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Electrical Conductivity of Milk: Ability to Predict Mastitis Status

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ABSTRACT

Electrical conductivity (EC) of milk has been introduced as an indicator trait for mastitis over the last decade, and it may be considered as a potential trait in a breeding program where selection for improved udder health is included. In this study, various EC traits were investigated for their association with udder health. In total, 322 cows with 549 lactations were included in the study. Cows were classified as healthy or clinically or subclinically infected, and EC was measured repeatedly during milking on each quarter. Four EC traits were defined; the inter-quarter ratio (IQR) between the highest and lowest quarter EC values, the maximum EC level for a cow, IQR between the highest and lowest quarter EC variation, and the maximum EC variation for a cow. Values for the traits were calculated for every milking throughout the entire lactation. All EC traits increased significantly ($P < 0.001$) when cows were subclinically or clinically infected. A simple threshold test and discriminant function analysis was used to validate the ability of the EC traits to distinguish between cows in different health groups. Traits reflecting the level rather than variation of EC, and in particular the IQR, performed best to classify cows correctly. By using this trait, 80.6% of clinical and 45.0% of subclinical cases were classified correctly. Of the cows classified as healthy, 74.8% were classified correctly. However, some extra information about udder health status was obtained when a combination of EC traits was used.

(**Key words:** electrical conductivity, milk, mastitis, indicator trait)

Abbreviation key: EC = electrical conductivity, **mS** = milliSiemens, **IQR** = inter-quarter ratio.

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INTRODUCTION

Electrical conductivity (**EC**) of milk has been introduced as an indicator trait for mastitis over the last decade (Hamann and Zecconi, 1998). The EC is determined by the concentration of anions and cations. If the cow suffers from mastitis, the concentration of Na^+ and Cl^- in the milk increases, which leads to increased EC of milk from the infected quarter (Kitchen, 1981). Most automatic milking systems have EC sensors incorporated for measuring EC during milking (in-line), and with the increasing use of such systems, more and more information about EC is available.

Electrical conductivity has mainly been expressed as a maximum value for each quarter or each milking in recent research (Maatje et al., 1992; Lansbergen et al., 1994; DeMol et al., 1999). Detection models based on maximum values and time-series analysis using historical information (DeMol et al., 1999) have shown promising results for detection of mastitis. However, problems with undetected sick cows and healthy cows being classified as sick still exist, and this may be explained by an insufficient description of the trait. It has been suggested that by extracting only the high EC measurements from a milking, valuable information about EC pattern may be lost (Lake et al., 1992; Nielen et. al., 1995). A cow suffering from mastitis may not always show an increased EC of milk from the infected quarter, but the within-milking variation in EC of milk from an infected quarter may be larger than variation in EC of milk from healthy quarters. Possible reasons for this are physical changes in mastitic milk, which may affect milk flow. A combination of the level and the variation of EC measurements may improve the description of the trait.

The objectives of this study were 1) to quantify the association of various EC traits, in this case the level and the variation within a milking, with udder health status; and 2) to determine whether a combination of the traits could improve the ability to classify cows in udder health categories.

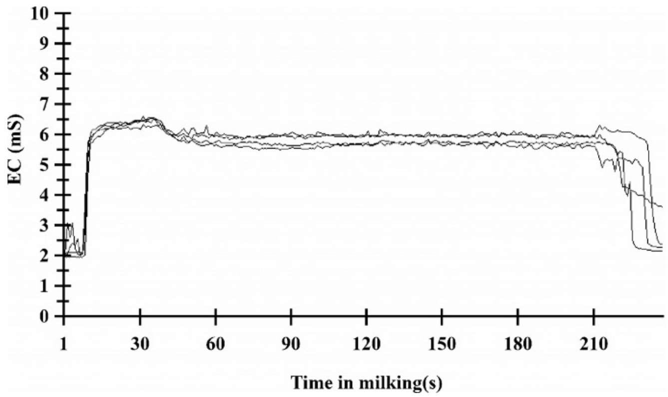

Figure 1. Electrical conductivity (EC) profiles (in milliSiemens [mS]) for all 4 quarters of a healthy cow.

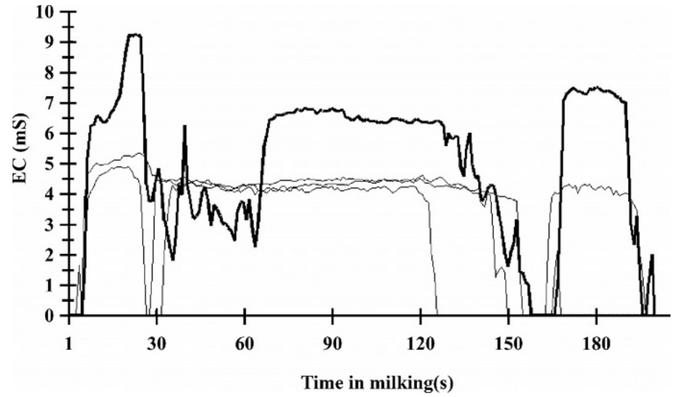

Figure 2. Electrical conductivity (EC) profiles (in milliSiemens [mS]) for all 4 quarters of a cow with clinical mastitis. The bold line indicates the EC profile of the infected quarter.

MATERIAL AND METHODS

Experimental Design

The data used were from a 5-yr experiment that was carried out from January 1997 to October 2001 at the research farm Ammitsbøl Skovgaard in Denmark. The cows used in the experiment were Danish Red, Danish Holstein, and Jersey. Each of the breeds was subdivided into two genetic lines. In total, 322 cows with 549 lactations were included in the study. Cows were housed in tie stalls and randomly assigned to 1 of 2 feeding levels: a normal energy density diet or a low energy density diet throughout lactation. For further description of the experimental design, see Nielsen et al. (2003).

Conductivity Measurements

Electrical conductivity was measured in milliSiemens (**mS**) in milk from each quarter during every milking at 2-s intervals. A prototype computerized milkmeter combined with a prototype "Mastitis detector" (S.A. Christensen, Kolding, Denmark) was used for data collection. Sensors for measuring EC were incorporated in the milking unit. The milking unit was constructed such that milk from the different quarters remained separated until after EC measurements were obtained. The equipment was calibrated monthly. Figures 1 to 4 show examples of EC profiles of all four quarters from one healthy (1) and 3 clinically infected (2 through 4) cows.

EC Data Manipulation

The first 8 recordings from every milking were omitted because of intake of air at the start of the milking. Records <3 mS and >12 mS were considered outliers and excluded from this study. For quarters with <20 valid measures, EC was coded as missing. The average of the 20 highest valid EC measures within a milking (X_{20}) and the variation of all valid EC measures within a milking (σ^2_{EC}) were calculated for each quarter. In addition, 4 EC traits based on X_{20} and σ^2_{EC} were defined. The following EC measures were computed for every milking: Max_X_{20} (the highest quarter X_{20} value within cow and milking), Max_σ^2_{EC} (the highest quarter σ^2_{EC} value within cow and milking), IQR_X_{20} (the inter-quarter ratio [**IQR**] between the highest and lowest quarter X_{20} value within cow and milking), and IQR_σ^2_{EC} (the IQR between the highest and lowest quarter σ^2_{EC} within cow and milking).

Udder Health Recording

In the experiment, an udder health surveillance scheme was applied. Quarter foremilk samples were taken on every cow at 8-wk intervals. The first foremilk samples were taken during the 1st wk after calving, and the last samples were taken near dry off. These samples were analyzed to obtain bacteriological information on possible IMI. When clinical mastitis was detected or suspected by the staff, veterinary assistance was applied, and additional milk samples were collected for diagnosis and treatment. Days where milk samples for bacteriological examination were taken or veterinary treatment was performed were called test days. Only morning milkings from the test days were included in this study. A more detailed description of the udder health recording in the experiment is found in Sloth et al. (2003).

Definition of Udder Health Status

The cows included in the study were defined as healthy, subclinically infected, or clinically infected. A

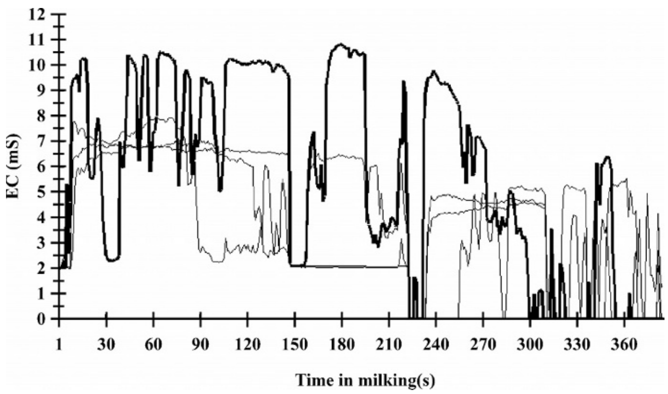

Figure 3. Electrical conductivity (EC) profiles (in milliSiemens [mS]) for all 4 quarters of a cow with clinical mastitis. The bold line indicates the EC profile of the infected quarter.

healthy cow was defined as a cow with negative bacteriological quarter foremilk samples on the test day and no veterinary treatment on the test day. A subclinically infected cow was defined as a cow with positive bacteriological quarter foremilk, but no veterinary treatment. A clinically infected cow was defined as a cow that received veterinary treatment after showing clinical symptoms of mastitis. All medical treatment was done by veterinarian, and the same protocol was consistent from cow to cow as far as possible. Positive bacteriological samples were found for all cows defined as clinically infected. Records beyond 305 d after calving were excluded. Subclinically and clinically infected cows with missing EC records for the infected quarter were excluded from the study, and cows with positive bacteriological foremilk on all quarters were omitted as well. A total of 2486 test day milkings remained after editing and were included in the analysis. There were 275 and 815 test days for clinically and subclinically infected cows, respectively.

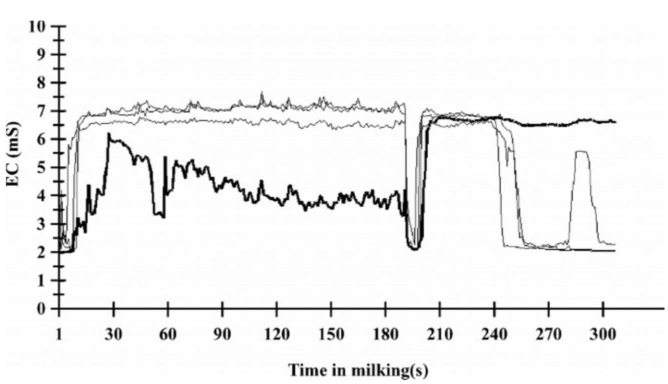

Figure 4. Electrical conductivity (EC) profiles (in milliSiemens [mS]) for all 4 quarters of a cow with clinical mastitis. The bold line indicates the EC profile of the infected quarter.

Statistics

The PROC GLM procedure in SAS was used to test for significant differences in EC traits between healthy and infected quarters and cows. The traits computed at cow level (Max_X_{20}, Max_ σ^2_{EC}, IQR_X_{20}, and IQR_σ^2_{EC}) were tested for their association with the cow's udder health status. For each test day, a predicted udder health status based solely on the EC traits was generated. Various threshold values for each of the EC traits were defined, and their ability to distinguish between healthy and infected cows was investigated. Threshold values for each trait were chosen such that they covered the range from what was expected for healthy cows to expectations for clinical infected cows. The threshold values for each trait will be described later. The threshold tests were performed first on a dataset consisting of only healthy and clinical cases and then on a dataset with only healthy and subclinical cases.

The ability of the traits to reflect the cow's udder health status was expressed as sensitivities and specificities. Cases where an EC predicted mastitis coincided with an observed mastitis were true positives (TP) and cases where EC failed to predicted an observed mastitis were considered false negative (FN). True negatives (TN) represented occasions when no mastitis was predicted, and the cows were healthy. Cases where healthy cows were classified as infected based on the EC traits were considered false positives (FP). The sensitivity is the percentage of infected cows that were classified as infected ((TP/(TP + FN)) × 100), and the specificity is the percentage of uninfected cows that were correctly classified as healthy ((TN/(FP + TN)) × 100).

To determine wether a combination of the traits increased the ability to classify cows in the correct health classes, a discriminant function analysis was performed using the PROC DISCRIM procedure in SAS. A discriminant function analysis is a method for separating 2 or more groups of individuals, given measurements on several variables. Various conductivity traits based on repeated EC measurements can be used as input variables in such an analysis. Discriminant function analyses require normally distributed input variables, so the ratio traits (IQR_σ^2_{EC} and IQR_X_{20}) were log-transformed prior to the analyses to obtain normality. The 4 EC traits were tested separately and in combination. Separate analyses were performed on subsets containing only healthy and clinically infected cows (Subset 1) or healthy and subclinically infected cows (Subset 2) to be able to compare the results from the simple detection model and the discriminant function analysis. Then, subclinically and clinically infected cows were pooled and defined as infected (Subset 3). Finally, analyses were carried out on the full data set containing

Table 1. Distributions of electrical conductivity values (means ± standard errors) for healthy, subclinically and clinically infected quarters.

	Healthy	Subclinical	Clinical
no.	10,431	2122	599
X_{20}[1]	$4.87^a \pm 0.01$	$5.37^b \pm 0.02$	$6.44^c \pm 1.53$
σ^2_{EC}[2]	$0.125^a \pm 0.004$	$0.217^b \pm 0.008$	$0.758^c \pm 0.013$

[a,b,c]Means or variances in the same row with different subscripts differ significantly ($P < 0.001$).

[1]X_{20} = Average of the 20 highest electrical conductivity quarter values within milking.

[2]σ^2_{EC} = Variation in electrical conductivity registrations for a quarter within milking.

all cows. The performance of the discriminant function analyses for classification of cows into correct udder health status was also expressed as sensitivities and specificities.

RESULTS

Level and Variation of EC Measurements

Electrical conductivity results obtained at the quarter level are given in Table 1. Compared with healthy quarters, X_{20} increased significantly ($P < 0.01$) for both observed subclinically and clinically infected quarters. The difference in X_{20} between subclinically and clinically infected quarters was also significant. The σ^2_{EC} increased for subclinically and clinically infected quarters as well, and the difference was greater for clinically infected quarters compared with healthy quarters vs. the difference between healthy quarters and subclinically infected quarters. At cow level, all EC traits were higher for the infected cows compared with healthy cows (Table 2). All differences in EC values between healthy, subclinically infected, and clinically infected cows were significant ($P < 0.01$). The difference was greater for clinically infected cows compared with healthy cows vs. the difference between healthy cows and subclinically infected cows for the EC traits reflecting EC variance.

Classification of Cows According to Health Status

Sensitivities and specificities for the ability of each EC trait to distinguish between healthy and clinically infected cows are given in Figure 5, and the ability to distinguish between healthy and subclinically infected cows is given in Figure 6. The points on each curve represent sensitivities and specificities for different threshold values for each of the EC traits. The threshold values to detect both clinically and subclinically infected cows were as follows for the different EC traits: Max_X_{20}, 5.0, 5.25, 5.5, 5.75, 6.0, and 6.5; Max_σ^2_{EC}, 0.1, 0.15, 0.2, 0.25, 0.3, and 0.4; IQR_X_{20}, 1.1, 1.125, 1.15, 1.2, and 1.3; and IQR_σ^2_{EC}, 3.0, 4.0, 6.0, and 8.0. For all traits, increasing the threshold value increased the sensitivity and decreased the specificity.

Sensitivities were higher for separation of clinically infected cows from healthy cows compared with sensitivities for separating subclinically infected cows from healthy cows, regardless of which EC trait was used. The IQR_X_{20} gave highest sensitivity and specificity for classification of both clinically and subclinically infected cows. By using IQR_X_{20}, 80.6% of the clinically and 45.0% of the subclinically infected cows were classified correctly. Of the cows classified as healthy, 74.8% were correctly classified. For the other traits (Max_X_{20}, Max_σ^2_{EC}, and IQR_σ^2_{EC}), the sensitivity ranged from about 56 to 73%; and the specificity was about 75%. Of

Table 2. Distributions of electrical conductivity traits (means ± standard errors) for healthy, subclinically infected, and clinically infected cows.

	Healthy	Subclinical	Clinical
no.	1353	778	340
Max_X_{20}[1]	$5.30^a \pm 0.03$	$5.75^b \pm 0.04$	$6.73^c \pm 0.06$
Max_σ^2_{EC}[2]	$0.242^a \pm 0.015$	$0.332^b \pm 0.020$	$0.818^c \pm 0.030$
IQR_X_{20}[3]	$1.124^a \pm 0.004$	$1.182^b \pm 0.006$	$1.369^c \pm 0.009$
IQR_σ^2_{EC}[4]	$6.85^a \pm 0.52$	$7.72^b \pm 0.68$	$16.93^c \pm 1.03$

[a,b,c]Means in the same row with different subscript differ significantly ($P < 0.001$).

[1]Max_X_{20} = maximum quarter X_{20} value (average of the 20 highest electrical conductivity quarter values within milking) within cow and milking.

[2]Max_σ^2_{EC} = maximum quarter σ^2_{EC} value (the variation in electrical conductivity registrations for a quarter within milking) within cow and milking.

[3]IQR_X_{20} = inter-quarter ratio between maximum and minimum quarter X_{20} value within cow and milking.

[4]IQR_σ^2_{EC} = inter-quarter ratio between the maximum and minimum quarter σ^2_{EC} within cow and milking.

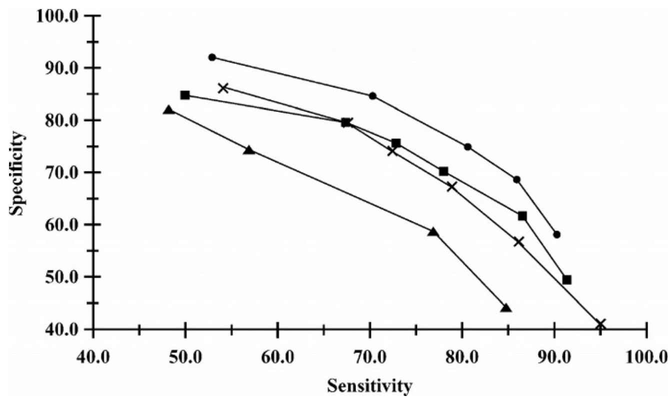

Figure 5. Sensitivities and specificities to separate healthy and clinically infected cows by using different electrical conductivity traits. Max_X_{20} (■) = highest quarter X_{20} (average of the 20 highest electrical conductivity quarter values within milking) value, Max_σ^2_{EC} (×) = highest quarter σ^2_{EC} (the variation in electrical conductivity registrations for a quarter within milking) value, IQR_X_{20} (●) = inter-quarter ratio between highest and lowest quarter X_{20} values, and IQR_σ^2_{EC} (▲) = inter-quarter ratio between the highest and lowest quarter σ^2_{EC} values. All values are given within cow and milking.

the traits reflecting variation in EC within milking, Max_σ^2_{EC} had a higher sensitivity and specificity than IQR_σ^2_{EC}.

Results from the discriminant function analyses are given in Table 3. Correct classification of healthy cows (specificity) was higher than for the threshold test. For the comparison of healthy vs. clinically infected cows (Subset 1), the specificity ranged from 94.5 to 97.4% for

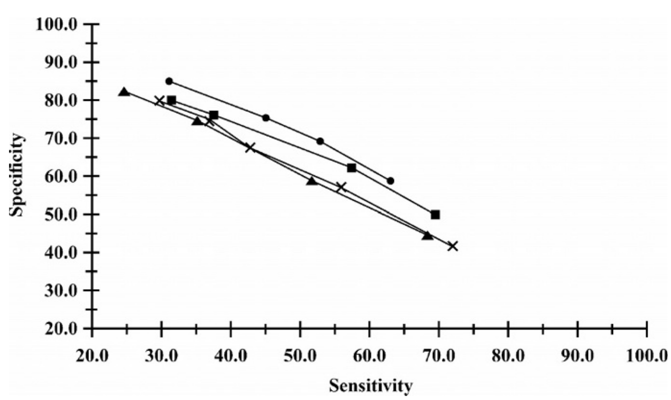

Figure 6. Sensitivities and specificities to separate healthy and subclinically infected cows by using different electrical conductivity traits. Max_X_{20} (■) = highest quarter X_{20} (average of the 20 highest electrical conductivity quarter values within milking) value, Max_σ^2_{EC} (×) = highest quarter σ^2_{EC} (the variation in electrical conductivity registrations for a quarter within milking) value, IQR_X_{20} (●) = inter-quarter ratio between highest and lowest quarter X_{20} value, and IQR_σ^2_{EC} (▲) = inter-quarter ratio between the highest and lowest quarter σ^2_{EC} values. All values are given within cow and milking.

single traits. When all 4 EC traits were included in the analysis, the specificity was 95.3%. Between 16.2 and 46.2% of the clinically infected cows were classified correctly when single traits were used in the discriminant function analysis. When used in combination, 47.9% of the cows were classified correctly as infected. Contrary to the threshold test, IQR_σ^2_{EC} performed better than Max_σ^2_{EC} in these analyses.

Specificity for Subset 2 (with only healthy and subclinically infected cows) was approximately the same as for Subset 1. The two traits reflecting the EC level performed similarly for classification of subclinically infected cows, as 15.9% were detected using IQR_X_{20} and 15.8% were detected using Max_X_{20}. For the traits reflecting the variation in EC, the discriminant function analysis could not separate between healthy and subclinically infected cows. When all traits were included in the analysis, nearly 20% of the subclinically infected cows were correctly classified.

For Subset 3 (where healthy cows were compared with cows with any level of mastitis infection), the specificity was somewhat lower than for the other subsets. The sensitivity was 41.4% for IQR_X_{20}, 41.8% for Max_X_{20}, 21.0% for Max_σ^2_{EC}, and 34.7% for IQR_σ^2_{EC}. Again, IQR_σ^2_{EC} performed better than Max_σ^2_{EC}. When a combination of the traits was used, 44.8% of the infected cows were classified correctly.

When discriminant function analysis was performed on the full data set, cows were classified into 3 groups: healthy, subclinically infected, and clinically infected. The specificity ranged from 92.9 to 97.4%. The IQR_X_{20} EC measurement gave the highest sensitivity, and 45.0% of the clinically infected cows where classified in the correct group. Only 1.9% of the subclinically infected cows were classified correctly. By using IQR_σ^2_{EC} and Max_σ^2_{EC} in the analyses, 18.5 and 17.4% of the clinically infected cows were classified correctly, respectively. None of the subclinically infected cows were classified correctly. When used in combination, the four traits were able to classify 92.9% of the healthy cows correctly. Of the clinically infected cows, 43.5% were classified correctly. For the subclinically infected cows, combining the 4 traits increased the correct classification to 7.8%. The misclassified diseased cows (both clinical and subclinical) were mainly classified as healthy.

DISCUSSION

EC Values on Quarter Level

In this study, EC was measured repeatedly and frequently during milking on a relatively large number of cows for a long period. The levels of EC in healthy, subclinically infected, and clinically infected quarters found in the present study agree reasonably well with

Table 3. Sensitivities and specificities for separation of healthy and infected cows by use of different EC traits; calculated for Subset 1 (healthy and clinically infected cows), Subset 2 (healthy and subclinically infected cows), Subset 3 (healthy and clinically + subclinically infected cows), and the full data set (healthy, clinically infected, and subclinically infected cows).

	Subset 1		Subset 2		Subset 3		Full data set		
EC trait[1]	Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity clinical	Sensitivity subclinical	Specificity
Max_X_{20}	17.9	91.5	15.8	91.5	41.8	79.8	30.6	1.9	93.6
Max_σ^2_{EC}	16.2	98.0	2.8	98.0	21.0	91.7	17.4	0	97.4
IQR_X_{20}	46.2	92.3	15.9	92.3	41.4	85.5	45.0	1.9	94.3
IQR_σ^2_{EC}	32.1	97.0	3.6	97.0	34.7	79.6	18.5	0	96.2
Combination	47.9	91.9	19.4	91.9	44.8	84.6	43.5	7.8	92.9

[1]Max_X_{20} = maximum quarter X_{20} value (average of the 20 highest electrical conductivity quarter values within milking) within cow and milking, Max_σ^2_{EC} = maximum quarter σ^2_{EC} value (the variation in electrical conductivity registrations for a quarter within milking) within cow and milking, IQR_X_{20} = inter-quarter ratio between maximum and minimum quarter X_{20} value within cow and milking, and IQR_σ^2_{EC} = inter-quarter ratio between the maximum and minimum quarter σ^2_{EC} within cow and milking. Combination is combination of all 4 electrical conductivity traits.

the literature review of Hamann and Zecconi (1998). Typically EC in normal milk is between 4.0 and 5.0 mS at 25°C. Electrical conductivity in milk increases with milk sample temperature (Wong, 1988), so EC is expected to be somewhat higher when EC is measured at milking because milk temperature is about 38°C when it leaves the teat cistern. In our study, EC measurements in milk from healthy cows generally ranged from 5.5 to 6.5 mS, and variation within the main part of the milking was negligible (Figure 1).

Several researchers have reported increased EC in milk from infected quarters. Mean EC values for clinically infected quarters in this study correspond well with the review of Hamann and Zecconi (1998), who presented values between 5.0 and 9.0 mS from several experiments. Figure 2 illustrates EC profiles for a cow infected with clinical mastitis. The infected quarter shows a higher EC level during most of the milking, especially in the beginning and at the end of the milking. Mean EC values obtained for clinically infected cows showed larger variation than mean EC values for healthy cows, which agrees with Hamann and Zecconi (1998). Results obtained in our study for subclinically infected cows correspond well with findings by Woolford et al. (1998) and Isaksson et al. (1987), who found absolute EC values to be from 6.45 to 6.85 mS and from 4.83 to 7.03 mS, respectively.

For the EC trait reflecting the variation within milking (σ^2_{EC}), significant differences between healthy, subclinically infected, and clinically infected quarters were found. The differences between milk from healthy and clinically infected quarters can be explained partly by physical changes in mastitic milk. Clinical mastitis usually causes clots in the milk that can slow milk flow from the teat and stick to the EC sensors and affect the measurements. During clinical mastitis with clot formation, the milk flow tends to be unstable because of clots, and the sensors may come in contact with air. In addition, a clinical infection may cause pain in connection with milking so the cow may fidget and cause air to slip in between the teat and the teat cup liner. Numerous EC profiles from the present study indicated a large variation in EC within the milking for clinically infected cows (Figure 3). The σ^2_{EC} was somewhat higher for both healthy and clinically infected cows compared with the findings of Nielen et al. (1995), who calculated EC standard deviations (which included 12 registrations) for the middle milking minute to be 0.16 for healthy quarters and 0.58 for clinically infected quarters. This corresponds to a σ^2_{EC} of 0.03 and 0.34, respectively. In our study, σ^2_{EC} were computed from data collected during the whole milking, and this may explain the differences between our study and that of Nielen et al. (1995).

In some cases of clinical mastitis, EC measurements within milking from an infected quarter may vary substantially without necessarily having an increased level at the beginning or the end of the milking. The profile of EC values shown in Figure 4 gives an example of this type of pattern. In this case, X_{20} for the infected quarter did not differ significantly from healthy quarters, but EC in milk from the infected quarter showed larger variation compared with the healthy quarters.

The significant differences in variation between healthy and subclinically infected quarters are not as easy to explain as the differences between healthy and clinically infected quarters. Usually there would be limited physical changes in milk from subclinically infected cows; so increased variation in EC measurements within milkings might not be expected. However, clots can be found in milk from chronic subclinically infected quarters, even if the cow is not showing other clinical symptoms. Standard deviations or σ^2_{EC} on EC measurements from subclinically infected cows have not previously been reported.

EC Values at Cow Level

As expected, IQR_X_{20} and Max_X_{20} were higher for both subclinically and clinically infected cows compared with healthy cows. In addition, our EC values correspond well with the literature (Nielen et al., 1992; Hamann and Zecconi, 1998). Mean IQR_X_{20} for subclinically infected cows was 1.18. Similar results were obtained by Woolford et al. (1998) who found IQR values for subclinically infected cows to be between 1.13 and 1.32.

The Max_σ^2_{EC} and IQR_σ^2_{EC} EC measurements increased for subclinically infected cows compared with healthy cows as well, but the increase was not as pronounced as the increase from the subclinically infected cows to clinically infected cows. Because of the significant difference in σ^2_{EC} between healthy and subclinically infected quarters, the difference between healthy cows and subclinically infected cows was expected.

Electrical Conductivity as an Indicator of Udder Health

Among the traits reflecting the EC level, IQR_X_{20} showed the highest association with both clinical and subclinical mastitis, regardless of whether the threshold test or the discriminant function analysis was used to classify the cows. By using IQR, non-udder health factors that affect EC in milk equally for all quarters, such as breed, parity, milking interval, time of day, milk fraction, milk composition, other diseases, and estrus, are taken into account (Linzell et al., 1974). Use of IQR has, therefore, been preferred in many studies (Nielen et al., 1992). However, Linzell and Peaker (1975) found that absolute conductivity and IQR had similar accuracy for detection of mastitis. Results presented by Fernando et al. (1982) showed that absolute conductivity in general gave similar, but sometimes superior, results compared with IQR. Sensitivities and specificities obtained in the present study when IQR_X_{20} and Max_X_{20} were used to distinguish between healthy and clinically infected cows were similar to those reported by others (Nielen et al., 1992; Hamann and Zecconi, 1998). The traits Max_σ^2_{EC} and IQR_σ^2_{EC} were calculated to express the variation in EC within milking and the variation between the quarters. It was expected that these traits could contribute relevant information about udder health status in addition to EC level. Sensitivities and specificities were lower when Max_σ^2_{EC} and IQR_σ^2_{EC} were evaluated as the only determinants of udder health compared with the traits reflecting EC levels. The traits Max_σ^2_{EC} performed better than IQR_σ^2_{EC} when using the threshold test. Overlapping distributions and high variation for the trait reflecting the variance may account for some of the difficulties in distinguishing between healthy and infected cows by only using Max_σ^2_{EC} or IQR_σ^2_{EC}.

Successful detection of cows infected with subclinical mastitis by use of EC information recorded during milking is a major challenge. In agreement with most other studies where EC thresholds have been used for separation of healthy and subclinically infected cows, sensitivity and specificity obtained in this study were generally low. Traits reflecting the level, and especially IQR_X_{20}, performed best to classify cows as subclinically infected. The traits reflecting the variance were not effective at separating the healthy and subclinically infected cows; this was expected because of the lack of difference in X_{20} and σ^2_{EC} between healthy and subclinically infected quarters.

When discriminant function analyses were used to classify cows according to udder health status, a combination of the EC traits increased the correct classification of both clinically and subclinically infected cows slightly. Specificities were higher when discriminant function analysis was used compared with the threshold test, but the ability to classify infected cows and, especially, subclinically infected cows to the correct groups was low. Fernando et al. (1982) used discriminant function analysis to separate uninfected and clinically infected quarters based on EC in foremilk and strippings and obtained sensitivities of 62.8 and 96.2%, respectively. They obtained a specificity of 90%. They had 24.6% false positives and 40.5% false negatives when EC in sample milk was used to classify uninfected and subclinically infected quarters.

Overlapping distributions of the EC traits between health groups and heterogeneous variance explains some of the difficulties associated with assigning cows to the correct health group. Despite the unusually high degree of surveillance in the present study, recordings of udder health still might have been incomplete (e.g., some clinically infected cows might not have been discovered). Bacteriological examination was used as the standard for subclinical infections. The reliability of bacteriological findings has been questioned (Hillerton, 2000), and the performance of EC as an indicator trait in this study would be impaired if cows were wrongly defined in a health class. Technical difficulties with recording EC may be a problem if the equipment is not properly maintained. In general, the EC traits, and in particular the IQR_X_{20}, reflected well the udder health status for healthy and clinically infected cows. However, some additional information about udder health status was obtained by including the other EC traits.

Extended Use of EC as an Indicator for Udder Health

Mastitis is one of the most costly diseases affecting dairy cows, and reducing the incidence of mastitis through genetic selection is, therefore, of great interest. Direct selection using clinical mastitis records can be used in some populations; or, more commonly, indirect selection can be used based on traits that are genetically correlated to mastitis, such as SCC. Electrical conductivity as an indicator of udder health has, until now, been used for the sole purpose of mastitis detection. In the future, monitoring udder health of dairy cows will include the use of additional automated sensor-based systems, especially in automatic milking systems. Today, such systems base detection of mastitis and control of the cow's udder health mostly on EC. Measurements are recorded at every milking, and information about the udder health status is obtained on a daily basis. In contrast, analysis of SCC in milk is normally performed at an interval of 3 to 8 wk. If EC records can be stored and transferred to a national recording system, this information can be utilized in a breeding program including selection against mastitis. However, to be included in the breeding program, EC has to express genetic variation and has to have a genetic correlation with mastitis. Literature presenting genetic parameters for EC is scarce, but Goodling et al. (2000) estimated heritabilities for EC to range from 0.27 to 0.39 in first lactation. Their estimates were based on the daily averages for EC in composite milk and are considered to be moderate to high. Furthermore, the genetic correlation between EC and clinical mastitis was found to be 0.65 (Goodling et al., 2001). For comparison, heritabilities for SCC are estimated to be in the range from 0.07 to 0.12 (Reents et al., 1995; Mrode and Swanson, 2003). Mrode and Swanson (1996) concluded that the average genetic correlation between clinical mastitis and SCC, based on values from the literature, was about 0.7. Because of these favorable properties of EC, it may be a potential trait in a breeding program. However, more research is needed to estimate genetic parameters for test day EC and genetic correlations among mastitis and EC.

CONCLUSION

Electrical conductivity in milk is influenced by the udder health status of the cow. Traits reflecting the EC level describe udder health status more accurately than traits reflecting the variation in EC within milking. Inter-quarter ratios of EC performed better than the absolute conductivity level for classification of both clinically and subclinically infected cows. However, some extra information about udder health status was obtained when a combination of the EC traits was utilized. The ability of the EC traits to separate subclinically infected cows from healthy cows in this experiment was not satisfactory. Electrical conductivity of milk may be a potential trait in a breeding program, but further research is needed to estimate genetic parameters for EC and genetic correlation to mastitis.

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