
THE PROCEEDINGS OF THE
NEW ZEALAND SOCIETY
OF
ANIMAL PRODUCTION
VOLUME 62 2002

Relationships between milk yield, milk composition and electrical conductivity in dairy cattle

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ABSTRACT

The purpose of this study was to investigate the relationships between electrical conductivity (EC) and milk yield and composition in Japanese dairy cattle. In total, 4380 quarters of 106 cows were used in this study. Individual cows were herd tested in the evening with a quarter-milker fortnightly on at least 6 occasions during the lactation. Herd test records were collected from 1990 to 1998. Each quarter was sampled for milk yield, concentrations of fat, protein, lactose and solids-not-fat (SNF) and EC. Each milk quarter sample was classified into one of 9 classes of EC value and one of 10 classes of quarter difference EC value (QdEC). The QdEC for each quarter was calculated as the difference between the EC value for that quarter and the EC value of the quarter with the lowest value within the same cow, on a given herd-test day. Statistical analyses were performed using a mixed linear model for repeated measures considering the fixed effects of quarter position, lactation stage and their interaction, parity, calving season and the EC or QdEC class, and random effects of cow and quarter within cow.

Previous studies have recommended criteria for healthy quarters of < 6.3 mS/cm for EC and < 0.3 mS/cm for QdEC. In the present study, quarters with values above these criteria did have significantly lower milk yields (by 15 to 20%), but these decreases became apparent above values for EC and QdEC of 5.4 mS/cm and 0.2 mS/cm respectively, much lower than the suggested criteria. Milk yield was reduced by approximately 2% for every 0.1 mS/cm increase in the QdEC. The higher value classes for EC, and for QdEC both showed significantly lower concentrations of fat, lactose and SNF ($P < 0.05$). In the present study, decreases in milk yield and concentration of fat and lactose occurred in quarters that would have been considered to be normal by the previously accepted criteria for EC and QdEC.

Keywords: electrical conductivity; milk yield; milk composition.

INTRODUCTION

It has been well known that mastitis causes milk yield loss and affects milk composition in dairy cattle. It is important to detect mastitis at an early stage to avoid economic loss to a dairy farmer. In the case of clinical mastitis, there are obvious losses in milk during the period from the rapid pathological change of a quarter until its recovery. However, in the case of subclinical mastitis, the loss of milk is not so obvious, but over a longer period the cumulative losses can be substantial.

The electrical conductivity (EC) measurement in milk is one of the screening tests for mastitis, and it has been evaluated widely (Milner *et al.*, 1997; Hillerton & Semmens, 1999; Biggadike *et al.*, 2002; Norberg *et al.*, 2004). In the present study, a milking machine was attached to the EC sensor in-line to measure the EC value for each quarter during milking time (Nielen *et al.*, 1995a, 1995b; De Mol & Ouweltjes, 2001).

Several methods have been used to distinguish between normal and mastitic milk using EC measurement. Typical EC of normal milk appears to be between 4.0 and 5.5 mS/cm at 25 ^{o}C. Oshima and Yamamoto (1988) recommended a combination of the measurement of the absolute value of EC plus the quarter difference value (QdEC), that is calculated as the difference between the EC value for that quarter and the EC value of the quarter with the lowest value within an individual cow on a given herd test day. The latter authors suggested that the mastitis test should be done repeatedly in order to detect an abnormal quarter, and they also proposed the following criteria 1) Normal: EC of milk < 6.3 mS/cm and QdEC < 0.3 mS/cm. 2) Suspected: EC of milk < 6.3 mS/cm and QdEC 0.3-0.5 mS/cm. 3) Abnormal: EC $\geq$ 6.3mS/cm or QdEC $\geq$ 0.5 (Oshima & Yamamoto, 1988; Oshima, 1985).

Somatic cell count (SCC) has also been proposed as an index to detect mastitis, and the relationship between SCC and milk yield have been summarized in detailed reviews by Hortet and Seegers (1998a, 1998b). However, there have been few studies of the relationships between EC and loss in milk yield. When a mean QdEC value was based on repeated measurements within individual cows, quarter milk production loss per milking was approximately 3% per 0.1 mS/cm of increase in QdEC (Oshima *et al.*, 1990). A rise of 1.0 mS/cm of the mean EC caused a decline of 0.88 kg/day in daily milk production (Nielen *et al.*, 1993).

This study is based on results obtained repeatedly during a long-term quarter-milking experiment. The objective of this study was to relate the reductions in quarter milk yield and milk composition to the value for EC and QdEC within the same udder, of individual cows.

MATERIALS AND METHODS

Cows from the Holstein herd of the Experimental Farm of the Nippon Agricultural Research Institute in Japan were used. They were fed with mainly roughages (silage, hays, cut grasses) and purchased formula concentrates (4-6 kg/day/cow), and were also grazed at pasture for limited periods during May to September. Milking was carried out twice a day at 5:30 a.m. and 3:30 p.m. at the milking parlour. The data were collected from September 1990 until November 1998. Total milk yield of these dairy cows was 6,000-7,000 kg/year in a lactation adjusted to 305 days.

Herd tests were carried out at the evening milking repeatedly in order to investigate change of quarter milk yield and composition and to compare quarters within the same individual cow. Individual cows were milked by a separate quarter-milker, and the milk from each quarter of a cow was collected in an individual cylinder. Cows were herd tested fortnightly on at least 6 times (6-18 times) during a lactation from 21 to 300 days after calving. Approximately 50 ml milk samples were collected into a plastic tube from every quarter. The EC of each sample was measured with a hand-held conductivity meter (Yokogawa Electric Co., model SC82) and the conductivity values were corrected to the level at 25 ^{o}C. Concentration of milk fat (Fat%), protein (Pro%), lactose (Lact%), solids-not-fat (SNF%) and total milk solids (TMS%) of each quarter milk sample was determined by using MILKOSCAN 113B (A/S Foss Electric, Denmark) at the Tokyo Metropolitan Livestock Experiment Station. In total, milk yields were recorded in 4380 quarters from 106 cows, and both milk yield and composition were recorded for 2160 quarter samples from 57 cows. In this study, data were used from which daily milk yield of individual cows were over 10 kg with no visible abnormalities in the milk samples.

Statistical analyses for quarter milk yield and composition were performed using a mixed model for repeated measures with the SAS computer package (Littell *et al.*, 1999). The model considered fixed and random effects. Fixed effects were position of the quarter, lactation stage, interaction between quarter position and lactation stage, parity, calving season and EC (or QdEC) class. Random effects were cow and quarter nested within cow. It was assumed that residual errors had a composite symmetrical structure within each quarter for the different measures throughout each lactation.

Quarter milk yields were classified into one of 9 or 10 classes in EC and QdEC, quarter milk compositions were classified into one of 8 or 9 classes in EC and QdEC (Table 1). When the effect of EC or QdEC class was significant, multiple comparisons between least squares means for each class were carried out with the Tukey-Kramer method at the 5% level.

RESULTS

For values of EC, 86.5% of the 4380 records were below 5.7 mS/cm with 83.2% between 4.5 and 5.7 mS/cm (Table 1). Only 2.3% of the quarters (99) had values above 6.3 mS/cm. Similarly for QdEC, 82.1% of quarters had values below 0.3 mS/cm, and only 8.4% had values above 0.5 mS/cm (Table 1).

EC, milk yield and composition

The values for EC are shown in 9 classes, each with a range of 0.3 mS/cm. There were no significant differences between classes 1 to 4 (below 5.4 mS/cm) in quarter milk yield (Table 2). However, the yield of class 5 (5.4-5.7 mS/cm) was 96.9% of class 1, and this was significantly lower than the yield of classes 1 to 4 ($P < 0.05$). The quarter yield in classes 6 to 9 (above 5.7 mS/cm) were all significantly lower than that of class 5 with those of classes 8 and 9 by 86.1% and 85.1% of class 1 ($P < 0.05$).

TABLE 1: Number (n) and relative frequency (%) of quarter herd test records classified for electrical conductivity (EC) and quarter difference of EC (QdEC[1]) for the analysis of milk yield and composition.

Quarter milk yield

class	EC (mS/cm)	n	%	QdEC (mS/cm)	n	%
1	< 4.5	144	3.3	0	1139	26.0
2	4.5 - 4.8	567	12.9	0.0 - 0.1	1240	28.3
3	4.8 - 5.1	1165	26.6	0.1 - 0.2	805	18.4
4	5.1 - 5.4	1150	26.3	0.2 - 0.3	413	9.4
5	5.4 - 5.7	763	17.4	0.3 - 0.4	259	5.9
6	5.7 - 6.0	346	7.9	0.4 - 0.5	155	3.6
7	6.0 - 6.3	146	3.3	0.5 - 0.7	175	4.0
8	6.3 - 6.6	57	1.3	0.7 - 0.9	72	1.7
9	6.6 ≤	42	1.0	0.9 - 1.2	74	1.7
10				1.2 ≤	48	1.1
	Total	4380		Total	4380	

Milk composition

class	EC (mS/cm)	n	%	QdEC (mS/cm)	n	%
1	< 4.5	103	4.8	0	578	26.8
2	4.5 - 4.8	337	15.6	0.0 - 0.1	586	27.1
3	4.8 - 5.1	635	29.4	0.1 - 0.2	437	20.2
4	5.1 - 5.4	528	24.4	0.2 - 0.3	193	8.9
5	5.4 - 5.7	337	15.6	0.3 - 0.4	141	6.5
6	5.7 - 6.0	148	6.9	0.4 - 0.5	56	2.6
7	6.0 - 6.3	42	1.9	0.5 - 0.7	84	3.9
8	6.3 ≤	30	1.4	0.7 - 0.9	30	1.4
9				0.9 ≤	55	2.6
	Total	2160		Total	2160	

[1] QdEC for each quarter was calculated as the difference between the EC value for that quarter and the EC value of the quarter with the lowest value within an individual cow on a given herd test day

For Pro%, there were no significant differences between any of the EC classes. However, Fat% and Lact% decreased significantly as EC increased, with significant differences between many of the adjacent classes (Table 2). SNF% and TMS% (not shown), decreased as EC class increased, as for Fat% and Lact%.

TABLE 2: Least square means (LSM) of quarter milk yield and composition for each class of electrical conductivity (EC) and quarter difference of EC (QdEC[1])

EC

class	Milk yield (kg)		Fat%		Pro%		Lact%	
	LSM	Ratio[2]	LSM	Ratio	LSM	Ratio	LSM	Ratio
1	2.27 a	100.0	5.17 a	100.0	3.42 a	100.0	4.70 a	100.0
2	2.31 a	101.8	4.81 b	93.0	3.43 a	100.3	4.65 a	99.0
3	2.30 a	101.5	4.63 c	89.5	3.39 a	99.0	4.57 b	97.2
4	2.26 a	99.7	4.33 d	83.8	3.39 a	99.0	4.51 c	96.0
5	2.20 b	96.9	4.18 e	80.8	3.38 a	98.6	4.41 d	93.9
6	2.07 c	91.4	4.02 ef	77.8	3.37 a	98.4	4.30 e	91.5
7	1.99 c	87.6	3.87 f	74.9	3.38 a	98.6	4.16 f	88.6
8	1.95 c	86.1	3.75 f	72.7	3.33 a	97.2	3.74 g	79.5
9	1.93 c	85.1						

QdEC

class	Milk yield (kg)		Fat%		Pro%		Lact%	
	LSM	Ratio	LSM	Ratio	LSM	Ratio	LSM	Ratio
1	2.30 a	100.0	4.46 a	100.0	3.36 a	100.0	4.56 a	100.0
2	2.30 a	100.0	4.43 a	99.2	3.35 a	99.7	4.54 b	99.4
3	2.30 a	100.0	4.37 ab	97.9	3.39 ab	100.8	4.50 c	98.7
4	2.20 b	95.9	4.35 ab	97.6	3.42 b	101.7	4.46 de	97.7
5	2.15 bc	93.7	4.26 ab	95.6	3.42 abc	101.8	4.42 e	96.8
6	2.12 bc	92.4	4.27 ab	95.8	3.45 ac	102.6	4.35 f	95.3
7	2.02 cd	88.0	4.36 ab	97.7	3.46 bc	102.8	4.24 g	92.9
8	1.93 d	83.7	4.20 ab	94.1	3.50 bc	104.0	4.07 h	89.2
9	1.85 d	80.2	4.09 b	91.7	3.52 c	104.6	3.86 i	84.6
10	1.80 d	78.3						

[1] QdEC for each quarter was calculated as the difference between the EC value for that quarter and the EC value of the quarter with the lowest value within an individual cow on a given herd test day
[2] Ratio: ratio to class 1
Means within each column with different adjacent letter are significantly different (P<0.05)

QdEC, milk yield and composition

There were no significant differences between classes 1 to 3 (below 0.2 mS/cm) in quarter milk yield (Table 2). However, the yield of class 4 (0.2 to 0.3 mS/cm) was 95.9% that of class 1, and this was significantly lower than the yields of classes 1 to 3 ($P < 0.05$). The yields of classes 5 to 10 were all significantly lower than that of class 1 and classes 7 to 10 were significantly lower than class 4. The yields of classes 8 to 10 were 83.7% to 78.3% that of class 1 ($P < 0.05$).

There was a significant relation ($P < 0.001$) between the values of QdEC for each class (x) and the quarter milk yield of that of class1, expressed as a % of class 1 (y). The following linear regression was obtained:

$$y = 100.37 - (18.24 \pm 1.15)\, x$$

This regression equation indicates that an increase of 0.1 mS/cm in QdEC is associated with a decrease of approximately 2% in quarter milk yield.

Pro% was significantly higher ($P < 0.05$) in the higher classes than in the lower classes, with the value for class 9 (3.52%) being 1.05 times the value for class1 (3.36%). In contrast, Fat% and Lact% decreased in the higher QdEC classes, as was the case for EC. The values for classes 8 and 9 were 94.2% and 91.7%, and 89.3% and 84.6% of those for class 1, for Fat% and Lact%, respectively.

DISCUSSION

As no other mastitis markers such as somatic cell count (SCC) measurement or bacteriological inspections were performed in this study, we can not comment on the causes of abnormality of quarters. However, Hamann and Zecconi (1998) reported that the value of EC showed differences of 0.4-1.2 mS/cm depending on the presence and the kind of bacteria. Moreover, they suggested, from the meta-analysis of relationship between EC and SCC, that the EC measurement in milk does not identify mastitic quarters or cows with sufficient accuracy, but that the within-cow comparison between quarters seems to be currently the best measurement under field conditions. Similarly, Pyörälä (2003) reported that EC measurement in milk alone is not sufficient for detecting mastitis, however, the use of an inter-quarter evaluation improve the sensibility and specificity of EC. Hamann and Krömker (1997) reported that changes in milk yield and milk composition indicate health problems in both the cow and the mammary gland, and suggested that indicators that were related to them were needed.

Many studies have reported a relation between daily milk yield and mastitis, using SCC as an index of mastitis (Hortet & Seegers, 1998a and 1998b; Rajala-Schultz *et al*., 1999; Koldewij *et al*., 1999). Although measurement of EC of milk has been recognised as an index of mastitis, EC has not been used widely in the study of loss in milk yield from mastitis.

Since milk yield is influenced not only by mastitis but also by many other factors, the most reliable method to evaluate the reduction of milk yield caused by mastitis is to compare quarters within the udder of an individual cow. Suggested criteria to detect abnormal quarter milk were: 1) values of EC over 6.3 mS/cm, and 2) values of QdEC higher than 0.5 mS/cm (Oshima & Yamamoto, 1988; Oshima, 1985). In the present study 86.5% of 4380 observations was distributed below 5.7 mS/cm and only 2.3% were above 6.3 mS/cm. Similarly, for QdEC, 82.1% of quarters were below 0.3 mS/cm, Oshima's criteria (1985), and only 8.5% were above 0.5 mS/cm

Results from this study indicate that reductions in milk yield and composition, except protein, occurred at values of EC and QdEC that were lower than the criteria recommended previously (Oshima & Yamamoto, 1988; Oshima, 1985). In an experiment with a low SCC herd, reduction of milk yield was detected with a small increase in SCC, from class SCC < 10×10^4 to class SCC 10-20×10^4 (Meijering *et al.,* 1978). Similarly, in another low SCC herd, a rise of 1 mS/cm in mean EC was associated with a decline of 0.88 kg/day in daily milk production (Nielen *et al.,* 1993). When a mean QdEC value was based on repeated measurements within individual cows, quarter milk production loss per milking was approximately 3% for every 0.1 mS/cm of increase in QdEC (Oshima *et al.,* 1990). Results from the present study confirm this latter trend; the linear regression in our study indicates that there is about 2% reduction in milk yield for every 0.1 mS/cm increase in QdEC.

The admixture theory (Barry & Rowland, 1953) proposed that milk is mixture of 'true milk' secreted from the mammary gland and 'dilution' caused by inflammation, based on the relationships between Na, Cl, K and lactose in the mammary alveoli. It has been shown that this admixture takes place through a paracellular pathway (Peaker, 1983). Oshima (1985) measured EC in 'true milk' to which 'dilution' liquid was added. When the percentages of the dilution liquid were 5, 10, and 20%, the corresponding values for QdEC were 0.25, 0.48 and 0.93 mS/cm (Oshima, 1985). The present results suggest that it may be more appropriate to take 0.2 mS/cm as the criterion for a healthy quarter rather than 0.3 mS/cm, because in the class of 0.2-0.3 mS/cm in QdEC, that is not considered to be abnormal at present. A reduction in milk yield had already occurred as observed in the present study. Furthermore, a value of 0.25 mS/cm for QdEC suggests that 5% of the dilution liquid from inflammation has already been added to the 'true milk'.

This study showed that measurements of EC can be an effective screening test for abnormalities in quarters because EC and QdEC were closely related to reduction of milk yield and alteration of milk composition, with lactose in particular showing a marked decrease at higher values of EC and QdEC. One probable cause of such abnormalities is certainly mastitis. EC should be measured frequently to increase its reliability as an indicator of abnormalities in quarters.

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