

Cow teat hysteresis as affected by time of measurement

R. GUPTA¹ and S. Y. REITSMA²

Department of Agricultural Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 2N2. Received 6 July 1987, accepted 12 December 1988.

Gupta, R. and Reitsma, S. Y. 1989. Cow teat hysteresis as affected by time of measurement. *Can. Agric. Eng.* 31:153-157. The effect of time of measurement (before, during, and after milking) on hysteresis of the cow teat end is reported. Hysteresis measurement is based on external teat end diameter changes in response to step input changes of vacuum level (0 - 30 kPa and vice versa) to the outside of the teat. These measurements were made on all four teats of each of four cows. Measurable teat and expansion and contraction took place both before and during milking, but not after milking. Hysteresis ratio was significantly ($P < 0.05$) higher during than before milking. This suggests teat end congestion as milking progresses. Also, increased ($P < 0.01$) teat delay rise time during versus before milking suggests a delayed response of teats due to congestion. Adequate liner closure around the teat end will help reduce congestion and the incidence of mastitis.

INTRODUCTION

A milking unit, consisting of four double-chambered teat cups and a claw, extracts milk by applying a vacuum (35 - 50 kPa below atmospheric pressure) to the outside of the teat, unlike hand milking which relies on pressure application above atmospheric pressure. The teat cup, comprising an outer metal shell and an inner liner, is placed around the teat and milk is extracted only because of vacuum inside the liner and not due to liner squeeze. The teats undergo large deformations which are uncomfortable, if not painful (Gates 1984). The liner is periodically closed for relief, providing a compressive load to the test surface. Liner closure is achieved by alternate introduction of a vacuum and atmospheric pressure to the space between the liner and the outer shell (called pulsation chamber), at a frequency of 1 Hz or less.

The conventional milking machine teat cup has been in use for the last 80 yr. Several investigators with various backgrounds have studied the milking machine in relation to efficiency of milk removal and udder health. The biological properties and physiological responses of the teat were often not considered. Gates (1984) addressed the teat as a "black box" of unknown responses. Reitsma (1977) emphasized dynamic teat responses in terms of teat end expansion and contraction and milk flow. Such responses are of prime importance to any method or system of milk removal.

Dynamic responses of the dairy cow's teat will help provide a better understanding of teat tissue behavior and provide a useful tool for improved design of milking machines. In this study, an experimental approach was taken to determine hysteresis present in the dairy cow's teat. Hysteresis, as a teat tissue response, will likely affect opening and closing of the streak canal. Therefore, hysteresis may affect milk flow rate and the incidence of mastitis in dairy cows. Mastitis is the costliest and most frequently occurring disease in dairy cows.

OBJECTIVES

The specific objectives of this paper are as follows:

1. To compare the hysteresis ratio of the teat end at: before, during, and after milking. (The hysteresis ratio is defined as the area between the loading (vacuum application resulting in teat end expansion) and unloading (vacuum release resulting in teat end contraction) curves as a percentage of the area below the loading curve (Gupta 1984).)
2. To plot and analyze step input vacuum level changes and responding teat end diameter changes in parallel as a function of time.
3. To compute applied vacuum level variables and teat responses, e.g. rise, fall and delay times, time duration of the teat more than half-way expanded and less than half-way expanded (i.e., more than half-way contracted), and teat end diameter ratio (expanded/unexpanded diameter), and
4. To plot hysteresis curves at the three times (i.e., before, during, and after milking) for a single milking as a function of the pressure differential across the teat canal and to compute hysteresis ratio.

REVIEW OF LITERATURE

Townsend (1969), Stettler (1973) and Gates (1984) are among the few investigators who studied the elastic behavior of teats. Townsend (1969) reported that the teat end behaves as a non-linear elastic body and that teat stiffness increases with increased loading. Stettler (1973) described the visco-elastic behavior of a three-element Maxwell model. Gates (1984) reported that teat tissue behaves as an incompressible pseudo-elastic material when subjected to loads from the machine milking process, and exhibits a nonlinear load-deformation curve that is fairly repeatable during cyclic load tests.

Hysteresis is a characteristic of an imperfect elastic response to deformation of many biological materials representing viscoelastic behavior of smooth muscle tissue. Hysteresis is defined as the failure of a system to follow identical paths of response upon application and withdrawal of a forcing agent (Fedullo et al. 1980). Hysteresis implies energy dissipation through heat and/or physiological chemical reaction, whether it is a result of mechanical friction, magnetic effects, thermal effects, or elastic deformations.

An investigation of Uhmman and Thalheim (1980) showed an increase in hysteresis for liners requiring a larger pressure differential for opposite sides of the internal liner wall to come into initial contact. The measurement conditions were essentially static and liner wall position was sensed by a dial gauge. Under dynamic measurement conditions Reitsma and Breckman (1985) showed that a slower change of vacuum level in the pulsation chamber decreases hysteresis present in the teat cup liner. Holownia (1979) studied hysteresis loss in rubber and reported that the change of shape of the rubber has a greater effect on hysteresis loss than the level of stresses present.

¹Present address (R.G.): Department of Agricultural Engineering, Cornell University, Ithaca, NY 14853, U.S.A.

²Present address (S.Y.R.): Lacto-Tech Service, 1025 Esdras Place, Windsor, ON, Canada N8S 2N1.

A recent review of literature by Gupta (1984) on hysteresis of the dairy cow's teat indicated that information seems to be lacking in this area. Gupta and Reitsma (1986) reported a higher hysteresis ratio (83%) in teat ends for a fast rate of vacuum level changes as compared to 63% for a slow rate.

EXPERIMENTAL METHODS

The measurement and analysis techniques, including a description of the teat chamber, teat end diameter transducer and milking procedure have been given in detail in a previous paper by Gupta and Reitsma (1987). The typical value of 150 ms was used for vacuum level rise and fall times to simulate conditions when using a teat cup liner. Measurements just before milking (before attaching milking unit), during milking (when peak milk flow was observed) and after milking were made. There was very little or no expansion and contraction of teat ends after milking. Therefore, only data taken before milking and during milking have been analyzed.

Statistical design

Layout of the statistical design of the experiment is shown in Table I. All four teats of each of four cows were used. Two measurements were made on one teat of each cow during one milking. One was made before the milking unit was attached to the teats and another during milking when peak milk flow was established from all four teats. The following statistical model was applied for an analysis of variance of all measured variables:

$$Y\{ijkl(j)\} = m + c(i) + p(j) + a(k) + s\{l(j)\} + c^*p(ij) + p^*a(jk) + c^*a(ik) + c^*p^*a(ijk) + s^*a\{l(j)k\} + e\{ijkl(j)\}$$

where:

- i = 1, ..., 4 cow no.
- j = 1,2 teat location (front, rear)
- k = 1,2 time of measurement (before, during milking)
- l = 1,2 side (left, right)
- $Y\{ijkl(j)\}$ = observation
- m = mean
- $c(i)$ = cow effect
- $p(j)$ = teat location effect
- $a(k)$ = time of measurement effect
- $s\{l(j)\}$ = side within teat location effect
- $c^*p(ij)$ = interaction between cow and teat location
- $p^*a(jk)$ = interaction between location and time of measurement
- $c^*a(ik)$ = interaction between cow and time of measurement
- $c^*p^*a(ijk)$ = interaction between cow, location and time measurement
- $s^*a\{l(j)k\}$ = interaction between side within location and time of measurement
- $e\{ijkl(j)\}$ = error term

RESULTS AND DISCUSSION

The mean and standard error (SE) of the mean of several step input variables are shown in Table II. The small SE of the mean for most of the step input variables verify uniformity of applied vacuum level changes to the teats. The step input period was consistent for cows on a particular day but varied somewhat from day to day. This may be explained by the effect of small changes in temperature and humidity on components used in the timer circuit which controls the two solenoid valves. However, the variation over days is so small that it is unlikely to affect teat responses. The small SE of the mean for minimum

Table I. Layout of the experimental design for the TMEAS experiment for all four teats of four cows over 4 d

| Cow | Teat location | Side | Day | | | |
|-----|---------------|-------|-----|----|----|----|
| | | | 1 | 2 | 3 | 4 |
| 1 | Front | Right | BD† | | | BD |
| | | Left | | | | |
| | Rear | Right | | BD | | |
| | | Left | | | | |
| 2 | Front | Right | | BD | | BD |
| | | Left | | | | |
| | Rear | Right | BD | | | |
| | | Left | | | | |
| 3 | Front | Right | BD | | | BD |
| | | Left | | | | |
| | Rear | Right | | BD | | BD |
| | | Left | | | | |
| 4 | Front | Right | | BD | | BD |
| | | Left | | | | |
| | Rear | Right | BD | | BD | |
| | | Left | | | | |

†BD, before and during milking measurements.

Table II. Means and standard error (SE) of the means of several step input variables for the TMEAS experiment

| Step input variable | Units | Mean | SE of the mean |
|------------------------|-------|------|----------------|
| Step input period | ms | 2076 | 0.19 |
| Maximum vacuum level | kPa | 30.2 | 0.02 |
| Minimum vacuum level | kPa | -0.1 | 0.02 |
| Vacuum level rise time | ms | 174 | 1.44 |
| Vacuum level fall time | ms | 144 | 1.09 |

and maximum vacuum level show that all teats were subjected to the same vacuum level over all days. The vacuum level rise time was generally more than 150 ms but the fall time was close to preset value of 150 ms. During vacuum application air may leak between the test chamber's mouthpiece and the teat resulting in a longer rise time. Once the vacuum level reaches its maximum value, there is a better seal between teat and mouthpiece. Therefore, little or no leakage occurs when the vacuum level returns to zero. Some of the cycles were deleted because of excessive leakage during vacuum application resulting in a much longer rise time which also affected teat responses. This was also noticeable on the strip chart recordings.

Table III shows the means of the teat responses before (B) and during (D) milking for all the four teats combined of each of the four cows. The results of an analysis of variance of all measured teat response variables are given in Table IV. Because of the small size of this experiment, a 10% probability level (close to significant) was also included (Steel and Torrie 1980).

The results in Table IV suggest that nearly all teat response variables differ considerably between cows and less due to teat location, time of measurement and side within a location. Reitsma (1977) found significant differences between teat

Table III. Means of the teat response variables measured before (B) and during (D) milking for the four teats combined of each of four cows

| Cow | Time of measurement | N‡ | Teat response variable† | | | | | | | | | | | | | | |
|-----|---------------------|----|-------------------------|-----------|----------|----------|----------|----------|----------|----------|----------|------|----------|--------------|--------------|--------------|---------|
| | | | VHO (kPa) | VHC (kPa) | TRT (ms) | TFT (ms) | TDT (ms) | TLT (ms) | TMT (ms) | ALD (mm) | ASD (mm) | TDR | DSP (mm) | ARL (kPa-mm) | ARU (kPa-mm) | HYS (kPa-mm) | HYR (%) |
| 1 | B | 4 | 29.1 | 4.0 | 178 | 355 | 135 | 1133 | 939 | 23.3 | 19.3 | 1.21 | 4.1 | 119.6 | 28.8 | 90.6 | 75.2 |
| | D | 4 | 30.0 | 4.4 | 270 | 315 | 236 | 1267 | 814 | 24.6 | 21.1 | 1.17 | 3.6 | 108.4 | 26.6 | 85.9 | 75.8 |
| 2 | B | 4 | 23.5 | 1.5 | 72 | 488 | 93 | 967 | 1110 | 20.6 | 17.7 | 1.16 | 2.9 | 72.1 | 17.5 | 55.0 | 75.4 |
| | D | 4 | 28.7 | 4.4 | 147 | 508 | 169 | 1085 | 991 | 20.4 | 18.1 | 1.13 | 2.3 | 74.4 | 17.8 | 57.0 | 75.8 |
| 3 | B | 4 | 23.8 | 4.4 | 131 | 221 | 70 | 1031 | 1040 | 20.0 | 17.5 | 1.15 | 2.6 | 58.2 | 17.6 | 38.8 | 68.7 |
| | D | 4 | 26.7 | 3.3 | 189 | 263 | 99 | 1070 | 1007 | 19.8 | 17.2 | 1.15 | 2.6 | 65.1 | 17.2 | 48.0 | 73.5 |
| 4 | B | 4 | 13.5 | 2.9 | 103 | 215 | 20 | 938 | 1138 | 22.2 | 17.2 | 1.30 | 5.1 | 72.9 | 29.7 | 42.9 | 58.1 |
| | D | 4 | 19.4 | 4.2 | 80 | 148 | 57 | 996 | 1079 | 21.0 | 16.7 | 1.27 | 4.4 | 83.5 | 28.2 | 55.1 | 65.0 |

†VHO, vacuum level at half-way expansion of the teat; VHC, vacuum level at half-way contraction of the teat; TRT, teat rise time; TFT, teat fall time; TDT, teat delay rise time; TLT, teat-less-than-half-open time; TMT, teat-more-than-half-open time; ALD, average largest diameter; ASD, average smallest diameter; TDR, teat and diameter ratio; DSP, step change in teat end diameter; ARL, area under loading curve (teat expansion); ARU, area under unloading curve (teat contraction); HYS, hysteresis; HYR, hysteresis ratio.

‡N, number of observations.

Table IV. Results of the analysis of variance for all measured teat response variables of experiment TMEAS

| Source of variation | Teat response variable† | | | | | | | | | | | | | | | |
|---------------------|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--|
| | VHO | VHC | TRT | TFT | TDT | TLT | TMT | ALD | ASD | TDR | DSP | ARL | ARU | HYS | HYR | |
| Cow | S‡ | | s | S | S | S | S | S | S | S | S | S | S | S | S | |
| Loc | | S | | S | s | | | | | | | | S | | S | |
| TMS | s | s | | | S | S | S | | | | | | | | s | |
| Side(LOC) | | | c | | | s | s | | | | | | | | | |
| Cow*LOC | c | S | | s | S | | | | | s | s | s | | s | S | |
| TMS*LOC | | s | | | | | | | | | | | | | | |
| Cow*TMS | | s | | | | | | | | | | | | | | |
| Cow*TMS*LOC | | S | | | | | | | | | | | | | | |
| TMS*Side(LOC) | | | | | | | | | | | | | | | c | |

†LOC, location (front,rear); TMS, time of measurement (before, during milking); VHO, vacuum level at half-way expansion of the teat; VHC, vacuum level at the half-way contraction of the teat; TRT, teat rise time; TFT, teat fall time; TDT, teat delay rise time; TLT, teat less-than-half-open time; TMT, teat more-than-half-open time; ALD, average largest diameter; ASD, average smallest diameter; TDR, teat end diameter ratio; DSP, step change in teat end diameter; ARL, area under loading curve (teat expansion); ARU, area under unloading curve (teat contraction); HYS, hysteresis; HYR, hysteresis ratio.

‡S, highly significant ($P < 0.01$); s, significant ($P < 0.05$); c, close to significance ($P < 0.10$).

location for step change in diameter, teat end diameter ratio, and average smallest diameter.

The vacuum level at half-way expansion (VHO) of the teat was significant for the factor time of measurement. This variable is higher during milking than before milking. Radiographic work of Mein et al. (1973) showed edema formation (i.e. blood and serum pooling within the tissue) during milking. This phenomenon may explain higher values of VHO during milking as compared to before milking. The vacuum level at half-way contraction (VHC) of the teat was significant for the time of measurement and usually higher during milking.

The teat rise (TRT) and fall times (TFT) were not significant for the factor time of measurement (see Table IV), whereas teat delay time (TDT) was highly significant for this factor. The TDT was always longer during milking than before. No significant difference in teat rise time at before and during milking and longer TDT during milking suggest that, due to the congestion developed at the teat end, the teat end takes longer time

to start expanding but once expansion starts, the rate of expansion is about the same for before and during milking.

The teat less-than-half-open (TLT) and more-than-half-open times (TMT) are highly significant for factor time of measurement. Teat-less-than-half-open time was longer during milking because of the large delay time which keeps the teat ends closed for longer times. Probably due to congestion developed at the teat end, the teat is closed for more time than it is open during milking as compared to before milking. The congestion adversely affects milk removal due to the physical blockage of the teat canal (Gates 1984).

The hysteresis ratio for each of the cows for front and rear teats separately at, before and during milking is shown in Fig. 1. Like other teat response variables the hysteresis ratio is highly significant for cows. It is also highly significant for location and significant for time of measurement. The presence of hysteresis in the teat end shows the visco-elastic behavior of the teat. But this behavior varies between cows, within a cow

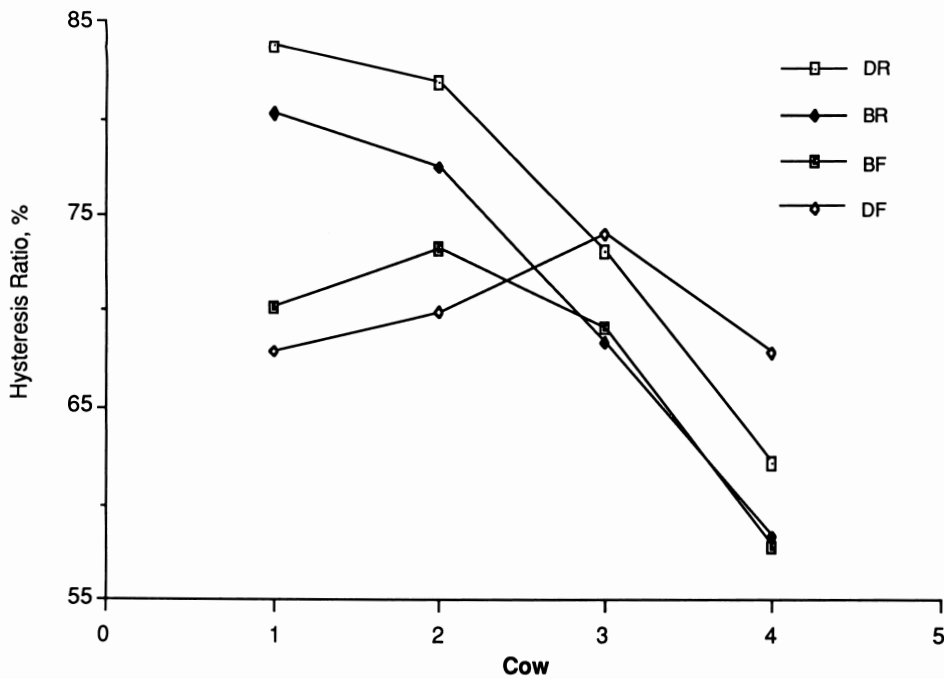


Figure 1. Mean hysteresis ratio vs. cow for front (F) and rear (R) teats separately observed before (B) and during (D) milking.

between front and rear teats and also for a teat within a milking. Differences in cows and teat location are probably due to different amounts of smooth muscle present at the teat end. Differences within a milking indicate that the physical condition of the teat end can change its visco-elastic behavior. This also confirms that hysteresis is a time-dependent phenomenon.

Figure 1 gives a clear picture of the hysteresis ratio for front and rear teats before and during milking separately. Generally, rear teats showed more hysteresis than front teats, as reported by Gupta and Reitsma (1987). Figure 1 also shows that the

hysteresis ratio was often higher during than before milking irrespective of teat location.

Figure 2 shows typical hysteresis curves for the front teat of a cow before and during milking. Curve B was observed before milking and curve D during milking. A higher hysteresis ratio during milking suggests congestion at the teat end as milking progressed. Thiel and Mein (1979) reported that the volume of the teat remained more or less constant during a single milking but the volume of the teat tissue increased as the volume of the teat sinus shrank. They reported a 50% increase in teat tissue

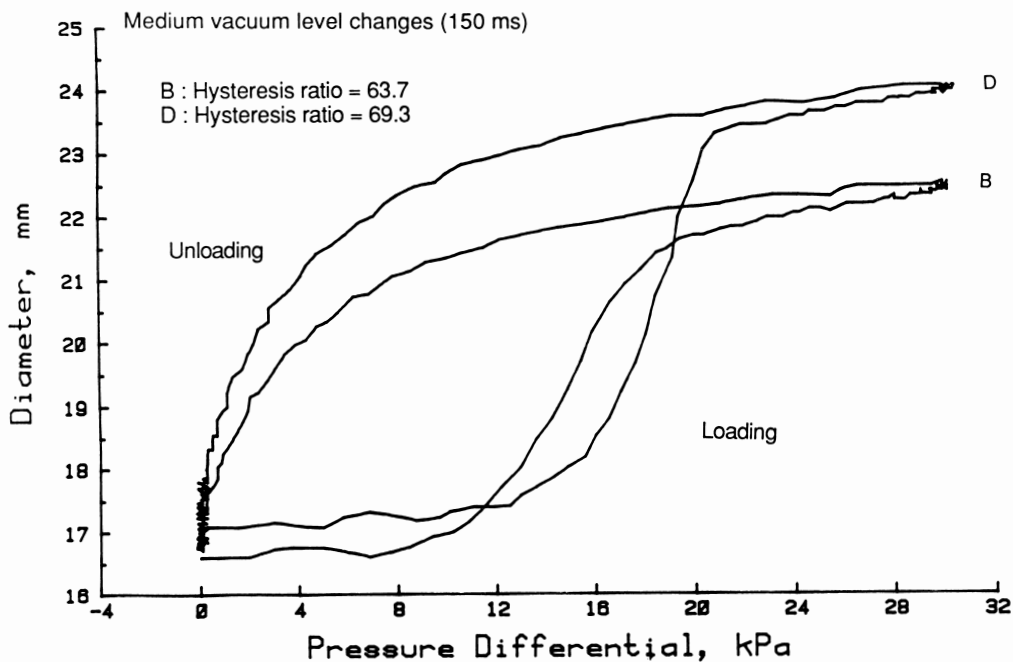


Figure 2. Hysteresis curves for front teat of a cow for two different times of measurements, before (B) and during (D) milking.

volume during the peak flow rate part of milking. This increase in volume refers to the congestion of fluids at the teat end which resulted in a larger hysteresis ratio during milking than before milking. Mein (1984) also reported a reduction of the effective cross-sectional area of the teat canal as congestion developed with time through a pulsation cycle.

Congestion increases if teats are not subjected to periodic liner squeeze. This suggests that liner closure is important for tissue relief. Inadequate liner closure is known to result in increased rates of infection as reported by Reitsma et al. (1981).

The higher hysteresis ratio found during milking may help explain why adequate line closure is necessary to relieve the teat from congestion.

CONCLUSIONS

The main conclusions based on the results of this study are:

1. Step input changes of vacuum level from 0 kPa (atmospheric pressure) to 30 kPa and vice versa result in measurable teat end expansion and contraction, and hysteresis both before and during milking but not after milking.

2. The hysteresis ratio of the teat end is significantly ($P < 0.05$) higher during the peak flow rate part of milking than just before milking (73% and 69% respectively).

3. A larger hysteresis ratio during than before milking indicates congestion at the teat end.

4. The larger ($P \leq 0.01$) teat delay rise time during than before milking shows the delayed response of teats due to congestion.

5. Adequate liner closure may help in reducing congestion.

6. Significant differences in teat responses are mainly due to cow differences.

ACKNOWLEDGMENTS

We thank the following persons for their help: Dave Breckman, Kent Wotherspoon, Ben Mogan and Dr. K. Mount. Financial assistance from Natural Sciences and Engineering Research Council of Canada and Manitoba Agriculture is greatly appreciated. We thank Western Dairy Research, Inc. for making a vacuum controller available.

REFERENCES

FEDULLO, A. J., Y. JUNG-LEGG, G. L. SNIDER, and J. B. KARLINSKY. 1980. Hysteresis ratio: A measure of the mechanical

efficiency of fibrotic and emphysematous hamster lung tissue. *Am. Rev. Respir. Dis.* 122:47-52.

GATES, R. S. 1984. Biomechanics of teat/liner interactions during machine milking: a finite deformation approach. Ph.D. Thesis, Cornell University, Ithaca, NY. 170 pp.

GUPTA, R. 1984. Hysteresis of the dairy cow's teat during machine milking. M. Sc. Thesis, University of Manitoba, Winnipeg, MB. 92 pp.

GUPTA, R. and S. Y. REITSMA. 1986. Hysteresis of the dairy cows' teat as affected by vacuum level rates of change. *Can. Agric. Eng.* 28(2):149-153.

GUPTA, R. and S. Y. Reitsma. 1987. Measurement and analysis techniques for hysteresis of the dairy cows' teat. *Can. Agric. Eng.* 29(1):51-57.

HOLOWNIA, B. P. 1979. Rubber hysteresis in biaxial and triaxial loadings. Ch. 8 in C. Hepburn and R. J. W. Reynolds, eds. *Elastomers: Criteria for engineering design.* Applied Sci. Publishers, London, U.K.

MEIN, G. A., C. C. THIEL, and D. N. AKAM. 1973. Mechanics of the teat and teatcup liner during milking: information from radiographs. *J. Dairy Res.* 40:179-189.

MEIN, G. A. 1984. Vacuum fluctuations and mastitis. Proc. 23rd Annual Meeting of the National Mastitis Council, Inc. Feb. 13-15, Kansas City, MS. pp. 163-171.

REITSMA, S. Y. 1977. Dynamic responses of the dairy cows' teat to linerless milking. Ph.D. Thesis, Cornell University, Ithaca, NY.

REITSMA, S. Y. and D. K. BRECKMAN. 1985. Measurement and analysis of milking machine teat cup operation. *Can. Agric. Eng.* 27(2):91-97.

REITSMA, S. Y., E. J. CANT, R. J. GRINDAL, D. R. WESTGARTH, and A. J. BRAMLEY. 1981. Effect of duration of teat cup liner closure per pulsation cycle on bovine mastitis. *J. Dairy Sci.* 64(11):2240-2245.

STEEL, R. G. D. and J. H. TORRIE. 1980. Principles and procedures of statistics; A biometrical approach. McGraw-Hill Book Co., New York, NY. pp. 87-91.

STETTLER, W., Jr. 1973. An investigation of the stretch characteristics of the streak canal and sphincter muscle in the teat of the lactating dairy cow. Ph.D. Thesis, University of Manitoba, Winnipeg, MB. 133 pp.

THIEL, C. C. and G. A. MEIN. 1979. Action of the cluster during milking. Ch. V. in C. C. Thiel and F. H. Dodd, eds. *Machine Milking. Technical Bulletin-1, Nat. Inst. Res. Dairy, Reading, England, and Hannah Res. Inst., Ayre, Scotland.* pp. 116-155.

TOWNSEND, J. S. 1969. A mathematical modeling approach to the study of the mechanics of milking machine operation. Ph.D. Thesis, Cornell University, Ithaca, NY. 89 pp.

UHMANN, F. and C. THALHEIM. 1980. Zum Bewegungsverhalten von Zitzengummis und deren Einfluss auf den Melkvorgang. *Agrar-technik* 30(4):172-175.