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BLOOD FLOW AND OXYGEN CONCENTRATION OF TEAT-END TISSUE BEFORE AND AFTER MACHINE MILKING

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Summary: The purpose of this study was to investigate blood supply and oxygen concentration supply to teat-end tissue before and after milking. Tissue oxygen concentration and pulse strength were measured close to the teat-end, just before and immediately after milking. The degree of hyperkeratosis of the teats was scored before milking. It was observed that some cows exhibited strong contraction of the teats both before and after milking. The time to establish a pulse reading was delayed significantly (3.2±6.0 s) after milking. Teat contractions reduced pulse intensity and oxygen concentration in teat-end tissue both before and after milking. The average oxygen concentration in teat-end tissue was lower both before and after milking for cows that experienced strong teat contractions than those that did not. No significant difference could be detected in average oxygen concentration before versus after milking. However, teat-end score was positively correlated with the minimum oxygen concentration after milking and was negatively correlated with average milk flow rate during milking. Our results suggest that the teat contractions are associated with poor blood flow and oxygen supply to the teat-end and may contribute to teat-end hyperkeratosis.

Keywords: Machine Milking, Bovine, and Biomechanics

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INTRODUCTION

Cows begin their first lactation with no teat-end hyperkeratosis (HK) and after a period of milking all cows exhibit some degree of HK. There is a great deal of variation in the degree of HK, however, among cows milked under the same conditions. Moreover, the degree of HK commonly differs among the four teats of the same cow. These are indications that:

a) HK is a direct result of the milking process, and

b) There is a cow and teat effect on the predisposition to develop HK.

The cumulative time that mechanical forces are applied to the teat-end by the opening and closing liner has been shown to be an important factor in the development of HK (Woolford and Phillips, 1978; Grindal, 1990). More recently it has been speculated that a more specific indicator of the development of HK may be the time of over milking, or time the machine remains on a teat with little or no milk flow (Rasmussen, 1993). The size and shape of teats has been shown to affect the development HK. Differing milking time, over-milking time and teat shape can not be the only reason for differences in HK between teats, because different teats of the same cow may also have different degrees of HK while being milked for the same duration.

The objective of this study was to investigate whether differences in physiology could explain predisposition for the development of HK. Specifically the relationship between blood flow and oxygen concentration and teat-end HK were examined.

MATERIALS AND METHODS

Tissue oxygen concentration and pulse strength were measured in the right-front teat of cows before and after milking with a pulse oximeter (SurgiVet, model V3304) during two successive afternoon milkings. Pulse oximetry combines the principles of optical plethysmography and spectrophotometry to determine arterial oxygen saturation values. Optical plethysmography uses light absorbance technology to reproduce waveforms produced by pulsating blood. Spectrophotometry uses various wavelengths of light to perform quantitative measurements about light absorption through given substances. A sensor uses two LEDs - a red (660 nm) and an infrared (940 nm) light emitting diode - to transmit light through the vascular bed to a photodetector. The difference in the intensity of transmitted light between red and infrared light is caused by the differences in the absorption of light by oxygenated (saturated) and deoxygenated (desaturated) hemoglobin. The resulting voltage difference is used to calculate the amount of oxygen saturation by comparing the value against tables contained in the pulse oximeter's memory. Minimal pulse amplitude is encountered in tissue with poor peripheral perfusion. Note that this method measures oxygen concentration in the vascular bed across the diameter of the teat and is a fundamentally different measurement than that reported by Persson (1991) Hamann et al (1994), and Hamann and Mein (1995), which measured oxygen concentration of the surface of the teat skin.

The pulse oximeter uses a serial autocorrelation technique on a digitized signal in real time comparing each signal with previous pulse data. If similar characteristics to previous data are found, the device confirms a valid pulse. This process takes 5 seconds of valid data (with sufficient pulse amplitude) in order to begin detecting pulse and oxygen data. The earliest possible oxygen measurement would thus occur 5 seconds after attaching the device. If the pulse signal were weak the delay would be longer. The display includes a series of LED bars indicating the strength of the pulse signal. This scale starts to blink immediately when the pulse is sensed before a reading is recorded. The time between applying the sensor and the appearance of pulse on the blinking scale was recorded as a measure of the time to re-establish pulse strength in the teat tissue sufficient for the instrument to detect.

The measuring site was as close as possible to the teat-end. The shape and teat-end HK was assessed before cluster attachment. The method presented by Britt and Farnsworth (1996) was used to score teat-end HK ranging from a score of 1 for little or no HK up to 4 for severe HK with cracking teat-end skin. Lactation number, stage of lactation (days in milk), milk yield and milking time were recorded for each cow.

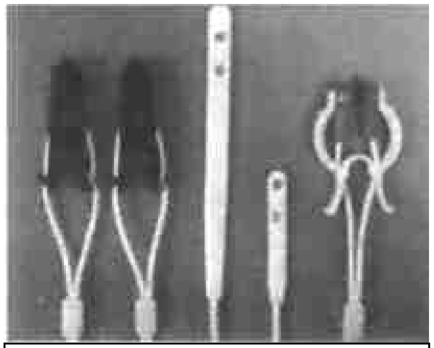

Figure 1. Pulse Oximeter Sensors. The sensor on the right was used for these studies.

Oxygen concentration data for the first 60 s after removal of the milking unit were included in the analysis. Only oxygen concentration and pulse rate measurements with more than 3 readings (15 s) were used for statistical analysis. Milk flow rate was calculated from milk yield and milking duration. Data for cows that were measured twice were averaged for both milkings.

The data were analyzed for all teats and separately for teats that were defined as having weak and strong teat contractions (see below) and for teats with low and high HK scores. A paired t-test was used to compare effects on the teats within the same class. An unpaired t-test was used to compare effects on the teats between classes.

RESULTS

Visual observation of teats indicated a wide degree of variation of frequency and strength of teat contractions both before and after milking. Touching the teats commonly triggered these contractions, although spontaneous contractions also occurred. Some teat contractions produced only mild skin wrinkling while other teats were visibly shortened and thickened with extreme skin wrinkling. Reduced pulse strength and oxygen concentration were recorded in the teat-end when contractions occurred. An example of the oxygen concentration measurement during a strong and mild teat contraction are shown in Figure 2.

No significant differenced in post versus pre milking oxygen concentration measures were found. Differences were noted, however, in the pulse rate and time to establish pulse reading. The average pulse before milking, as well as the minimal and maximal was significantly higher than after (Table 1), probably as a result of the milk letdown response. In the majority of measurements, the time between applying the sensor and appearance of pulse was longer after than before milking and longer than the normal 5 s delay of the measuring device (Table 1). This suggests a reduced pulse strength and reduced blood flow immediately after teat cup removal.

The variation in oxygen concentration due to teat contraction was much larger than the differences observed when comparing pre to post milking conditions. Efforts were made to investigate the influence of teat contraction on milking performance and teat condition. The range (max – min) in oxygen concentration during a 60 second recording was taken as a measure of the strength of teat contraction. The highest tissue oxygen fluctuations recorded in one teat ranged from 84 to 97 % (Figure 3). Teats that contracted strongly before milking also demonstrated strong contractions after milking (Figures 2 and 3). Teats that had more than 3% difference between minimal and maximal oxygen concentration, and at least one value less than 94%, were defined as having strong teat contractions.

Differences in tissue oxygen variables could be identified when the teats were divided according to strength of contraction (Figure 2 and Table 2) and teat-end scores (Table 3). Strong contractions correlated inversely with oxygen concentration and directly with time to establish pulse before and after milking (Table 2). A significant inverse relation was found between teat-end HK and average milk flow rate during milking (Table 3). This relationship was also verified with a separate data set (Davis, 2000) that included additional 74 measurements (Table 3).

The inverse relation between teat-end HK and minimal teat-end tissue oxygen concentration (averaged values for each teat score) after milking approached significance at 95% confidence level ($p < 0.059$) (Table 3). Regression analysis of minimal oxygen concentration after milking and teat-end score also showed the same tendency. The relationship between teat-end HK and the variation in oxygen concentration (max-min) after milking was significant ($p<0.05$) (Table 3). This suggests an association between teat-end HK and teat contractions.

DISCUSSION

Teat-end HK is the result of mechanical forces applied by the opening and closing liner during milking. The relationship between these mechanical forces and teat-end HK formation has demonstrated in several studies. Woolford and Philips showed that linerless milking does not cause HK. Rasmussen (1993) showed that early cluster removal improved teat-end condition significantly. Grindal (1990) showed that persistent exposure of the teat-ends to the same orientation of liner collapse created a hyperkeratotic line on the teat-end along the orientation of the collapse plane. This differs from the round ring developed in normal milking in which the collapse plane of the liner is in general different for each milking. In experiments conducted using no liner collapse teat-ends showed little or no HK. It is clear that HK development is a result of the physical stressed applied to the teat when the liner collapses.

The work of Peeters (1977) showed clearly that teat contractions continue (and in fact may be amplified in some cows) during milking. The variation in milk flow rates during milking reported by Williams et al (1981) were attributed to teat contractions. Increasing penetration of the teat into the liner and increasing milking vacuum both tended to decrease the variation in flow rate. There was substantial variation, however, between cows in the variation in flow rate (and probably strength of teat contractions) in this study.

Teat contraction will make teat-end tissue somewhat harder. Reduced circulation will also contribute to hardening of teat-end tissue. It has been shown that the milking liner applies a larger compressive load when bending around harder artificial teats (Reinemann et al 1994). The area of highest tissue stress has been shown theoretically to occur in the area of HK formation (Bathazar and Scott, 1978). Hardening teat-end tissue caused by teat contractions will therefore intensify the mechanical force applied to the teat during milking and also intensify the tissue stresses. These factors are likely to contribute to increased HK development. It was found in this study that teats with a high degree of HK also had a low milk flow rate. The work of Williams et al 1981 showed that low flow rate cows exhibited a higher degree of teat contraction.

Teat-end tissue oxygen availability might also be a significant factor in the ability of teats to recover from the mechanical pressures applied during milking. The results of this study were restricted by the limitations of the measuring equipment that requires 5 s of equilibration before yielding the first oxygen measurement, hence losing the most critical oxygen measurement period reflecting the situation during milking.

Teat contractions attracted research attention from a wide range of physiological aspects (Williams et al. 1978, 1981 Mein and Williams 1984, Lefcourt 1982a and b). Hamann and Burvenich (1994) suggested that, in addition to other consequences (as described by Lefcourt 1982a and b), the “spontaneous rhythmic contraction of the teat support the outflow of venous blood and lymph and thereby the physiological status of the teat is ensured”. Our results, that strong teat contractions were associated with lower teat-end tissue oxygen concentrations and pulse strength, support this statement. However, this advantage of teat contraction may become a disadvantage during milking. The venal blood and lymph “pumping” capacity of teat contractions is maintained as long as the muscles contract isotonicaly. While pumping out venal blood and lymph, teat muscle contractions reduce arterial blood flow to the teat-end. During the time of low blood flow, the contracting muscles consume the oxygen available in the tissue until muscle relaxation allows resumption of arterial blood flow to the tissue. Muscle contraction is therefore, associated with two aspects of tissue oxygen reduction that accompany the extracellular fluids circulatory advantage of the teat contractions. a) Temporary obstruction of arterial blood flow, and b) increased oxygen consumption by the contracting muscle fibers. This is not a problem between milkings because the contraction is isotonic and oxygen is required to provide energy to the contracting muscles and for maintenance. This is not the case when contractions occur during milking.

During milking the teat is stretched in the milking liner. If longitudinal contractions occur they are isometric (Williams et al. 1981, Mein and Williams, 1984). The “pumping” capacity is reduced and oxygen will be consumed by the contracting muscle fibers. It appears from this study that pulse amplitude is reduced during milking reducing blood circulation in teat-end tissue. During milking oxygen is needed in teat-end tissue to provide energy to the contracting muscles, for maintenance and in addition for recovery from the mechanical forces imposed by the collapsing liner. This additional oxygen demand may further stress teat-end tissue.

The variety between teats in intensity and rate of teat contraction during milking that were shown by Peeters (1977), Lefcourt (1982), and Williams et al. (1981) were verified in this study. Lefcourt (1982) showed that in some cows contractions were reduced during milking while in some cows contractions were maintained or increased during milking. The results from this study suggest that teat the variation in the strength of teat contractions may explain some of the variation in the formation of HK.

Table 1. T-test of teat-end tissue oxygen concentrations, pulse rate and time for first pulse to register just before milking and during the first 60 sec after milking.

Variable	n	Before Milking		After Milking		p-value
		AVG	STD	AVG	STD	
Average Tissue Oxygen Concentration (%)	21	94.6	1.8	94.9	1.5	0.5461
First Tissue Oxygen Concentration (%)	21	93.0	3.5	94.3	2.6	0.1173
Minimal Tissue Oxygen Concentration (%)	20	92.5	2.9	93.4	2.4	0.2518
Maximal Tissue Oxygen Concentration (%)	20	95.8	1.5	96.1	1.9	0.5977
Tissue Oxygen Concentration Difference (%)	20	3.4	2.7	2.7	1.6	0.3933
Average Pulse (bpm)	20	87.3	8.4	84.6	8.4	**0.0002**
First Pulse (bpm)	20	89.2	11.9	86.7	9.4	**0.0240**
Minimal Pulse (bpm)	20	85.3	9.8	82.5	7.8	**0.0348**
Maximal Pulse (bpm)	20	91.5	11.0	87.9	9.5	**0.0053**
Time first pulse was recorded (sec)†	16	9.1	2.2	12.8	6.3	**0.0355**

† The time interval between applying the sensor and recording the first pulse.

Table 2. T-test of teat-end oxygen concentration and pulse variables for teats with high and low level oxygen fluctuations (and teat contraction) just before milking and during the first 60 sec after milking.

Variable	Tissue Oxygen Fluctuations						P<
	Low			High			
	Before Milking						
	n	AVG	STD	n	AVG	STD	
Average Tissue Oxygen Concentration (%)	8	96.3	1.7	13	93.6	0.9	**0.0024**
CV (SD % of AVG)	8	0.75	0.18	13	1.70	1.34	**0.0253**
First Tissue Oxygen Concentration (%)[†]	8	95.8	1.4	13	91.4	3.3	**0.0004**
Minimal Tissue Oxygen Concentration (%)	8	95.0	1.0	13	91.2	2.5	**0.0001**
Maximal Tissue Oxygen Concentration (%)	8	97.0	1.3	13	95.2	1.2	**0.0105**
Tissue Oxygen Concentration Range (%)	8	2.0	0.6	13	4.0	3.0	**0.0302**
Average Pulse (bpm)	8	81.9*	6.4	12	90.9*	7.9	**0.0120**
First Pulse (bpm)†	8	81.1	5.8	12	96.6*	12.5	**0.0008**
Minimal Pulse (bpm)	8	78.6	5.0	12	89.7	9.7	**0.0039**
Maximal Pulse (bpm)	8	84.6	7.3	12	97.7*	12.1	**0.0062**
Time first pulse was recorded (sec)[†]	7	8.7	2.1	9	9.3*	2.4	0.5948
	After Milking						
Average Tissue Oxygen Concentration (%)	8	95.9	1.1	13	94.3	1.4	**0.0113**
CV (SD % of AVG)	8	0.75	0.34	13	1.80	0.94	**0.0022**
First Tissue Oxygen Concentration (%)[†]	8	96.0	1.9	13	93.3	2.3	**0.0078**
Minimal Tissue Oxygen Concentration (%)	8	95.3	1.3	13	92.4	2.2	**0.0010**
Maximal Tissue Oxygen Concentration (%)	8	97.0	1.4	13	95.5	2.0	0.0541
Tissue Oxygen Concentration Range (%)[‡]	8	1.8	1.0	13	3.1	1.8	**0.0316**
Average Pulse (bpm)	8	78.4	5.9	13	88.0	7.5	**0.0043**
First Pulse (bpm) [†]	8	79.5	5.9	13	91.5	8.3	**0.0009**
Minimal Pulse (bpm)	8	76.5	6.0	13	86.2	6.4	**0.0032**
Maximal Pulse (bpm)	8	82.4	8.4	13	91.3	8.8	**0.0328**
Time first pulse was recorded (sec)[†]	7	10.9	2.3	9	14.4	8.0	0.1936

**High fluctuations = Minimum oxygen concentration less than 94 % and oxygen concentration range (max – min) > 3 %. The data cows with repeated measures across two nights were averaged.

*Significant difference between similar variables before and after milking.

[†] time to record first pulse reading after applying the sensor to the teat.

Table 3. Milk flow rate during complete milking, teat-end tissue oxygen variables just before milking and during the first 60 sec after milking, and time of pulse appearance after milking of low (1+2) and high (3+4) HK teats.

Variable	Low HK score (1+2)			High HK score (3+4)			P<
	n	AVG	STD	n	AVG	STD	
Milk Flow Rate (pnd/min)	9	7.69	1.94	9	5.98	1.35	**0.0477**
Milk Flow Rate (pnd/min) *	29	5.79	2.44	45	4.15	1.78	**0.0032**
	Before Milking						
Average Tissue Oxygen Concentration (%)	11	94.4	1.5	10	94.9	2.2	0.5337
First Tissue Oxygen Concentration (%)†	11	92.4*	4.3	10	93.6	2.2	0.4474
Minimal Tissue Oxygen Concentration (%)	11	92.3*	3.4	9	92.8	1.7	0.6511
Maximal Tissue Oxygen Concentration (%)	11	96.1	1.1	9	95.4	1.9	0.3794
Range tissue Oxygen Concentration Difference (%)‡	11	3.9*	3.4	9	2.7	0.9	0.2724
Time first pulse was recorded (sec)[†]	9	8.9*	2.2	7	9.3	2.4	0.7415
	After Milking						
Average Tissue Oxygen Concentration (%)	11	95.1	1.7	10	94.7	1.3	0.5763
First Tissue Oxygen Concentration (%)†	11	94.8	1.9	10	93.7	3.1	0.3669
Minimal Tissue Oxygen Concentration (%)	11	94.4	1.6	10	92.3	2.8	**0.0585**
Maximal Tissue Oxygen Concentration (%)	11	96.2	1.6	10	95.9	2.3	0.7627
Range tissue Oxygen Concentration Difference (%)‡	11	2.0	1.4	10	3.6	1.5	**0.0180**
Time first pulse was recorded (sec)[†]	9	12.9	8.1	7	13.0	7.5	0.9585

* from Davis, (2000).

Significant difference ($P<0.05$) before and after milking of this parameter.

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Figure 2. Teat-end tissue oxygen concentration before (B) and after (A) milking of a cow with no visible teat contractions (triangles) and a cow with strong visible contractions (squares). Sensor was applied immediately after cluster removal. Measured at the same milking.

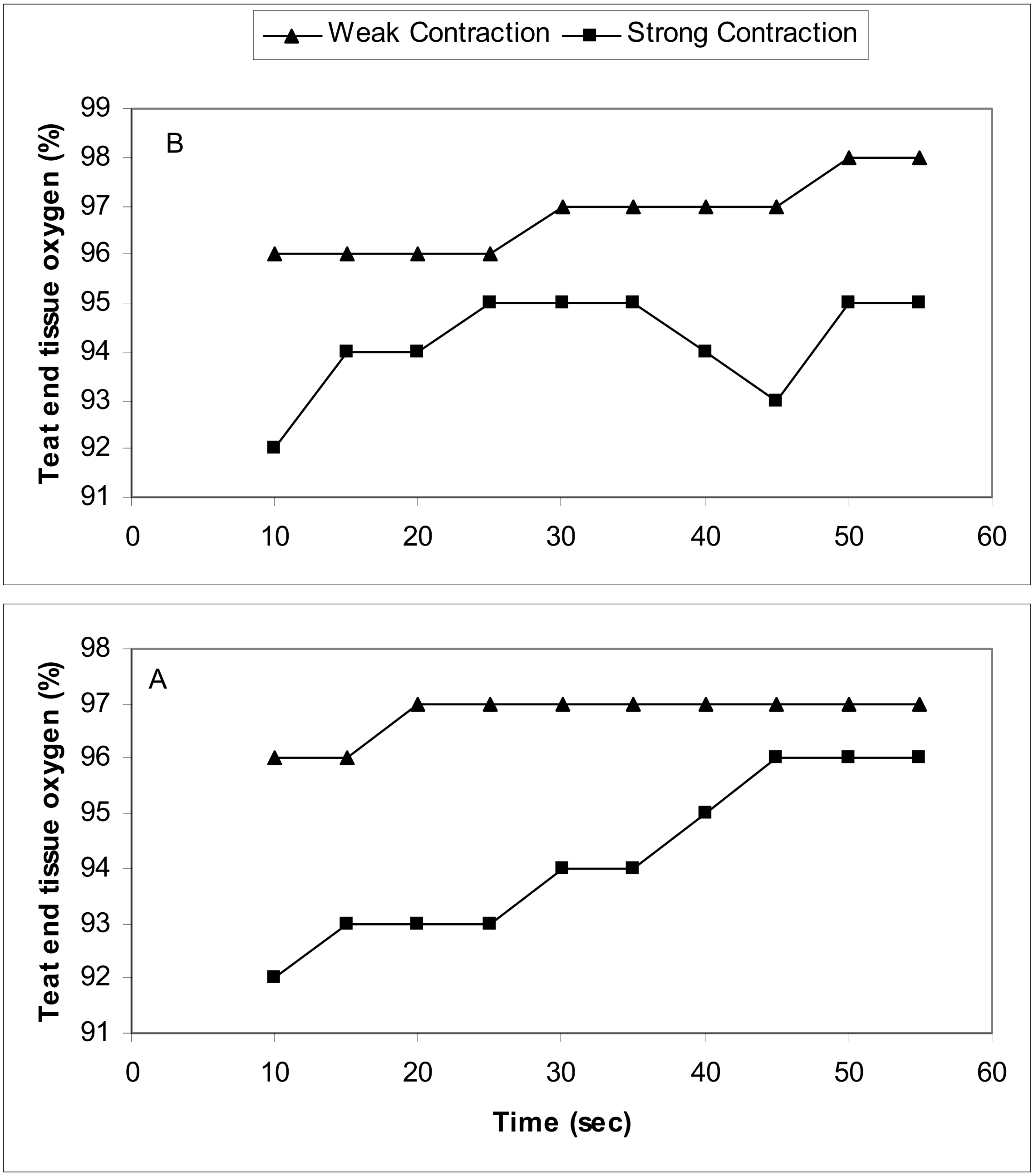

Figure 3. Oxygen concentration and pulse rate a teat with a strong contraction, before (triangles) and after (squares) milking. Time "0" is the time the sensor was applied (…… = missing data probably due to low pulse intensity or signal distortion).

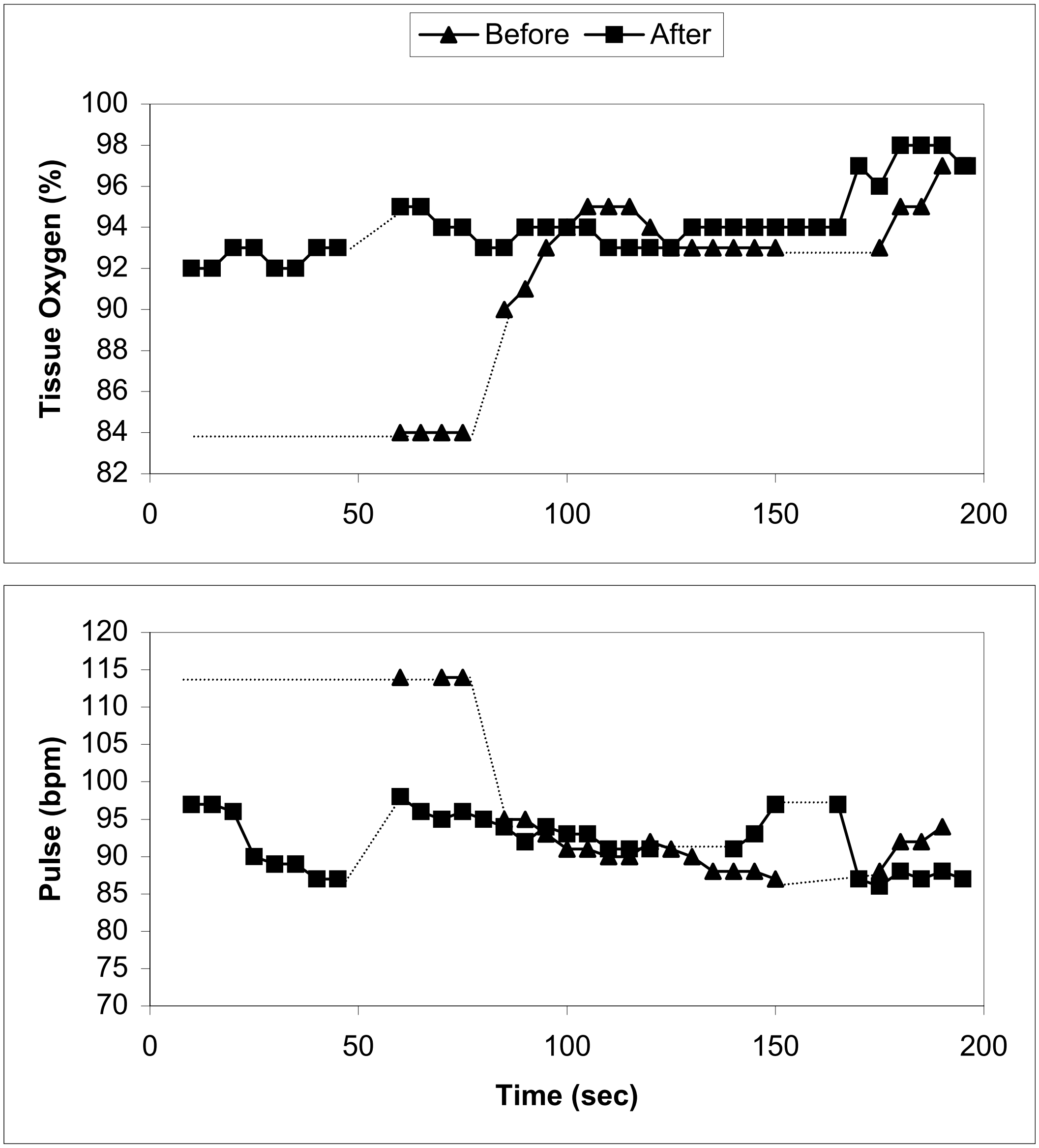

Figure 4. Regression between minimal oxygen concentration during the first 60 seconds after milking and teat-end score. Numbers near points indicate number of teats with this score. Triangles represent the raw data and circles represent the average oxygen concentration for each score.