B indicates that the measuring parameter increases proportional to the concentration and the incubation time, up to a time interval of 60 min. Longer incubation times, besides that they are not indicated for practical use, do not offer any benefits in terms of sensitivity. Indeed, in two out of three tested concentrations, the observed ΔS (%) values are slightly lower. This behavior can, also, be attributed to physical absorption of rennet's enzymes onto the surface of the electrodes over prolonged incubation interval times. Data, also, reveals that, compared with the Au/TA/ACM biosensors, the kinetics of the reaction is considerably faster. For an incubation time of 30 min, the absolute signal changes increase from −15% (Au/TA/ACM biosensors) to −55%, while at incubation time intervals of 15 min, analytical useful signal changes of −32% can be achieved.

The proposed biosensors were further tested in various commercial samples in both liquid and solid form, and the observed signal changes were compared with the milk-clotting power, as it was determined in our laboratory, using the Berridge method.¹² As can be seen in Table 2, ΔS (%) values reflect the milk-clotting power of the tested samples, indicating the suitability

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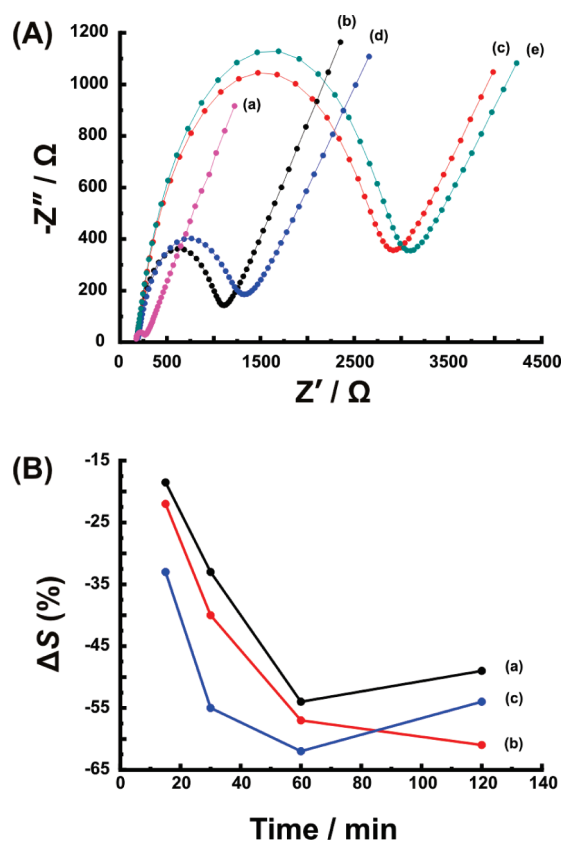


Figure 5. (A) Nyquist plots of the Au/(2 mM) DTSP biosensors at various modification and interaction steps: (a) bare gold electrodes, (b) Au/DTSP electrodes, (c) Au/DTSP/ACM biosensors, and (d) the biosensors after incubation for 2 h at 37 °C in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5, and (e) in a solution of 20 mM imidazole, pH 5, which was used as a blank. (B) Performance of the Au/(2 mM) DTSP/ACM biosensors at (a) 0.05, (b) 0.1, and (c) 0.2% w/v solutions of rennet in 20 mM imidazole, pH 5, at 37 °C, for different incubation time intervals.

Table 2. Application of Au/DTSP/ACM Biosensors to Various Rennet Samples^a

sample	incubation time, min	form	clotting power (Berridge method ¹²)	proposed biosensors ΔS (%)
Hansen	15	liquid (1 + 1 v/v)	1:36 600	-24
Danisco	15	liquid (1 + 1 v/v)	1:61 900	-51
Hansen	15	solid (0.05% w/v)	1:130 000	-44
Ipirotopoula	15	solid (0.05% w/v)	1:48 500	-12
Hansen	5	solid (0.2% w/v)	1:130 000	-42
Ipirotopoula	5	solid (0.2% w/v)	1:48 500	-14

^a At electrochemical measurements, the standard deviation of the mean ranges from 9 to 16%, $n = 3$.

of the proposed biosensors for the evaluation of the clotting power of rennet in both liquid and solid samples. It is important to note that analytical useful ΔS (%) values can also be obtained within 5 min of incubation, thus making the proposed biosensors especially attractive for routine use. Further evaluation of the observed signal changes is beyond the scope of this work. The response of the proposed biosensors should be correlated with units of milk-clotting power under specific measuring conditions.

FT-IR Studies. The suitability of the 1 + 4 v/v ACM + 0.2 M NaCl mixture at pH 6.5, as immobilization solution for the

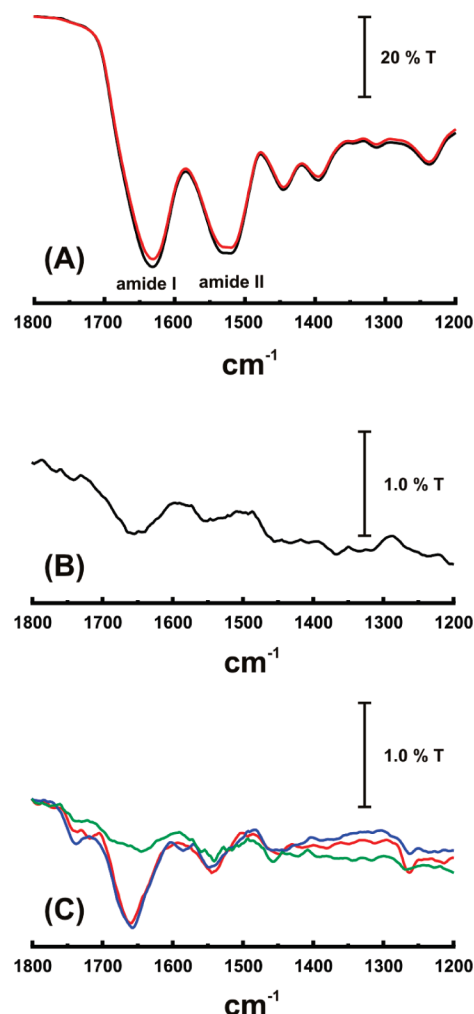


Figure 6. IR spectra of (A) an undiluted suspension of ACM (black line) and a 1 + 4 v/v ACM + 0.2 M NaCl mixture (red line), at pH 6.5; (B) immobilized ACM onto DTSP-modified gold surfaces (black line); (C) immobilized ACM onto TA-modified gold surfaces (red line) and their spectra after incubation for 2 h at 37 °C in a 0.2% w/v solution of rennet in 20 mM imidazole, pH 5.0, (green line) and in a solution of 20 mM imidazole, pH 5.0, used as a blank (blue line).

modification of Au/TA electrodes, was confirmed by IR studies. As shown in Figure 6A, the absorption bands of amide I and amide II, which are closely connected with the structure of ACMs,³⁶ are identical to those recorded for the undiluted suspension of the ACM.

Immobilization of ACMs onto the TA- and DTSP-modified gold surfaces as well as the interaction of them with rennet were also probed with IR spectroscopy. In particular, we recorded the IR spectra of the fully functionalized surfaces before and after their incubation in the working buffer solution (blank) and in a 0.2% w/v solution of rennet in the same buffer solution for 2 h at 37 °C. Spectra were recorded over the range 400–4000 cm⁻¹; however, for better observation of amide I and amide II bands, a selected area over 1200–1800 cm⁻¹ is only presented. The spectra of immobilized ACM (Figure 6B,C) show a high degree of similarity to that of the suspension of ACM (Figure 6A), indicating that covalent binding to thiol SAMs does not significantly impair the structure of the micelles. An average shift of 27 cm⁻¹ for amide I and amide II bands is observed.

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Specifically, the IR spectra of immobilized ACMs over SAMs of TA and DTSP exhibit the characteristic amide I band, which is primarily attributed to an out-of-phase combination of C=O and C–N stretchings of amide groups, at 1660 and 1655 cm^{-1} , respectively. Also, the amide II band, which is attributed to an out-of-phase combination of in-plane C–N stretching and N–H bending of amide groups, is observed at 1549 and 1544 cm^{-1} , respectively.

By comparing the spectra corresponding to Au/TA/ACM surfaces before and after their immersion in the solution of rennet, the observed decrease of the intensity of amide I band suggests a partial loose of α -helix content,³⁷ due to the aggregation of casein micelles. This decrease is accompanied by the appearance of two shoulders at 1620 and 1680 cm^{-1} , attributable to the intermolecular β -sheet aggregates, even though the aggregation process is more complex than a simple α -helix to aggregated β -sheet transition.³⁸ The spectral contributions of β -sheet aggregates are not clearly detectable, due to the low concentration of immobilized casein micelles over the examined surfaces; however, they appear with low intensities (the overall amide I band is appearing asymmetric around 1660 cm^{-1}). Other spectral observations based on amide II or/and amide II' are not further discussed, as the low signal-to-noise ratio at those bands cannot ensure the extraction of safe conclusions. Finally, IR spectra corresponding to Au/TA/ACMs surfaces, before and after incubation in blank solution, are almost identical, thus

suggesting that, in the absence of rennet, the secondary structure of casein micelles remains unaffected.

CONCLUSIONS

This study employs single-use functional biosensors, based on gold electrodes modified with negatively, neutrally, and positively charged thiol-based SAMs, as probes to evaluate the clotting activity of rennet for the first time. Biosensors that developed on dithiobis-*N*-succinimidyl propionate SAM were found to exhibit better sensitivity and faster kinetics compared with those developed on thioctic acid or cysteamine SAMs.

The proposed biosensors were successfully tested at various commercial samples in powder or liquid form. Relative changes of the charge-transfer resistance reflect the milk-clotting activity, as it is calculated with a reference method. Interestingly, reliable signal changes were also obtained within 5 min of incubation, indicating the suitability of the proposed biosensors for use in routine analysis. In our opinion, the present work offers a true alternative to the existing instrumental methods or methods based on visual observation, incorporating the simplicity and advantages of biosensors.

ACKNOWLEDGMENT

The research project is funded by the Research Committee of the University of Ioannina. The authors thank Prof. N. Chaniotakis and Dr. V. Vamvakaki for their valuable assistance in obtaining the IR spectra and AFM images presented in this work.

Received for review July 6, 2010. Accepted September 2, 2010.

AC1017925

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