HYSTERESIS OF THE DAIRY COWS' TEAT DURING MACHINE MILKING

by

Rakesh GUPTA

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Master of Science
in
Department of Agricultural Engineering

Winnipeg, Manitoba

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ABSTRACT

The major objective of this research was to determine the hysteresis present in the dairy cows' teat based on teat end expansion and contraction. Step changes in vacuum level from 0 kPa (atmospheric pressure) to 30 kPa were applied to the outside of the whole teat inside a teat chamber. Each of these two vacuum levels were applied alternately for approximately 1 s per 2 s period. Changes in vacuum level and external teat end diameter were measured with a pressure and teat end diameter transducer respectively.

Three experiments were performed. Measurements of main interest were: (1) area under the hysteresis loading curve, (2) area under the hysteresis unloading curve, (3) hysteresis, and (4) hysteresis ratio. In the first and third experiment, vacuum level rise and fall times were 150 ms. In the second experiment, three different rates of vacuum level changes were applied to the teat. These rates represented rise and fall times of 50, 150, and 300 ms respectively.

Teats displayed a strong viscoelastic behavior based on the large differences between loading (teat end expansion) and unloading (teat end contraction) curves. Hysteresis ratio ranged from 58 to 84%. Generally, rear teats have a larger hysteresis ratio than front ones. Rate of loading and unloading has a marked effect on hysteresis ratio which decreased from 83 to 63% when changing the vacuum level rise and fall times from 50 to 300 ms. At a slow rate of vacuum level

changes (300 ms rise and fall time) about 35 to 40% of the energy input to the teat is recovered. At a fast rate of vacuum level changes (50 ms rise and fall times) only 15 to 20% of the energy input to the teat is recovered. Teats display a significantly larger hysteresis ratio, likely due to congestion of fluids in the teat wall, during peak milk flow as compared to just before milking.

ACKNOWLEDGEMENTS

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The author feels a great sense of gratitude to his parents and other close relatives for their prayers for his successful completion of studies and safe return to India.

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Chapter I

INTRODUCTION

A milking machine occupies a very important place on today's modern dairy farms for mechanical harvesting of milk. Basically, a key component of the milking machine, the two-chambered teat cup (ASAE 1984), removes milk from the cows' udder when supplied with a source of energy. Functionally, the operation of the milking machine teat cup is the most critical part in any of today's milking systems (Reitsma and Breckman 1983). The principle applied to machine milking has been in use for the past 80 years. However, there is little known about the effect of the milking machine teat cup on the teat itself, in terms of its biological responses.

Of all the teat responses to machine milking, mastitis has been studied quite extensively. Effect of liner design, pulsation rate, pulsation ratio, type of pulsation, vacuum level, and vacuum fluctuations on mastitis have been studied widely (for example, Dahlberg 1941; Meigs et al. 1950; Mochrie et al. 1953; Porter et al. 1955; Dodd and Oliver 1957; Schmidt et al. 1964; Kingwill et al. 1979; O'-Shea and O'Callaghan 1978; Mein 1984). Dynamic responses like teat end expansion and contraction and milk flow rate of the teat to both step and sinusoidal changes in vacuum level have been studied by Reitsma (1977).

The teat is a biological structure which comes in direct contact with only one moving part of the milking machine, i.e. the teat cup liner. The teat deforms asymmetrically due to compression by the closing liner and experiences external loading, applied by the liner and milking vacuum, at every pulsation cycle during every milking. Many biological tissues can withstand forces normally encountered but up to a limited extent. Deformations of the teat end due to externally and uniformly applied vacuum level changes have been studied by Reitsma (1977); but hysteresis, accompanying such deformations under loading and unloading, has not been studied yet. This study makes an attempt to determine the hysteresis present in the dairy cows' teat when loaded and unloaded by externally applied step changes in vacuum level. These changes applied to the teat are from atmospheric pressure to a given vacuum level and vice versa.

Hysteresis is a characteristic of many biological materials to deformation due to loading and unloading. It is defined as the failure of a system to follow identical paths of response upon application and withdrawal of a forcing agent (Ruch and Patton 1965; Fedullo et al. 1980). Hysteresis implies energy dissipation through heat and/or physiological chemical reaction (Chu and Blatz 1972), whether it is a result of mechanical friction, magnetic effects, thermal effects, or elastic deformations (Holman 1978). Because hysteresis represents the capability of the teat to dissipate energy, it will likely affect streak canal opening and closing. The latter may therefore affect milk flow rate and the incidence of mastitis in dairy cows. Mastitis is generally considered the most widely spread disease of dairy cows and also the most expensive in terms of economic losses.

The major objective of this research was to determine the hysteresis present in the dairy cows' teat based on teat end expansion and contraction when applying step changes in vacuum level uniformly to the outside of the teat during milk removal. The following variables were also of interest:

1. rise time of both teat end expansion and increasing vacuum level,
2. fall time of both teat end contraction and decreasing vacuum level,
3. hysteresis ratio[1] of the teat end, and
4. teat end diameter ratio (expanded/unexpanded diameter).

This study will also look into some of the following physiological responses of the dairy cows' teat:

1. Does hysteresis differ for front and rear teats?
2. How does the external teat end diameter respond at different rates of loading and unloading?
3. Does the rate of load change affect the magnitude of hysteresis?
4. Do teat end responses change in a single milking?

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[1] Hysteresis ratio is defined as the area between the loading (teat end expansion) and unloading (teat end contraction) curves as a percentage of the area below the loading curve (Reitsma and Breckman 1983).

The vacuum level changes applied to the teat were step changes from 0 kPa (atmospheric pressure) to a vacuum level of 30 kPa and vice versa.

The teat responses in terms of hysteresis provide information on the viscoelastic behavior of teat tissue, which is likely important in both milk removal and udder health.

The primary purpose of this study was to get basic, quantitative data on teat responses due to vacuum level changes applied uniformly around the teat using a teat chamber for measurement of vacuum level and teat end diameter changes. In summary the dynamic responses describing teat behavior are: rise time, fall time, delay rise time between vacuum level and teat end diameter changes at the start of the rise, teat end diameter ratio, hysteresis ratio, and the pressure differential across the streak canal at half way during loading (teat end expansion and streak canal opening) and unloading (teat end contraction and streak canal closing) of the teat.

Chapter II

REVIEW OF LITERATURE

The first attempt to milk a cow mechanically, to save labor and replace the time consuming centuries-old practice of milking by hand, was tried about 150 years ago (Hall 1979). Since then the use of milking machines has increased and many attempts have been made to improve and modify milking machines for more efficient and safer removal of milk. No doubt, these developments contributed significantly to improving the output per unit of labor but not to a similar reduction of problems like mastitis, which has existed since man domesticated cows.

Several investigators with various backgrounds have studied different aspects of the milking machine and the mammary gland of the dairy cow. For example, engineers have studied the principles involved in the action of the milking unit and ways to improve the design to remove milk more efficiently. Veterinary and animal scientists have devoted their studies to factors affecting the physical and physiological responses of the dairy cow. Factors like maintenance, labor efficiency, milking routines, and cleaning have been studied by several investigators with various backgrounds (Reitsma 1977).

The following three areas were of main concern during the literature review for this study:

1. milking machine components (e.g. liner) and parameters (e.g. vacuum level and pulsation) in relation to mastitis,
2. hysteresis of smooth muscle and tissue, and
3. congestion of fluids in tissue due to the application of a vacuum level.

The first area contains a large amount of literature. A much smaller amount of literature was found in the second area. Not a single study was located in the third area. A computer search furnished relevant information on the research which has been and is in progress in the area of machine milking. That information indicates that much of the research has been and is concentrated on the two-chambered teat cup and effects of changes of machine parameters on milking efficiency and udder health. Much less attention has been given to the teat and its responses to conditions applied to it. Hall (1979) stated that commercially successful milking machines have been established without any clear understanding of the underlying principles. Reitsma (1977) stated:

> 'Much of the research on machine milking has consisted largely of reporting observations on the actions of the milking machine and its effects on the animal, rather than analyzing in detail the principles involved and its action and effects.'

There are numerous studies in the area of machine milking and mastitis; no attempt will be made to give a complete listing here. The following four areas of the literature are reviewed briefly:

1. milking machine function and mastitis,
2. functional anatomy of the teat,

3. hysteresis of smooth muscle, and
4. teat responses.

2.1 MILKING MACHINE FUNCTION AND MASTITIS

"Mastitis robs the dairyman of significant income." said McDermott and Erb (1984). Mastitis is inflammation of the udder caused by infection, injury, secretory malfunction, or physiological changes (Kingwill et al. 1979). Mastitis is not only present in machine milked herds, but it was often a serious problem in hand milked herds, and occurs frequently in suckled beef herds and dry cows (Hunter and Jeffrey 1975, cited by Kingwill et al. 1979). The mode of infection is not fully understood but it is accepted that infection can occur when the teat is exposed to pathogenic organisms which may penetrate the streak canal of the teat and possibly result in an infection. Actually new infections occur infrequently even under high bacterial exposure conditions. It also depends on the effectiveness of the defence mechanism of the gland and on the likelihood of the bacteria being flushed out by milk before they can become established in the gland (Reiter and Bramley 1975).

Use of mechanical milking equipment has been associated many times with an increased incidence of mastitis. Earlier research was focused on effects of the change from hand milking to machine milking. Most of the experiments indicated higher levels of infection and high bacterial count milk in machine milked herds. Hart and Stabler (1920) conducted an extensive study. Klimmer and Haupt (1930) concluded that more work is required to determine the transmission or non-transmission of acute infection from cow to cow by the milking machine because they did not find such transmission in their experiment. Thomas and Anantakrishnan (1949) and Shaw and Nambudripad (1964) found that the bacteriological quality of milk obtained by using a machine was relatively better than that from hand milked animals. Meigs et al. (1950) reported less mastitis upon changing from machine to hand milking. Consequently it must be noted that early bacteriological work is of less importance in the light of our present day knowledge. There have been changes in the types of machine then available, the way they were used, and management practices.

The milking machine, either because of its physical characteristics and/or the way it is used, can contribute to infection. Several investigators have studied the effect of different milking machine factors on the incidence of mastitis. Main factors most likely to affect the penetration of bacteria through the streak canal are the vacuum, pulsation, liner design, and the combination of these applied to the teat in the teat cup liner. Gomez et al. (1979) have reviewed the following machine milking factors related to mastitis: vacuum fluctuations and excessive vacuum, overmilking, pulsation rate, liner characteristics, diameter and height of milk pipe line, shape of teats, and general milking hygiene.

One of the main factors in machine milking that may contribute to mastitis is excessive vacuum (Burkey and Sanders 1949; Little and Plastridge 1946; both cited by Mochrie et al. 1953). Porter et al. (1955) did not find any difference between high and low vacuum milking machines on udder health. Others (Kingwill et al. 1979; Golikov and Mironov 1979; Langlois et al. 1981) reported cows milked with high vacuum are more likely to get infection. Thompson et al. (1978) studied abrupt loss of milking vacuum and found increased risk of mastitis infection. Townsend (1965) indicated the importance to measure vacuum fluctuations and later on many researchers studied the relationship between vacuum fluctuations at the teat end and mastitis and reported increased risk of infection (Beckley and Smith 1962; Stanley et al. 1962; Braund and Schultz 1963; Schmidt et al. 1964; Cousins et al. 1973; Thiel et al. 1973; Kingwill et al. 1979; Mein 1984). The work of Nyhan (1969) gave one of the first strong associations between irregular vacuum fluctuations and increased infection. However, the explanation of a link between higher incidence of mastitis and vacuum fluctuations is not fully understood.

An impact mechanism has been reported as a possible cause of mechanical transfer of bacteria deep enough into the cows' teat to increase the risk of infection (Thiel et al. 1969). A partial vacuum at the teat to draw bacteria into the teat canal has also been reported (Davis 1935; Johnston 1938; Little 1937, all cited by Espe and Cannon 1942; Noorlander et al. 1973). But Espe and Cannon (1942) did not find any evidence of a vacuum at the external orifice of the teat. A complete breakdown in pulsation can result in a serious mastitis problem (Kingwill et al. 1979). Reitsma et al. (1981) recommended a duration of liner closure of one-third of a second to reduce the incidence of mastitis. The effect of prolonged or shortened milking times on mastitis, milk yield and milk secretion rate have been undertaken by many other investigators (e.g. Elliott 1961a, 1961b; Elliott et al. 1960; Guidry and Paape 1970).

Because all the factors to the teat are applied by the liner and the pressure changes on its inside and outside, it's design and operating characteristics influence mastitis. Dodd and Oliver (1957) found a higher incidence of mastitis in quarters that were milked with moulded rather than with extruded liners, but the incidence of new infections was similar for quarters. Attaching the machine before adequate milk let down has occurred, leaving the machine attached after milk flow has ceased, non-stripping, and the effect of incomplete milking have also been studied in relation to mastitis (e.g. Burkey and Sanders 1949; Little and Plastridge 1946; both cited by Mochrie et al. 1953; Schalm and Mead 1943; Dodd and Foot 1947; Neave et al. 1954).

This brief review indicates that several individual and combined milking machine factors contribute to mastitis. However, no study shows that general adoption of the recommendations made on these factors would markedly reduce the level of infection (Kingwill et al. 1979).

2.2 FUNCTIONAL ANATOMY OF THE TEAT

To better understand and improve the process of milk removal it becomes necessary to know the physical and biological properties and responses of the teat. The skin of the teat is composed of two layers and is free from hairs and sweat or sebaceous glands (Venzke 1940). Foust (1941) designated the teat of the cow as a membranous tube. It forms the passage way for milk removal from the inside of the teat to the outside. Teat shape and size have received less attention. Foust (1941) and Schmidt (1971) reported the shape to vary from cylindrical to conical, whereas Hickman (1964) divided it into three categories: cylindrical, funnel, and bottle. The shape of the tip of the teat also varies. Johansson (1963) described it as round, flat, plate-shaped, and funnel-shaped. This discription was modified by Appleman (1973) to: pointed, round, flat, disk, and cone.

The length of the teat varies significantly from cow to cow and little within cow between front and rear. Generally the front teats are longer than the rear ones (Reitsma 1977). On an average the front teats are about 1 cm longer than the rear teats (Johansson 1963). Length of the teat has been reported from 2.5 cm to 15.2 or 17.8 cm (Foust 1941). Emmerson (1928, cited by Reitsma 1977) indicated length and external diameter of front and rear teats separately. Front teats, with an external diameter of 2.8 cm, had an average length as 6.6 cm, while rear teats averaged 5.3 cm in length and a diameter of 2.5 cm.

The wall thickness varies little from the proximal to the distal ends of the same teat, but differs, approximately 5 to 10 mm in different specimens (Foust 1941). The teat has been reported as being composed of three layers (Pounden and Grossman 1950). The canal at the lower end of the teat, connecting the teat cistern to the outside is known as the streak or teat canal. Its length varies from 8 to 14 mm (Venzke 1940). The average length of the streak canal has been reported as 8.6 mm with a range of 7 mm to 11.5 mm (Murphy and Stuart 1955, cited by Reitsma 1977). A radiographic method was used to find changes in teat canal with lactation age and within first lactation

(McDonald 1968a, 1973). McDonald (1968b) reported an average canal length for 88 teats as 10.77 mm and a canal diameter at three locations: smallest at the distal end with an average of 0.40 mm, 0.46 mm in the middle and 0.77 mm at the proximal end. In a later study McDonald (1975) reported changes in streak canal diameters between milking periods. He found that the teat canal was dilated immediately after removal of the milking machine with greater dilation in the middle and the distal parts of the canal. He also reported that after 4 hours and later the proximal part of the teat canal was more dilated than the middle or the distal.

The streak canal (teat duct, or papillary duct, or lactiferous outlet) is surrounded by an involuntary sphincter muscle. Pounden and Grossman (1950), in their extensive study of wall structure and closing mechanism, reported that four structures appear to contribute to closure of the streak canal. These are: (1) the muscle bundles, (2) Furstenberg's rosette, (3) elastic fibres, and (4) disquamated epithelial cells. Mastitis is likely to occur if the sphincter muscle is destroyed (Stettler 1973). Rhythmic contractions of the teat sphincter have also been studied by several researchers (Witzel 1965; Peeters and Bruycker 1975; Lefcourt 1982a, 1982b). The canal is lined with keratin and if it is removed infection is more likely to occur (Milne 1978).

In one of the very few studies on elastic behavior of the teat, Townsend (1969) reported that the teat end behaves as an elastic body while teat stiffness increases with increased loading. He also obtained tension-length and stress-strain curves. In an other study

Stettler (1973) presented stretching characteristics of the streak canal and sphincter muscle. He reported that the force required to stretch the streak canal to the same opening is approximately 20% less for the second stretch than that required for the first stretch. The force required to stretch the streak canal before and after milking did not differ much (for the same opening). The transient response of the streak canal to the applied radial stretch showed a viscoelastic behavior.

The anatomy and physiology of the teat and streak canal have also been studied by Espe and Cannon (1942), Petersen et al. (1944), Appleman (1969), while Chandler et al. (1969) have done ultrastructural observations on the teat duct. The nerve regeneration in the udder was the subject of a study by Espe (1947).

2.3 HYSTERESIS OF SMOOTH MUSCLE

The word hysteresis has been derived from Greek, and means 'to lag behind' (Katchalsky and Neumann 1972). Hysteresis, a phenomenon which the earlier investigators were unwilling to accept (Ruch and Patton 1965), has been studied by several authors in recent years. Basically hysteresis is defined as the failure of a system to follow identical paths upon application and withdrawal of a forcing agent (Ruch and Patton 1965; Fedullo et al. 1980).

One of the main functions of any kind of muscle is to contract. Smooth muscle, different than other types of muscle (skeletal and cardiac), resists stretching and increases in size as a result of exercise showing plasticity (Ruch and Patton 1965; Guyton 1959).

Hysteresis is a characteristic of an imperfect elastic response to deformation of many biological materials (Agostini and Mead 1964), representing a viscoelastic behavior of smooth muscle (Olsen 1981).

The pressure-volume (p-v) curves of the lung have been studied for a long time but only within the last 30 to 35 years have they been described thoroughly. A hysteresis loop is formed upon inflation and deflation of the lung. The area enclosed by the inflation-deflation pressure-volume curves is known as the hysteresis area. This area is proportional to the amount of mechanical energy dissipated as heat during an expansion-contraction cycle. The hysteresis of the lung p-v curve can be partially explained by progressive involvement of increasing numbers of alveoli during loading. Other major factors are tissue elasticity which limits alveolar sizes, variable surface tension, and stress relaxation which results from the viscoelastic behavior of tissue (Ruch and Patton 1965). Apter and Marquez (1968) indicated that hysteresis is a response of composite flexible biomaterials to a step function stretch. This represents the viscoelastic behavior of the fibrous component of biomaterials, i.e. muscle. Chu and Blatz (1972) have described a hysteresis model for biaxial deformation of living animal tissue (cats' mesentery). They reported that energy input to the tissue can explain tissue response over a wide range of stretch.

Holownia (1979) studied hysteresis loss in rubber under uniaxial, biaxial and triaxial compression and found that hysteresis loss was minimum in triaxial loading. Further, the change of shape of the rubber has a greater effect on hysteresis loss than the level of stresses present. He and Vogel (1980) represented hysteresis loss as the percentage of the total strain energy, i.e. area under the loading curve. Fedullo et al. (1980) represented hysteresis loss as the percentage of the area of the rectangle enclosing the pressure-volume curve.

Many experimenters studied the elastic properties of arteries and veins of living tissue (e.g., Wesly et al. 1975; Greenwald et al. 1982). Muscle tone on airway hysteresis has been studied by Sasaki and Hoppin (1979).

2.4 TEAT RESPONSES

Deformation of the teat end, i.e. expansion and contraction during milking, is a teat response. These responses are the combined effect of teat tissue properties and the geometry and changes of pressure (usually a change in vacuum level) such as vacuum level amplitude, rate of pressure changes and liner closure. Basic dynamic responses of the teat end, due to changes in vacuum level around the teat, are: external teat end diameter changes, milk flow rate changes through the streak canal, and flow or no flow of milk. Mastitis also represents a teat response to the conditions applied during and after machine milking. The effect of machine milking on the incidence of mastitis was discussed in section 2.1.

Reitsma (1977) indicated that dynamic teat responses are of paramount importance in studying any system or method of milk removal. Scott et al. (1980) reported that teat responses can provide information for designing milking systems and a better understanding of the physical and physiological behavior of the teat.

In an extensive study Reitsma (1977) presented teat end diameter changes and changes in milk flow rate as a function of step and sinusoidal pressure changes. This study resulted in a number of useful conclusions. He concluded that teat ends require a minimum duration of liner closure to relieve the teat end from exposure to the milking vacuum level. For more information see: Reitsma et al. (1974, 1975); Reitsma and Scott (1975, 1979a, 1979b, 1979c). In a later study Reitsma et al. (1981) concluded that one-third of a second or more of liner closure, per pulsation cycle, is required to reduce the risk of new mammary gland infections. Balthazar and Scott (1978) predicted responses of the dairy cows' teat using finite element analysis. They reported that values calculated using this method are in close agreement with the experimentally determined values by Reitsma (1977). Stresses were calculated in three directions: radial, longitudinal, and tangential in each of three layers of the teat wall. They concluded that the streak canal is opened mainly by radial and tangential stresses, because these stresses were found concentrated in the area of the streak canal. Scott et al. (1980) indicated that finite element analysis has great potential in the study of teat behavior.

Delwiche et al. (1980) studied teat milk flow using an ultrasonic measurement technique. A study by Williams et al. (1981) showed that the compressive load applied by the liner and its duration can affect milk flow. They indicated that milk flow rate increases if either the compressive load or its duration is increased. This is attributed to less congestion in the tissues of the teat surrounding the streak canal. Muscular effects have been reported as of secondary importance.

Reitsma (1981) showed that physiological responses of the dairy cows' teat can be used as design criteria for the pulsation system.

The author of this study did not find any literature relating hysteresis of the teat to machine milking or other milk removal operations. Therefore, information seems to be lacking in this area.

Chapter III

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Measurements of external teat end diameter changes in response to applied changes in vacuum level were made to meet the main objective of this study i.e. to determine hysteresis of the teat end. This required development, fabrication, and application of transducers and other instrumentation to collect and analyze measurements.

A particular protocol for acquiring data using a computerized data acquisition system during milk removal was followed. Computer programs were developed to analyze large quantities of data of dynamic signals. A statistical design helped in data collection and interpretation.

3.1 EXPERIMENTAL EQUIPMENT

An experimental teat chamber was used to apply the desired changes in vacuum level to the teat and to measure applied vacuum level changes and responding teat end diameter changes . A microcomputer, with two floppy disk drives, controlled a data acquisition system for data collection and later analysis. Specialized devices and circuits were used to generate desired changes in vacuum level. A teat end diameter transducer measured teat end diameter changes.

3.1.1 Teat Chamber

A schematic diagram of the teat chamber to apply the desired changes in vacuum level uniformly around the whole teat is shown in Fig. 3.1. The teat chamber consists of three main parts: a stainless steel top cover with a handle, a plexiglass cylinder (ID 65 mm and length 150 mm), and a bottom cover. A cut-off mouthpiece of a liner, through which the cow's teat is inserted, is attached to the center of the circular top cover. This top cover also contains the electrical connector for the teat end diameter transducer. The on-off switch on the handle activates the circuitry controlling two solenoid valves. The shielded cables for the teat end diameter transducer and for the switch pass through the hollow handle. An air nipple with a pressure transducer is attached to the cylinder near its center. The bottom cover with a float provides an automatic discharge of the milk collected during milking.

The teat chamber is used for all measurements because a conventional teat cup deforms the teat asymmetrically. Also the teat chamber provides an easy method for applying uniform changes in vacuum level around the teat and for making measurements.

3.1.2 Generation, Application, and Measurement of Vacuum Level

Fig. 3.2 shows a schematic diagram of the components used to generate desired changes in vacuum level. Two solenoid valves,[2] connected via a Y connector (14.3 mm ID) and a rubber hose (14.3 mm ID)

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[2] Model 8210D95, Ascoelectric Ltd., Brantford, Ont. N3T 5M8.

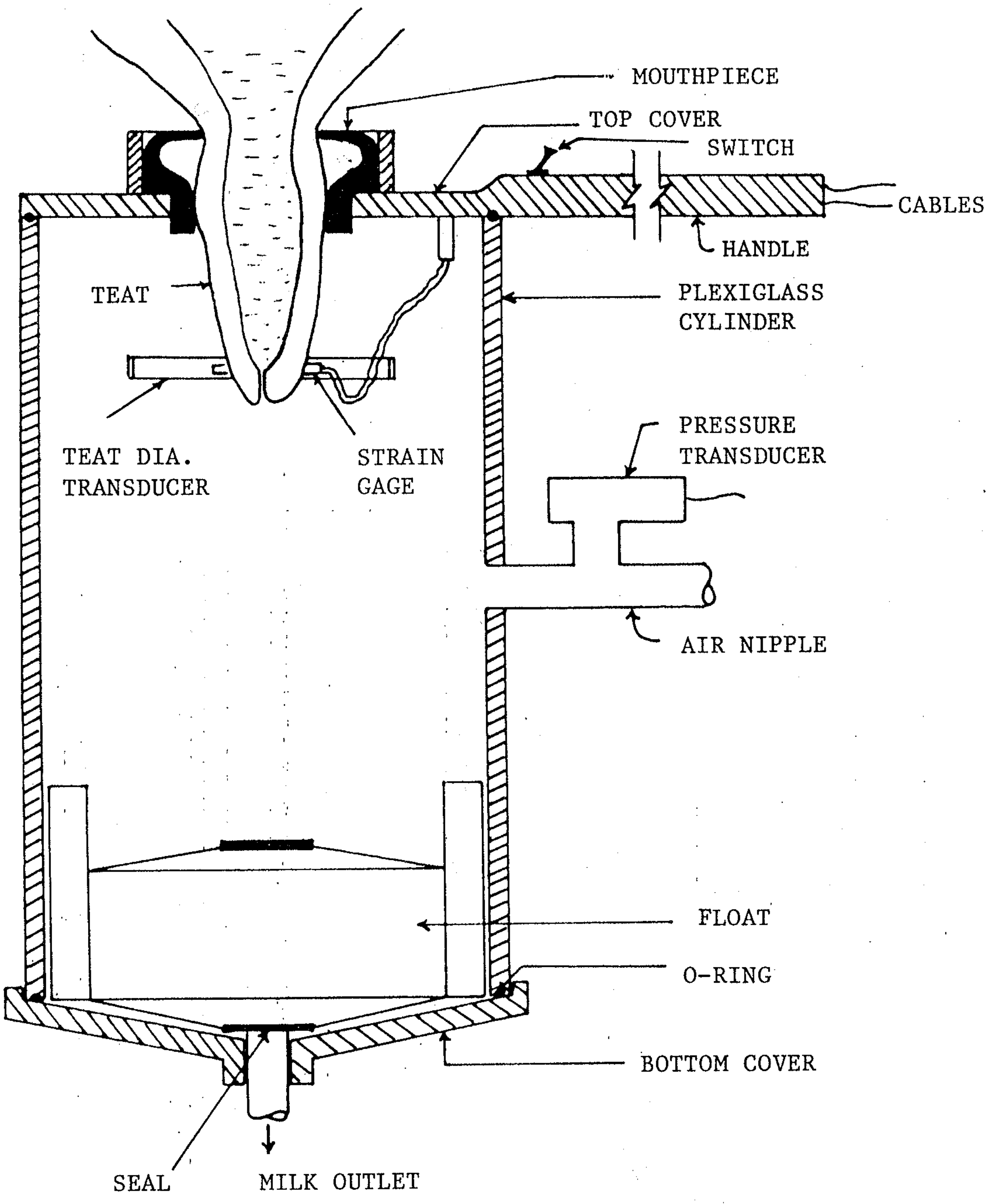

Fig.3.1. Schematic diagram of the teat chamber.

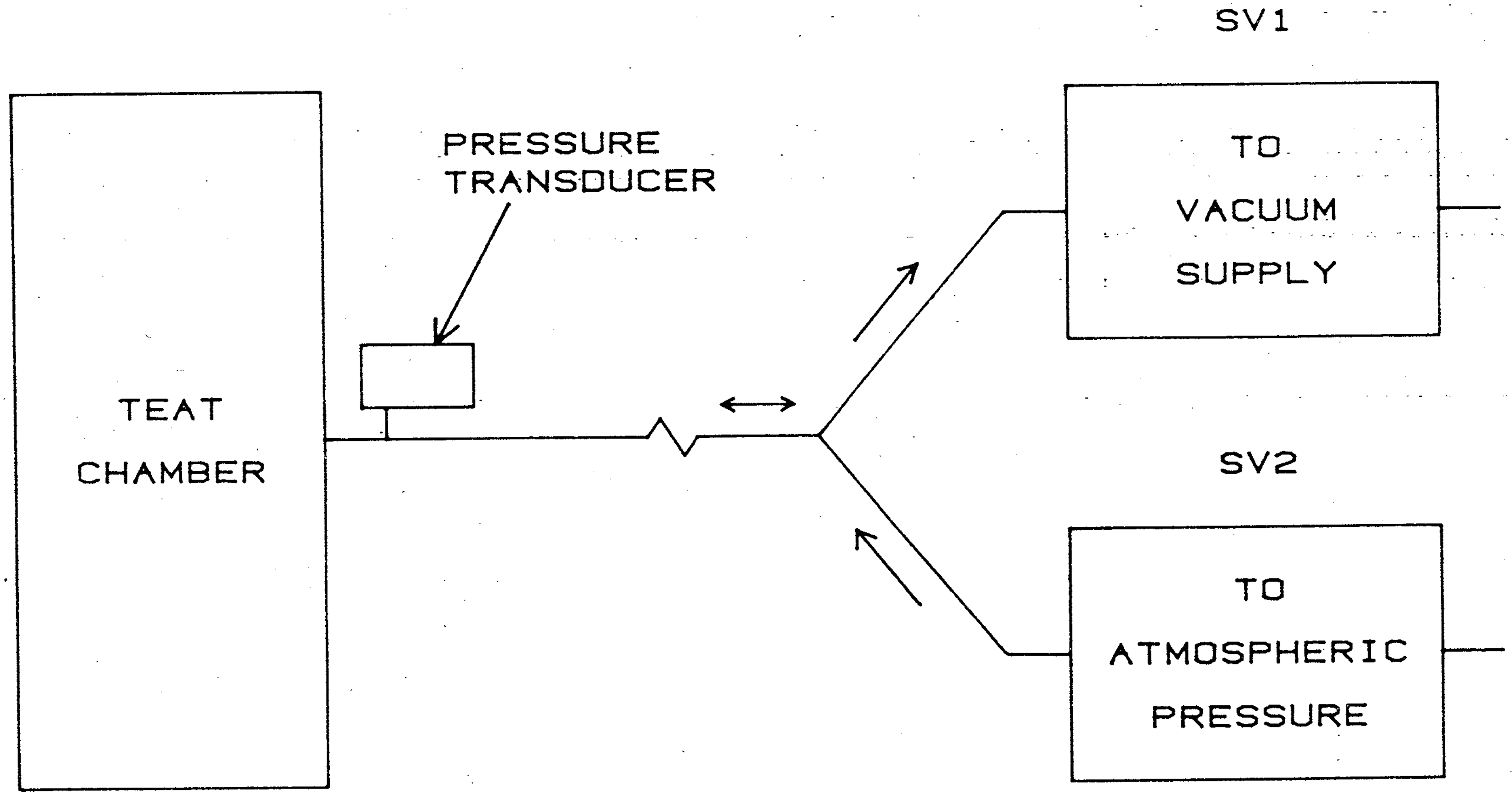

Fig.3.2. Block diagram of the components used in generation of step pressure input.

to the teat chamber form the system for generating changes in vacuum level. Solenoid valve no.1 (SV1) connects to a vacuum supply and solenoid valve no.2 (SV2) connects to atmospheric pressure. A special timer circuit controls a relay operating both valves. The relay alternately opens one valve while closing the other valve. An integrated circuit pressure transducer[3] senses the vacuum level changes applied around the teat in the teat chamber (see Fig. 3.2). A U-tube mercury manometer[4] is used in calibrating the transducer. A typical calibration curve is shown in Fig. 3.3. The linear least square fit line was used to convert the output voltage to a vacuum level in kilopascals. A typical linearity was about 0.35%, which is more than adequate.

3.1.3 Measurement of Teat End Diameter Changes

A teat end diameter transducer developed and used by Reitsma (1977), was used to measure external diameter changes of the teat end. This consists of two stainless steel strips (cut from 0.127 mm thick shim stock) each with a length of 55 mm and a width of 7 mm. Both strips are hinged at both ends with eyeglass hinges. To reduce friction, moving surfaces were carefully filed and sanded. The hinges are fastened to the strips with small screws, which gives an opportunity to replace a strip if needed. A strain gage[5] was mounted

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[3] Model LX1704GB, National Semiconductor Corp., Santa Clara, CA 95051.

[4] Model 1230-90 WM, Dwyer Instruments, Inc., Michigan City, IN 40360.

[5] Type CEA-06-500-UW-120, Micro-Measurements, Romulus, MI 48174.

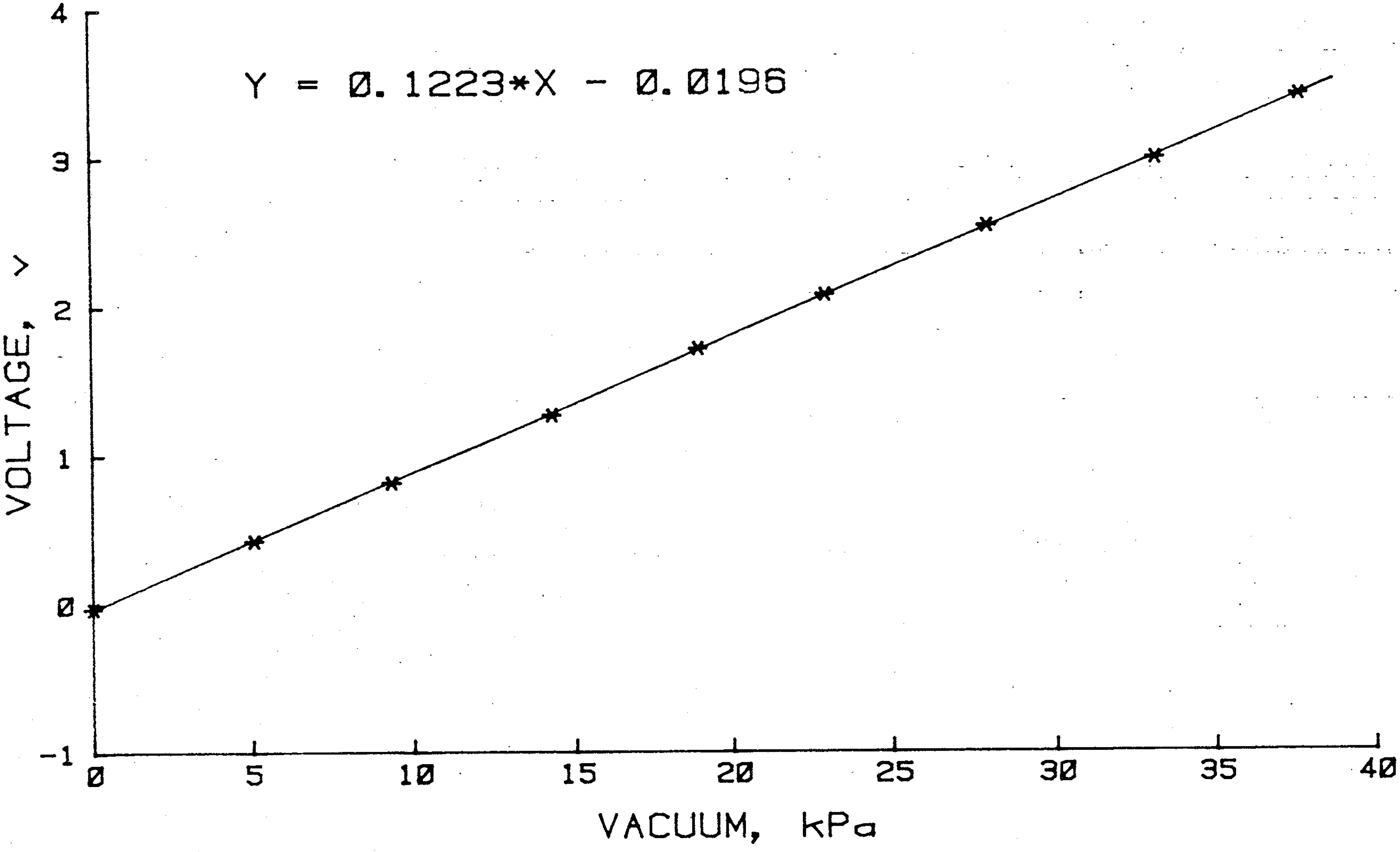

Fig.3.3. Typical calibration curve of pressure transducer.

on the outside of each strip. The gage terminals were moisture proofed with silicon lacquer.[6] Two gages were connected in opposite arms of a Wheatstone bridge with two dummy resistors (each 120 Ohms) in the other opposite arms.

The output voltage of the transducer showed a good linear relationship. A quadratic relationship resulted in a better fit which was used to convert measured output voltages into diameters. The transducer was calibrated using a cylindrical rod with different fixed diameters. The calibration range was from 13 mm to 29 mm in steps of 2 mm. A typical calibration curve is shown in Fig. 3.4. The largest deviation from the fitted curve was about 0.1% of the full range which is more than adequate. The natural frequency of the transducer is about 77 Hz.

A piece of double sticking cellophane tape was used on the inside of each of the strips during measurements to avoid dislocation.

3.1.4 Collection of Data

A block diagram of the measurement system for data acquisition is shown in Fig. 3.5. The system consists of two transducers, a portable Corona[7] computer, and a Taurus-one[8] data acquisition/control unit. Analog input and output signals to and from both transducers

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[6] M-LINE Accessories, Measurement Group, Inc., Raleigh, NC.

[7] Model no. PPC-21 Corona Data Systems, Inc., 31324 Via Colinas, Suite 110, Westlake Village, CA 91361.

[8] Model TAURUS ONE/10 Taurus Computer Products Inc., 1755 Woodward Drive, Ottawa, Ont. K2C 0P9.

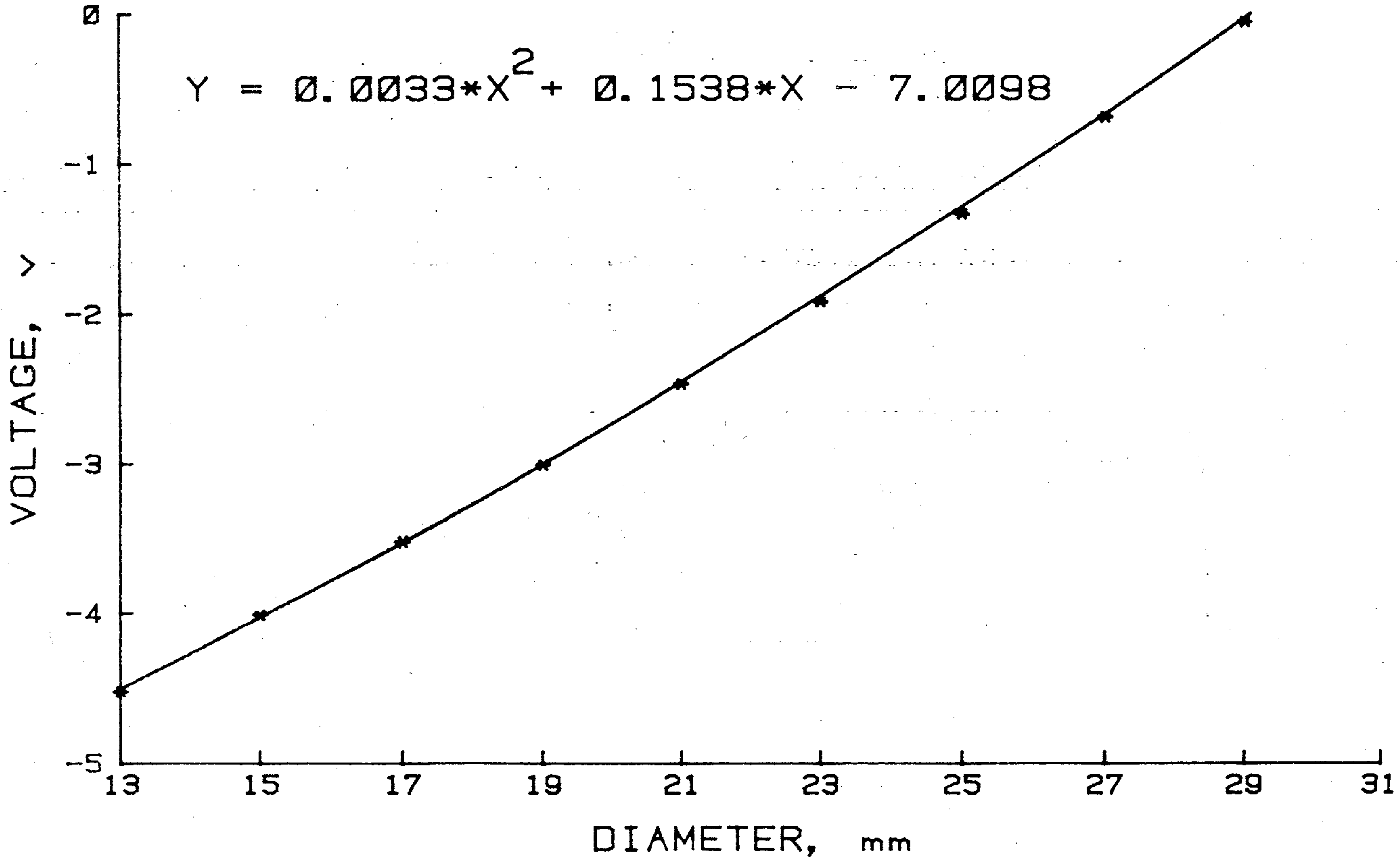

Fig.3.4. Typical calibration curve of teat end diameter transducer.

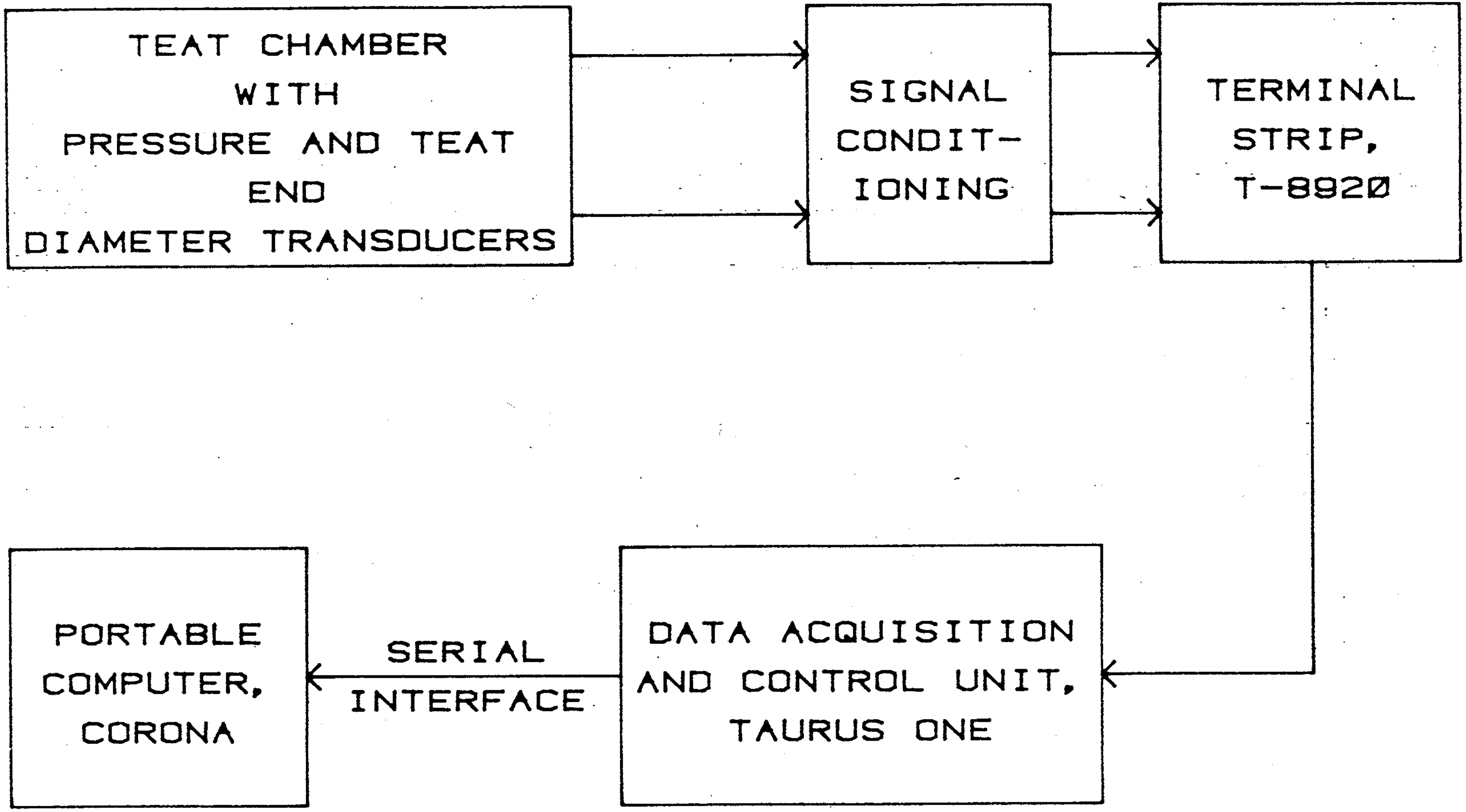

Fig.3.5. Block diagram of the measurement system for collecting teat end diameter changes data.

to and from both transducers are sent from and received by a signal conditioning box. This contains a DC-power supply for both transducers, an amplifier circuit[9] for the teat end diameter signal, a rescaling circuit for the pressure transducer, and a timer circuit for controlling operation of the two solenoid valves. Both transducers' final output signals are received on a terminal strip[10] on channel zero from the pressure transducer and on channel one from the teat end diameter transducer. The Taurus-one data acquisition/control unit takes readings on channel zero and one after a specified time interval. Readings are sent to the computer via a serial interface (RS-232C) in straight binary format. As the readings are received in the computer's communication buffer they are stored on a floppy disk[11] for later analysis.

The data acquisition system was set to take two readings (i.e. one scan of one reading on channel zero and another on channel one) after every 4 ms. Enough readings were taken to analyze ten continuous cycles of both transducers' signals. Because the data acquisition system is in 'Port Output' mode it transfers readings to the computer during acquisition, i.e. the data acquisition system is taking readings, as well as transferring them to the computer. Readings received in the computer's communication buffer are in straight binary format, and they are stored as such to reduce storing time.

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[9] Model 2B31, Analog Devices, Route 1 Industrial Park, P.O. Box 280, Norwood, MA 02062.

[10] T-8920 Analog Input Panel, Taurus Computer Products Inc., 1755 Woodward Drive, Ottawa, Ont. K2C 0P9.

[11] Datalife, Verbatim Corporation, Sunnyvale, CA 94086.

3.2 EXPERIMENTAL PROCEDURES

All the experiments were conducted at the Glenlea Research Station of the University of Manitoba. A single milking parlour stall was placed next to a concrete pit made in a floor area next to the dairy barn. The arrangement is convenient for the type of measurements done in this study on cows' teats.

3.2.1 Experimental Milking Protocol

Before the start of experiments, cows were milked several times in the new milking parlour to train them. Normally they are milked in their stanchion barn using a pipeline milking system. Also preliminary tests were conducted to test all the instrumentation and computer programs before running actual experiments.

A protocol was developed on the basis of a statistical design and used for each experiment. First, the pressure and teat end diameter transducers were calibrated and all data points were recorded on a disk. The outputs from both transducers, at the same time, were recorded on strip chart paper using a 2-channel recorder.[12] Also written notes were made.

After analysis of all calibration data the first cow entered the one stall milking parlour. Her udder was washed with a warm iodine solution, dried with a paper towel, and a few streams of milk removed from each teat. Shortly thereafter a conventional milking unit was

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[12] Model Brush Mark 220, Gould Inc., Brush Instrument Division, 3631 Perkins Avenue, Cleveland, Ohio 44114.

was attached to the teats. The unit was removed whenever measurements on the teats needed to be taken. After completion of measurements the milking unit was reattached to complete milking.

Next the teat chamber (described in section 3.1.3) was applied to one of the four teats scheduled for measurements according to the statistical design. First the complete chamber, with both solenoid valves operating, was applied to simplify teat insertion through the mouth-piece opening. Next the switch on the handle was turned off (stopping solenoid operation) and the plexiglass cylinder was removed with the bottom cover attached. Then the teat end diameter transducer was attached to the teat end and the cylinder re-attached to the top cover and the switch on the handle turned on. Teat ends were marked at about 12 to 13 mm from the teat end. The top edge of the teat end diameter transducer, with double sticking cellophane tape on the inside, was positioned on the marking on the teat end. Application and use of the teat end diameter transducer and teat chamber require two persons. During data collection one person holds the teat chamber while a second person operates the strip chart recorder and computerized data acquisition system.

After data collection the operator turns the switch on the top cover's handle off resulting in atmospheric pressure in the chamber. Next the teat chamber is removed and the milking unit reattached to the teats. At the end of milking, the milking unit is removed and the teats dipped with a teat disinfectant solution. The above procedure was used in all experiments for all cows.

3.2.2 Statistical Design

A statistician from the Department of Statistics at the University of Manitoba advised on the experimental designs. Three experiments were performed. The first experiment, here after called HYSIS, was done to help design the second and third experiments. The layout of the HYSIS experimental design is shown in Table 3.1. Four cows were selected from the herd at the Glenlea Research Station. They were numbered randomly from 1 to 4. The front right and the rear right teat of each cow were selected for measurements. Each day the cows were milked in the same sequence but the measurements were taken on the teats according to the statistical design in Table 3.1. The

TABLE 3.1

Layout of the experimental design for the HYSIS experiment for four cows over four days with two replications.

	REPLICATION			
	1		2	
	DAY			
COW	1	2	3	4
1	FR	RR	FR	RR
2	RR	FR	RR	FR
3	FR	RR	FR	RR
4	RR	FR	RR	FR

FR : Front Right Teat RR : Rear Right Teat

teat sequence for each cow was reversed from day to day. Measurements on the first and second day were repeated on the third and fourth day respectively. The measurements were made during afternoon milkings, starting at 2.30 p.m. The cows were milked during the morning milkings starting at 6.30 a.m., with conventional milking units for the pipeline milking system in the stanchion barn.

An analysis of variance of all measured variables was applied, using the model:

$$Y(ijk) = m + c(i) + r(j) + p(k) + c*p(ik) + e(ijk)$$

Where i = 1,......,4 cow no.
j = 1,2 replication
k = 1,2 teat location (front, rear)
Y(ijk) = observation
m = mean
c(i) = cow effect
r(j) = replication effect
p(k) = teat location effect
c*p(ik) = interaction between cow and teat location
e(ijk) = error term

The second experiment, hereafter called RLOAD, consisted of three treatments applied to three cows over three days. Treatments 1, 2, and 3 represented three different rates of loading in terms of three different vacuum level rise and fall times. The layout of the experimental design is shown in Table 3.2. Treatments 1, 2, and 3 are three vacuum level rise and fall times (50, 150, and 300 ms). The value of 150 ms represents a typical value for liner opening and

TABLE 3.2

Layout of the experimental design for the RLOAD experiment applying three treatments to three cows over three days.

COW	TEAT LOCATION	DAY 1	DAY 2	DAY 3
1	FR,RR	T1	T2	T3
2	FR,RR	T2	T3	T1
3	FR,RR	T3	T1	T2

FR : Front right teat   RR : Rear right teat

Treatments T1, T2, and T3 represent rise and fall times of 50, 150, 300 ms respectively for the pressure input.

closing times. The 50 ms and 300 ms were chosen to determine the effect of a faster and slower rate of loading and unloading on teat responses.

Each day the measurements were done on the front right and the rear right teat of each cow. The cows were milked in the same sequence with a different treatment for each cow. Three treatments on three cows over three days made this experiment a Latin-square, but the two teat locations of each cow made it a split-plot on the original Latin-square design. The following model for an analysis of variance of all measured variables was applied:

$$Y(ijkl) = m + t(i) + c(j) + d(k) + p(l) + t*p(il) + e(ijkl)$$

Where $i = 1,2,3$ treatment no.

$j = 1,2,3$ cow no.

k = 1,2,3 day no.
l = 1,2 teat location (front, rear)
Y(ijkl) = observation
m = mean
t(i) = treatment effect
c(j) = cow effect
d(k) = day effect
p(l) = teat location effect
t*p(il) = interaction between treatment and teat location
e(ijkl) = error term

In the third experiment, here after called TMEAS, all four teats of all 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 milk flow was stabilized from all four teats. Layout of the experimental design is shown in Table 3.3.

The following 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

TABLE 3.3

Layout of the experimental design for the TMEAS experiment for all four teats of four cows over four days.

COW	TEAT LOCATION	SIDE	DAY 1	DAY 2	DAY 3	DAY 4
1	Front	Right	BD			
		Left			BD	
	Rear	Right		BD		
		Left				BD
2	Front	Right				BD
		Left		BD		
	Rear	Right	BD			
		Left			BD	
3	Front	Right			BD	
		Left	BD			
	Rear	Right				BD
		Left		BD		
4	Front	Right		BD		
		Left				BD
	Rear	Right			BD	
		Left	BD			

BD : Before and during milking measurements.

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 of measurement

s*a{l(j)k} = interaction between side within location and time of measurement

e{ijkl(j)} = error term

The first experiment was run from 26th June to 29th June, the second from 4th July to 6th July, and the third from 10th to 13th July 1984.

3.2.3 Data Processing and Analysis

A particular format was set up and followed for recording the data as discussed in subsections of this section. All data were recorded on double sided double density 320 K floppy disks. Several computer programs were developed, and tested with data from several preliminary measurements.

3.2.3.1 Calibration Data

As indicated earlier (section 3.2.1) the pressure and teat end diameter transducers were calibrated before and after data acquisition on each experimental day. This procedure also verifies proper operation of both transducers during acquisition of data. Calibration data were collected and processed using a computer program. The program asks first which transducer needs calibration. Typing 0 or 1 via the key board initializes calibration of the pressure or teat end diameter transducer respectively. For calibration of the pressure transducer the program asks to enter an X-value, i.e. pressure in cm of Hg. These are read from an U-tube mercury manometer to the nearest millimeter. For calibration of the teat end diameter transducer the program asks to enter an X-value, i.e. a diameter in mm. Y-values, i.e. voltage either from the pressure or the teat end diameter transducer, are taken by the data acquisition system and sent to the computer. Both X-values and corresponding Y-values are stored in an array. Usually nine points were taken for calibration of each transducer.

After taking calibration data for the pressure transducer, a linear least square fit is performed and the results displayed on to the screen. The results contain: equation of the fitted line, predicted values, residuals, and percent linearity. If the linearity is within 0.5% the data are stored on disk, otherwise a recalibration is performed.

For the teat end diameter transducer a quadratic fit is done and the results displayed on to the screen. By checking the magnitude of the largest residual, data are rejected or recorded on disk. Calibration constants e.g. intercept and slope are also recorded on disk along with all data. Typical calibration curves for pressure and teat end diameter transducer are shown in Fig. 3.3 and Fig. 3.4 respectively.

3.2.3.2 Vacuum Level and Teat End Diameter Data

A computer program was developed to analyze teat end diameter responses due to applied vacuum level changes. An example of both signals is shown in Fig. 3.6. The program starts with reading data points (voltages) for both signals and storing these in two arrays, one for vacuum level and the other for diameter readings. After reading all data points the program asks for calibration information, cow number, date, teat location, and the time of measurement, i.e. before, or during, or after milking.

Next, the computer searches through array NUM to find when the pressure starts changing from the maximum vacuum level to atmospheric pressure. Then, 750 points are taken from both arrays, i.e. NUMV and NUMT, which results in about one and a half cycle for analysis. Next, these readings (voltages) are converted into appropriate physical quantities using all calibration constants and stored in arrays VAC and DIA. These two arrays are analyzed together. Array elements 201 to 220, and 456 to 475 in both arrays are used to find the average lowest vacuum level (ALV), average smallest diameter (ASD), average highest vacuum level (AHV), and average largest diameter (ALD) respectively. The difference between AHV and ALV represents the step change in vacuum level. The difference between ASD and ALD represents the step change in teat end diameter. The average smallest diameter after contraction (unloading) of the teat (ASDU) is also lo-

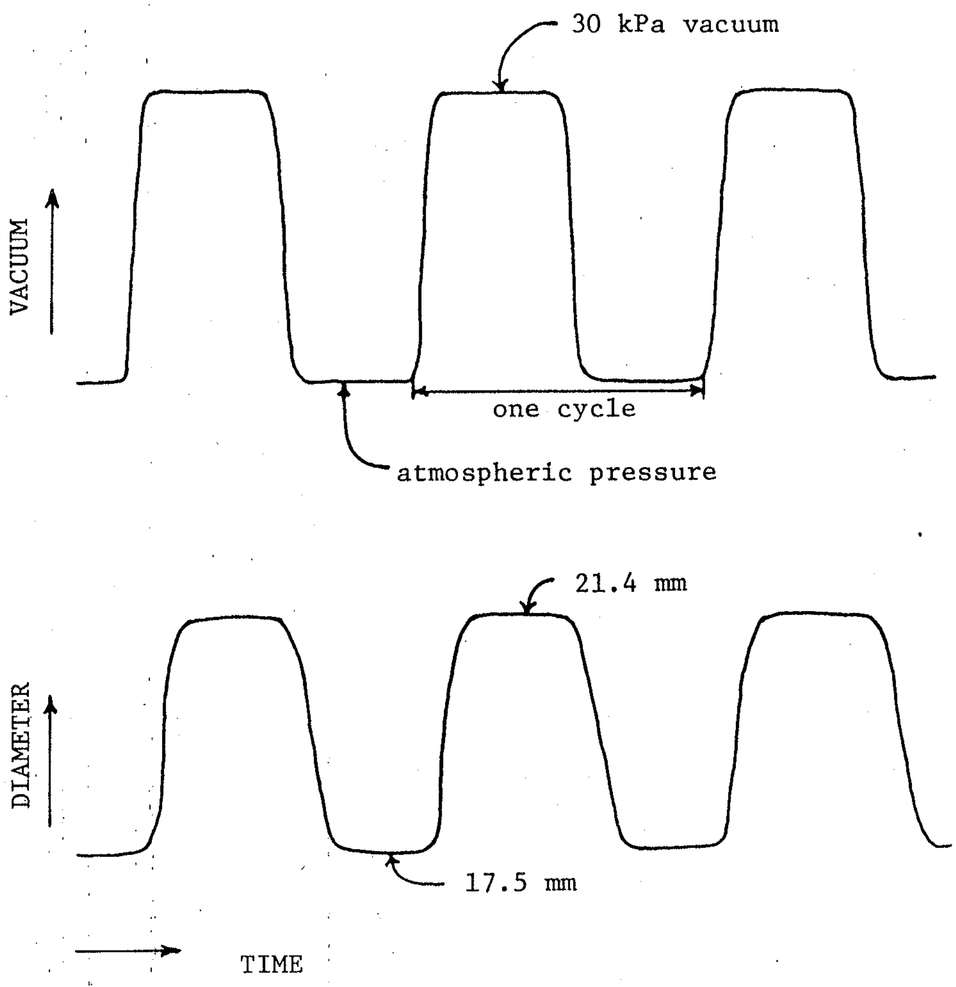

Fig.3.6. Typical example of step pressure input signal and teat end diameter response signal.

cated using DIA array elements 711 to 730. Threshold values at 10, 50, and 90% levels of the step change for both signals are calculated.

Next rise time and fall time of both signals are calculated. The rise time is taken as the time to go from 10% to 90% of the step change. The fall time is taken as the time to go from 90% to 10% of the step change (see Fig. 3.7).

The computer searches through the arrays VAC and DIA to find where these threshold values lie for each cycle. The number of whole and partial intervals between critical points are found. Finally, using linear interpolation between successive points the response variables for both signals are calculated.

Next the hysteresis ratio is computed. An expected hysteresis curve, drawn before running any experiments, is shown in Fig. 3.8. The curve a-b-c represents the loading of the teat during which the teat end expands. The area under the loading curve with respect to the Y-axis is the energy input (strain energy) into the teat. The curve c-d-e represents the unloading of the teat during which the teat end contracts. The area under the unloading curve with respect to the Y-axis is the energy returned by the teat end. The difference between these two areas represents hysteresis of teat end tissue. The hysteresis ratio represents hysteresis as a percentage of the area under the loading curve.

To determine hysteresis ratio, four points are located in each of the two arrays, VAC and DIA:

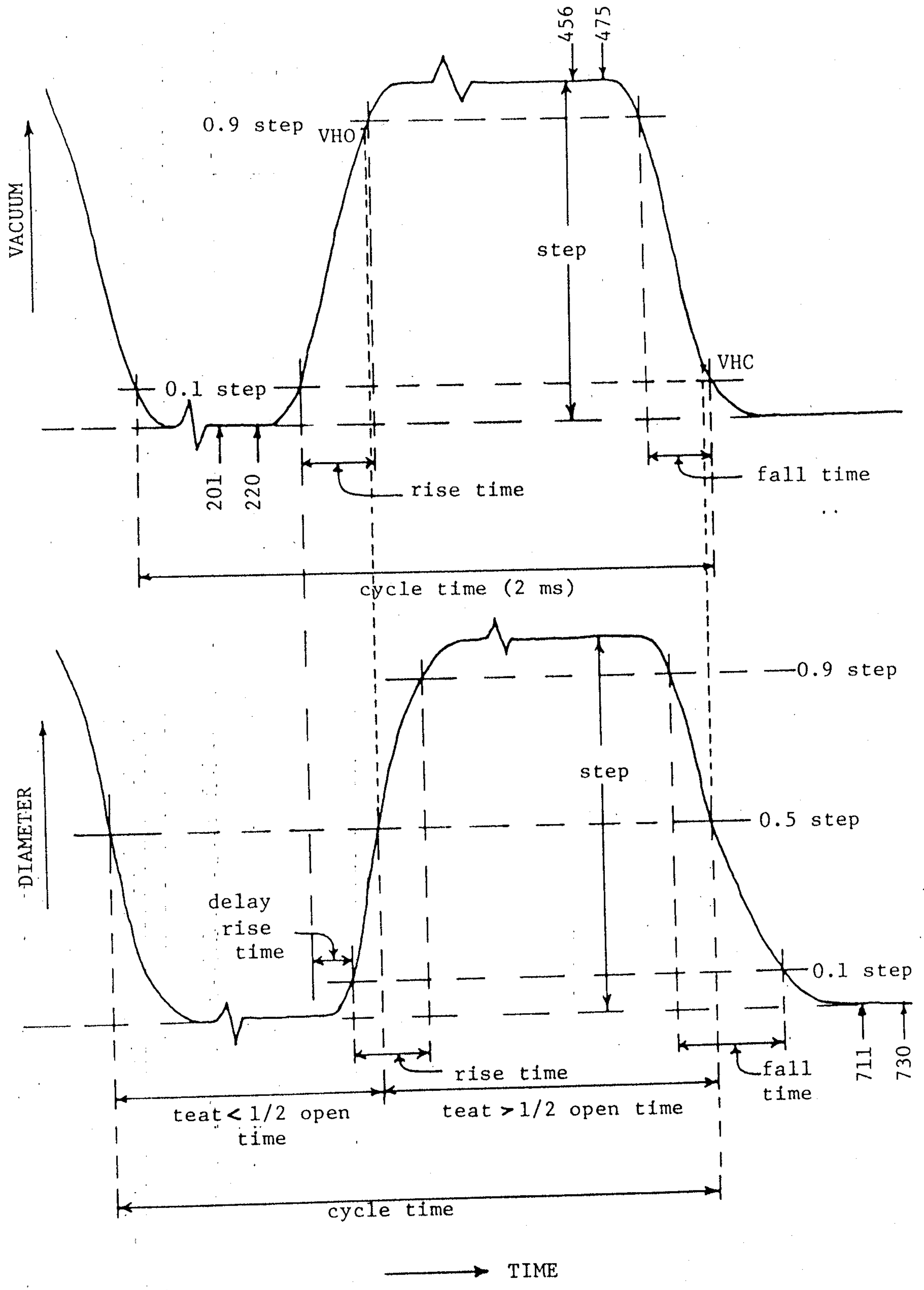

Fig.3.7. Example of step pressure input and teat end diameter response variables.

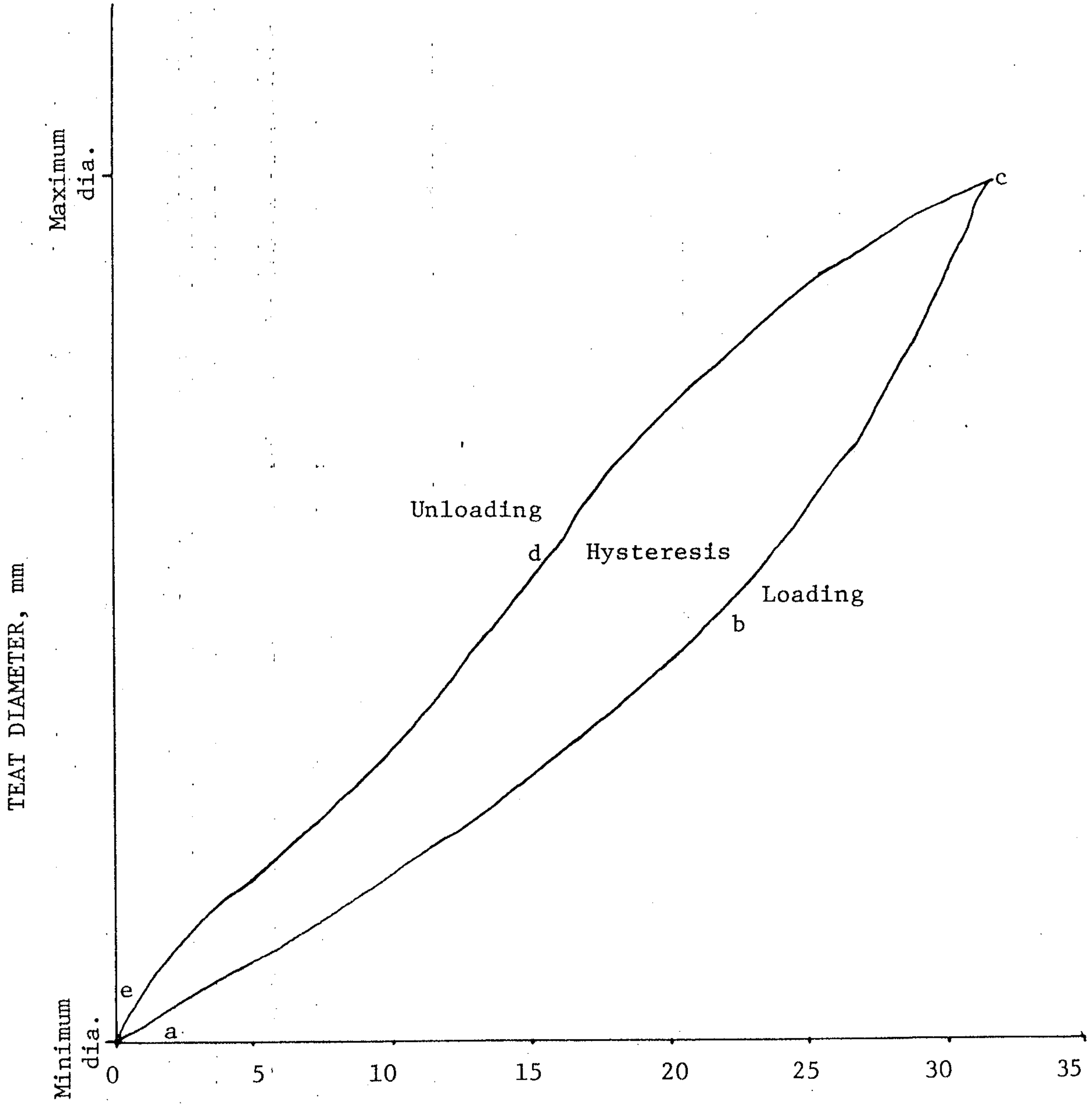

Fig.3.8. Expected hysteresis curve for the dairy cow's teat.

1. loading start point, a
2. loading end point, c
3. unloading start point, c, and
4. unloading end point, e

These points are located using ALV and AHV in the VAC array and ALD and ASDU in the DIA array. ALV is used to locate the first point because the vacuum level starts rising before the diameter. ALD locates the second point because the diameter reaches its maximum value after the vacuum level. AHV helps in locating the third point because the vacuum level starts dropping before the diameter. The fourth point is located using ASDU because the diameter reaches its minimum value after the vacuum level. Once these four points are located corresponding points from both arrays are taken. Points for loading are stored in arrays: LVAC and LDIA, whereas the points for unloading are stored in arrays: UVAC and UDIA. Using the trapezoidal rule of integration, areas under the loading and unloading curves with respect to the Y-axis are calculated. The difference between these two areas represents hysteresis. The hysteresis ratio is the ratio (as a percentage) of the hysteresis to the area under the loading curve. The vacuum levels at half way loading (VHO) and unloading (VHC) are also calculated. The diameters at 50% of its step, during rise and fall, are calculated in the beginning. The corresponding vacuum levels from VAC array are the VHO and VHC.

The above completes the analysis of one cycle. The program repeats the above for the other nine of the ten cycles. Next, results from all cycles, 25 variables per cycle, are printed as output. Any cycle with erroneous results is deleted from further analysis. An average of the remaining of ten cycles is calculated and printed. These final results form the input data for a statistical analysis.

Chapter IV

RESULTS AND DISCUSSION

The results of each of the three experiments, HYSIS, RLOAD, and TMEAS, are first discussed separately. The common results for hysteresis in these three experiments are discussed in the final section of this chapter.

The terminology used for step vacuum level input and teat response variables is described in detail in section 3.2.3.2 and is illustrated in Fig. 3.7.

4.1 EFFECT OF TEAT LOCATION

The mean and standard error (SE) of the mean of several step input variables are shown in Table 4.1. These results verify uniformity of applied changes in vacuum level in the teat chamber to the teats of the cows (4 cows with the right front and right rear teat of each cow and each measurement repeated twice, see section 3.2.2). The step input period was consistent for cows on a particular day but varied somewhat from day to day. This may be explained by a smaller temperature change per milking on a day than between milkings on different days. The timer circuit, which controlled opening and closing of the solenoid valves, was somewhat sensitive to temperature changes.

TABLE 4.1

Mean and standard error (SE) of the mean of several step input variables for the HYSIS experiment.

Step input variable	Units	Mean	SE of the mean
Step input period,	ms	2068	1.67
Maximum vacuum level,	kPa	30.3	0.03
Minimum vacuum level,	kPa	0.0	0.03
Vacuum level rise time,	ms	165	1.84
Vacuum level fall time,	ms	148	0.80

The rise and fall times of vacuum level changes were set at 150 ms. The reasons are: (1) to apply the same rate of loading and unloading to the teat in the teat chamber, and (2) to simulate typical conditions for the rate of liner opening and closing. A teat cup liner has rise and fall times of the order of 150 ms (Reitsma and Breckman 1983). The vacuum level rise time was generally more than 150 ms (see Table 4.1) but the fall time was close to this value. During vacuum application air may leak between the teat chamber's mouthpiece and the teat resulting in a longer rise time. Once the vacuum level reaches a maximum value, there is a better seal between teat and mouthpiece. Therefore, 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 higher rise time which also affected teat responses. This was also noticeable on the strip chart recordings.

The means of the teat response variables of front and rear teats separately of four cows are shown in Table 4.2. This experiment was performed to determine, in particular, possible differences in hysteresis ratio for teat location. All teat responses, except hysteresis ratio, have been studied quite extensively by Reitsma (1977). He found significant differences between teat locations for the teat responses of: step change in diameter, teat end diameter ratio, and average smallest diameter. The main response of interest, in this study, is the hysteresis ratio of the teat end. One front and one rear teat of each cow were selected to determine if front and rear teats respond differently or not. Therefore, the hypothesis that the hysteresis ratio is the same for front and rear teats was tested.

The results of an analysis of variance for all measured variables are shown in Table 4.3. The probability levels of significance used in the results are: $P<=0.01$ (highly significant), $P<=0.05$ (significant), and $P<=0.10$ (close to significant). These are indicated with the letters S, s, and c respectively. The reasons for indicating the probability level of 10% are: (1) a small number of animals used in this study, and (2) a small number of observations. Because of this the significant differences between main factors and interactions, which were clear from plots, were significant at a probability level between 5% and 10% (Steel and Torrie 1980).

The analysis of variance in Table 4.3 showed no significant differences between replications for any of the measured variables. This suggests a good repeatability of measurement techniques. How-

TABLE 4.2.

Means of the teat response variables for front and rear teats separately of four cows for experiment HYSIS.

Cow	Teat location	N	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	FR	2	25.0	6.7	84	285	86	1038	1037	23.0	19.7	1.17	3.4	87.9	28.7	59.0	65.7
	RR	2	29.4	2.8	152	308	141	1096	971	23.1	19.3	1.20	3.8	110.7	23.6	87.1	78.4
2	FR	2	28.5	3.6	95	401	137	1045	1020	20.0	16.8	1.19	3.2	96.2	19.6	77.3	77.5
	RR	2	23.1	2.8	94	346	70	981	1078	20.1	15.9	1.27	4.2	88.2	24.5	65.7	72.7
3	FR	2	22.2	7.3	93	514	76	1031	1043	21.2	18.3	1.16	2.9	69.5	23.4	46.1	66.6
	RR	2	30.0	1.2	119	567	185	1093	975	19.9	17.1	1.15	2.8	89.0	18.9	69.9	78.7
4	FR	2	22.5	5.0	174	245	63	1016	1057	18.2	16.1	1.13	2.2	48.2	16.9	30.7	65.0
	RR	2	24.4	3.6	147	273	70	1041	1040	19.5	16.9	1.15	2.7	60.6	17.4	43.5	71.7

FR : front right teat
RR : rear right teat
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 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
N : number of observations

TABLE 4.3.

Results of the analysis of variance for all measured teat response variables of experiment HYSIS.

S : Highly significant (P<=0.01)   s : Significant (P<=0.05)   c : Close to significant (P<=0.10)

Source of variation	Teat response variable														
	VHO	VHC	TRT	TFT	TDT	TLT	TMT	ALD	ASD	TDR	DSP	ARL	ARU	HYS	HYR
Replication															
Cow				c				s	s			s	c	c	
Location	c	s													c
Location*cow	s				c										

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 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

ever, there were cow and teat location differences. Therefore, plots were done for the means of replications of front and rear teats separately of each cow to see the nature of a particular variable for teat location. The major results are illustrated in Fig. 4.1 through Fig. 4.7.

The vacuum levels, at half way expansion (VHO) and contraction (VHC) of the teats, were determined. The VHO was close to significant for the factor location and significant for the interaction of location and cow (see Table 4.3). The plot of VHO for front and rear teats separately for each cow is shown in Fig. 4.1. Generally rear teats expand to half of their step change at higher vacuum levels than front teats (see Table 4.2 and Fig. 4.1). This may be explained by the teat delay rise time (TDT) of the teat. A plot of the mean TDT for front and rear teats separately for each cow is shown in Fig. 4.3. This variable is close to significant for the interaction of location and cow. It is clear from the plot (see Fig. 4.3) that generally TDT is more for rear than for front teats , except for cow no. 2 who showed the same type of behavior in Fig.4.1 as explained later. This suggests that rear teats respond with a longer delay than front teats. This also could explain why the vacuum level at half way opening of the rear teat is more than that for the front teat. The rate of vacuum level changes is the same for both teats. Rear teats appear to resist expansion more than front teats. However the second cow usually showed a reversed trend compared to the other three. She was near the end of her lactation period and therefore, was giving less milk than the others. It was also observed during measurement

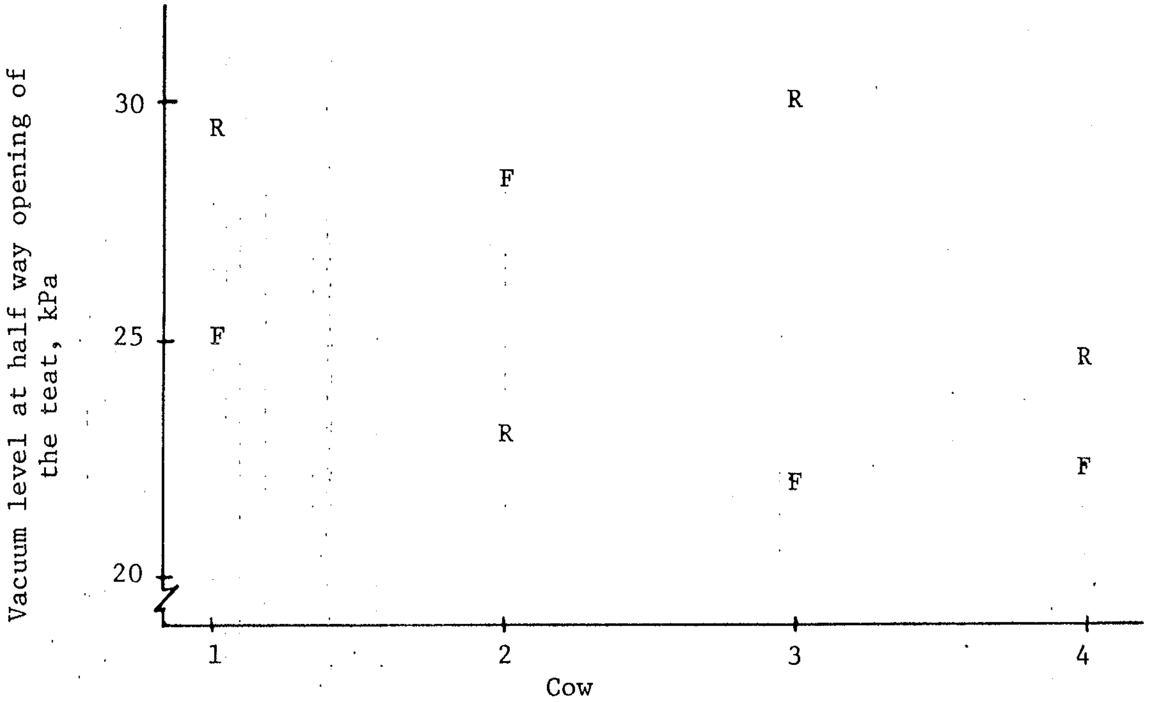

Fig.4.1. Mean vacuum level at half way opening of the teat vs. cow for front (F) and rear (R) teats.

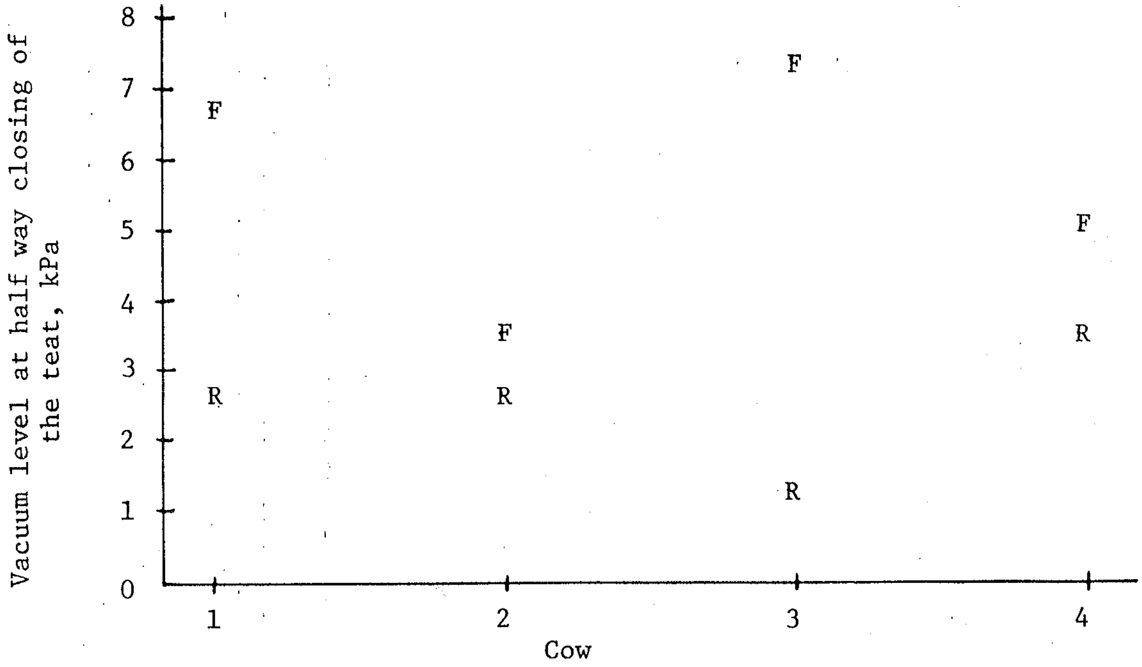

Fig.4.2. Mean vacuum level at half way closing of the teat vs. cow for front (F) and rear (R) teats.

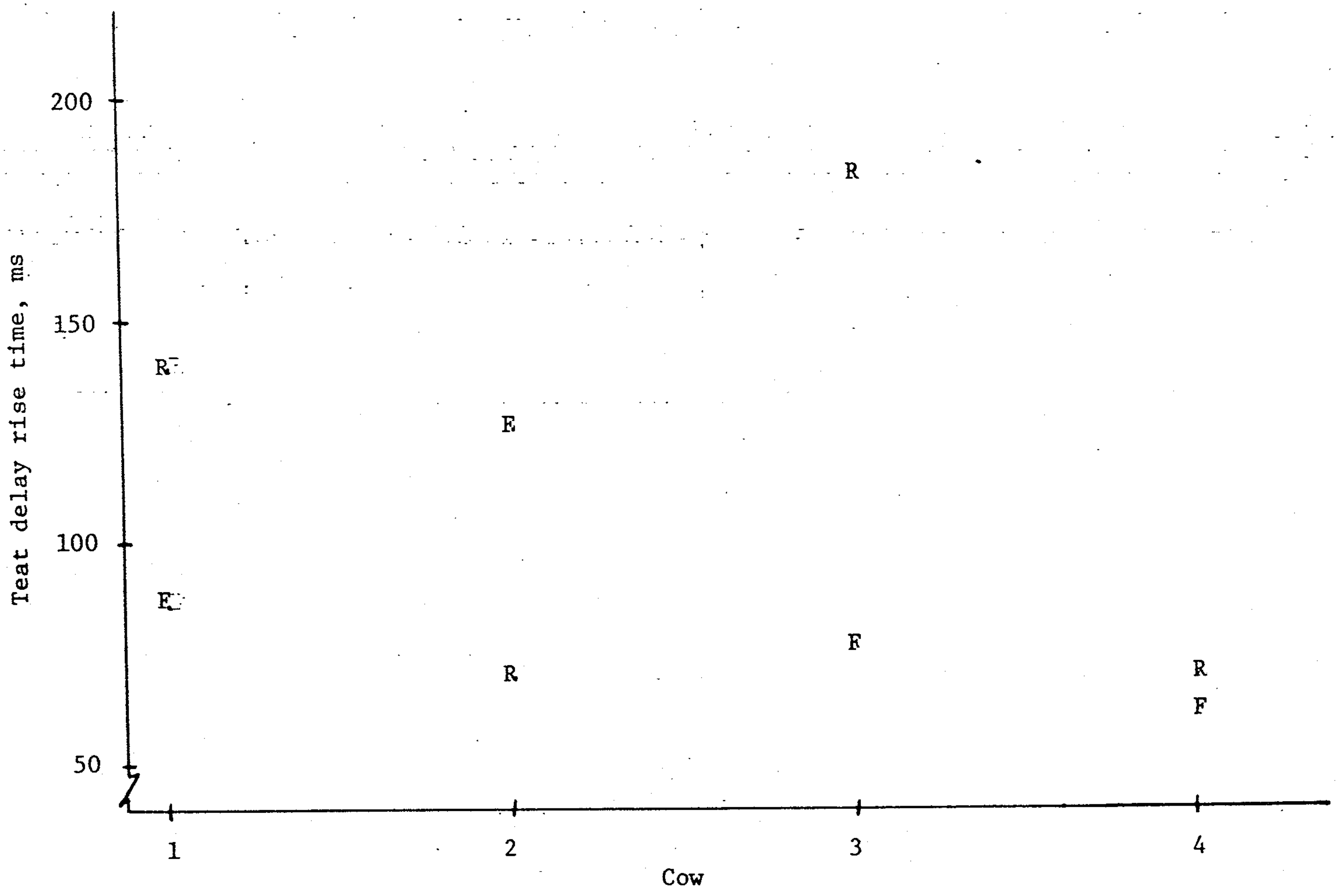

Fig.4.3. Mean teat delay rise time vs. cow for front (F) and rear (R) teats.

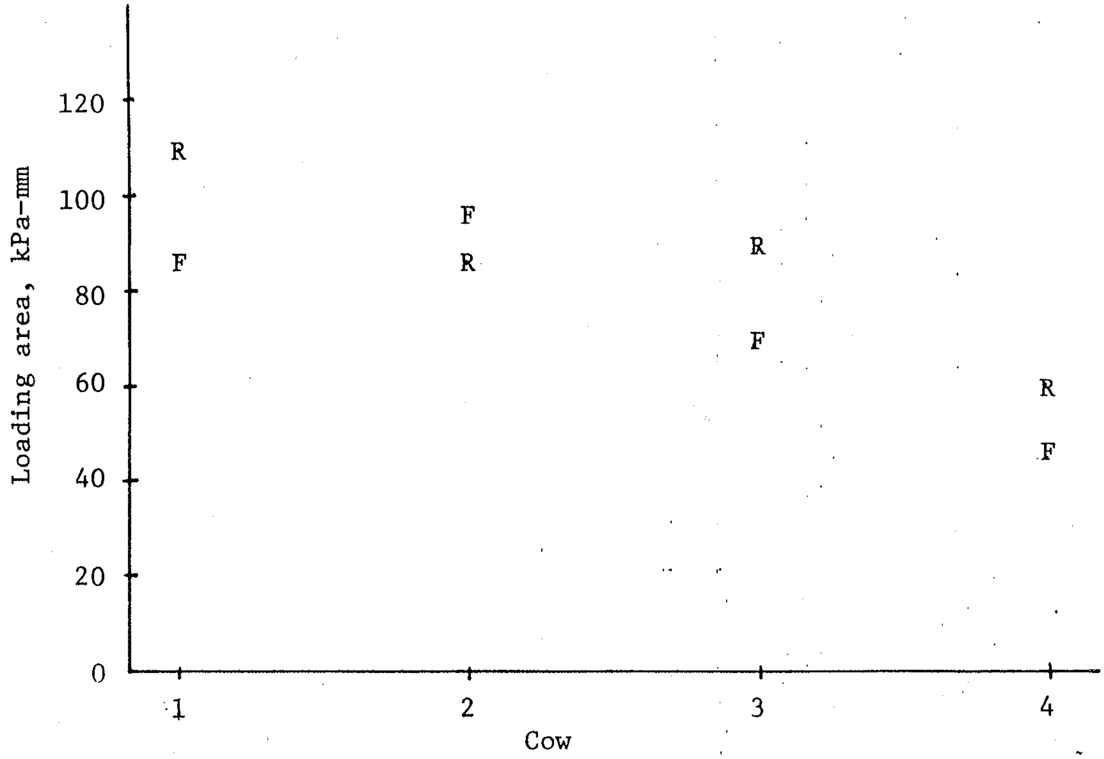

Fig.4.4. Mean area under the loading curve vs. cow for front (F) and rear (R) teats.

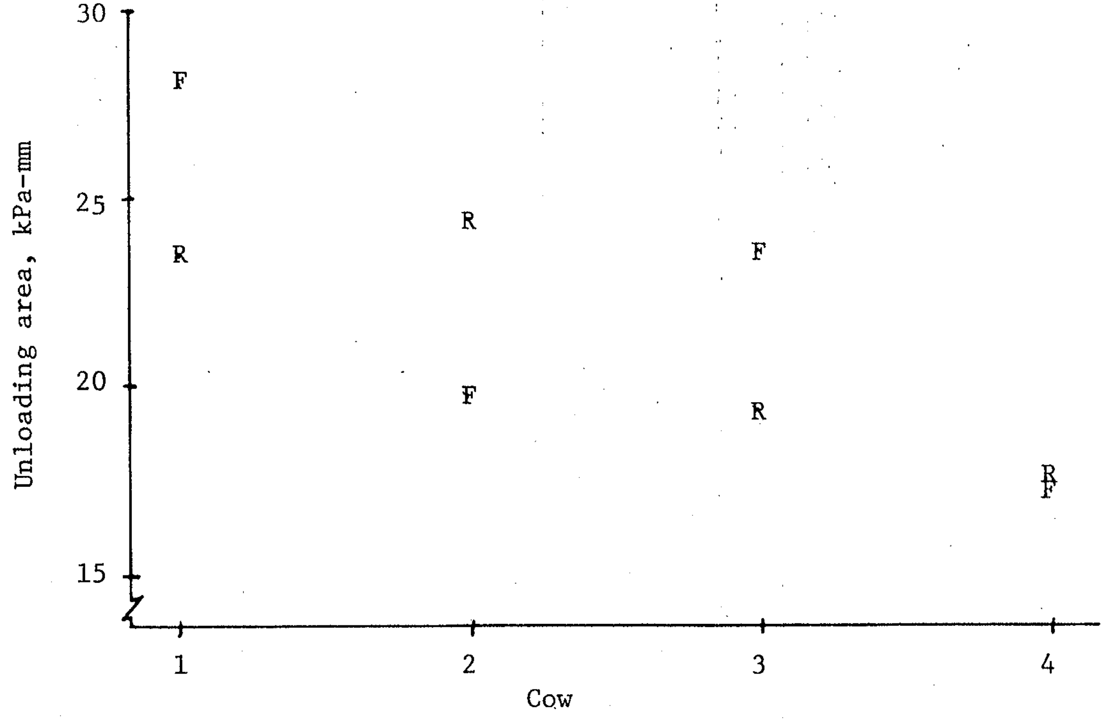

Fig.4.5. Mean area under the unloading curve vs. cow for front (F) and rear (R) teats.

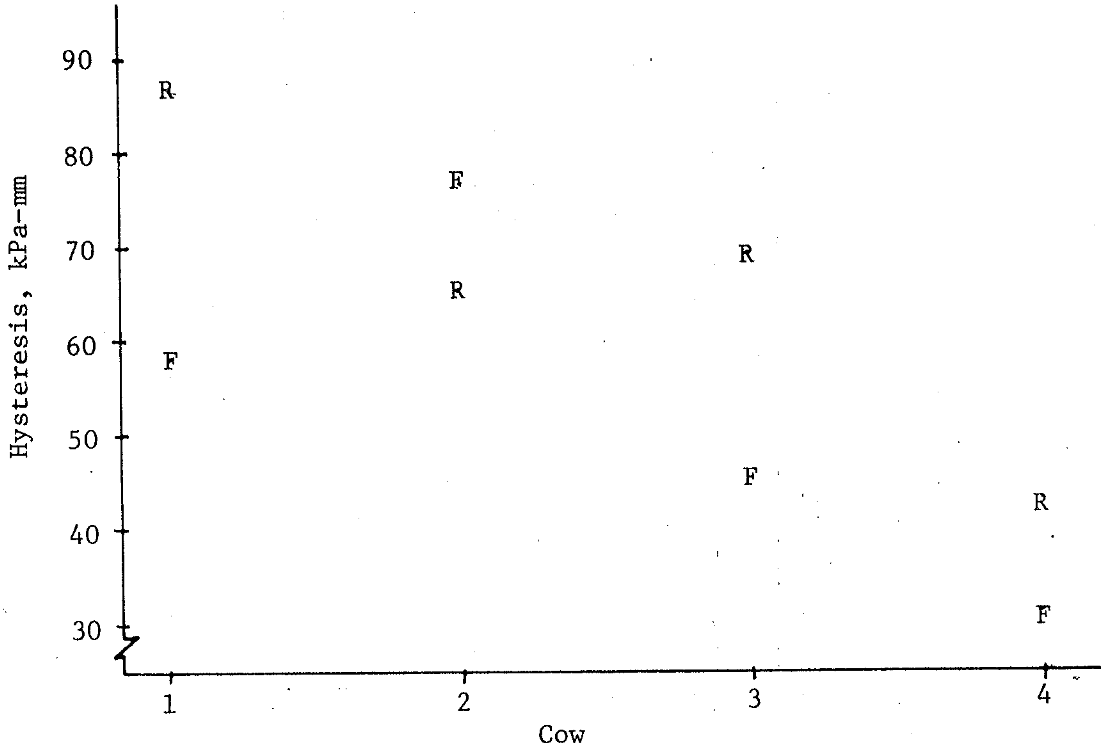

Fig.4.6. Mean hysteresis vs. cow for front (F) and rear (R) teats.

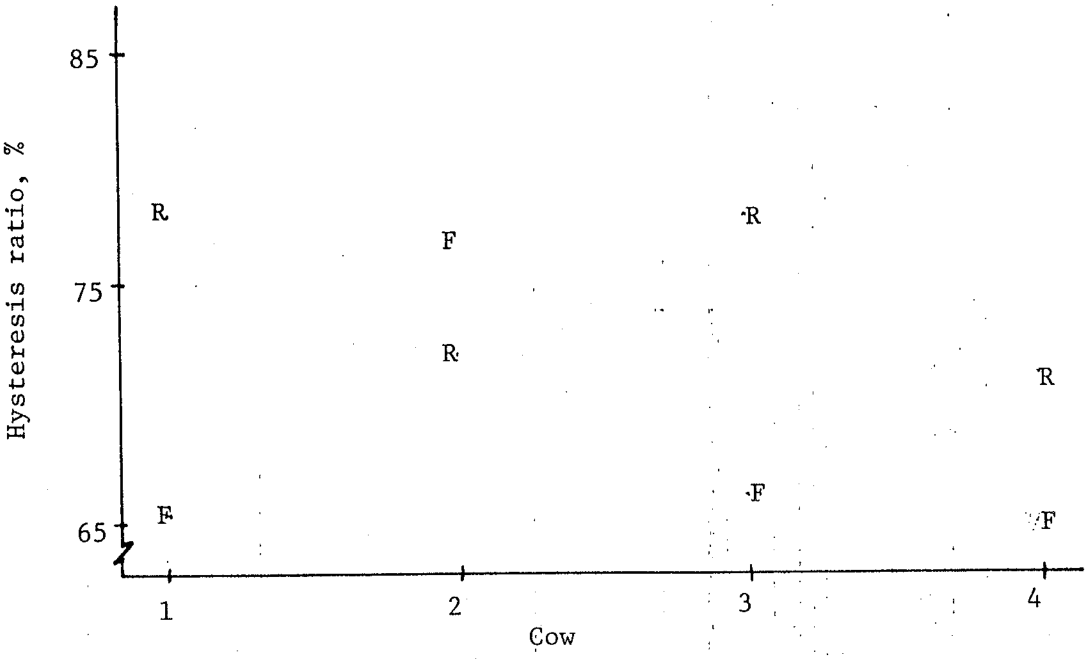

Fig.4.7. Mean hysteresis ratio vs. cow for front (F) and rear (R) teats.

that her rear teats milked out before the front teats, resulting in overmilking of the rear quarters. It is possible that her rear quarters produced less milk than the front quarters, which is not common. Front quarters usually produce less milk than rear quarters and also milk out more quickly (Mein et al. 1973). Probably all the above mentioned factors contributed to the reversed behavior of the second cow. That resulted in a significant interaction between location and cow for the VHO and close to significant for TDT.

The vacuum level at half way closing (VHC) of the teat was also determined. It is plotted for front and rear teats separately for each cow in Fig. 4.2. This variable was significant for the factor location (see Table 4.3). The vacuum level at halfway closing (contraction) of the teat is higher for front than rear teats, suggesting that front teats reach half way contraction earlier than rear teats. This also suggests that rear teats display a stronger viscoelastic behavior than front teats. The vacuum levels for rear teats in particular are close to atmospheric pressure. Probably, in a conventional milking unit the collapsing liner closes the teat canal before pulsation chamber pressure is close to atmospheric pressure. Reitsma and Breckman (1983) have reported pressures in the pulsation chamber at liner halfway opening and closing and they are about half of the step change in vacuum level.

The teat rise time did not differ significantly between front and rear teats. Usually teat rise time was shorter than vacuum level rise time. Mean teat rise time was longer for the fourth cow. The teats of the fourth cow felt much stiffer than those of the other three. The teat fall time was close to significant for the factor cow. Although the rate of loading and unloading of the teat was the same, teat rise times (expansion) and fall times (contraction) differed considerably. The fall times were consistently much longer than the rise times. Therefore, teat ends do not behave the same during expansion and contraction. The third cow milked very fast and usually milk flow was continuous during teat chamber operation. This explains the longer fall times of her teat ends.

The variables teat less than half open time (TLT) and more than half open time (TMT) are not significant for any of the factors (see Table 4.3).

Four variables for dimensional changes of the external teat end diameter were analyzed: (1) average smallest diameter (at atmospheric pressure), (2) average largest diameter, (3) step change in teat end diameter, and (4) teat end diameter ratio. The contracted (ASD) and expanded (ALD) teat end diameter differed significantly between cows. The overall mean contracted teat end diameter for front and rear teats were 17.7 mm and 17.3 mm respectively. Under the test conditions of this study rear teats tended to expand more than front teats. Both teat end diameter ratio and step change in diameter showed no significant differences for any factor (see Table 4.3). Reitsma (1977) reported that front teats have a smaller diameter than rear teats at atmospheric pressure and expand significantly more. This could be because of the differences in the cows.

Next, several measurements are related to teat end hysteresis. Fig. 4.4 shows the mean area under the loading curve for front and rear teats separately of each of the four cows. It differs significantly between cows, but not for the factor location and interaction of location and cow. Note that the teats of cow no. 2 deviate from the others. Although the step change in diameter was not significant for cows, the area under the loading curve was generally larger for the teats which expanded more. One cow whose teat expanded 4.3 mm on one day had an area under the loading curve of 112.9 kPa-mm, whereas the same teat expanded 2.4 mm at the second replication with an area under the loading curve of 62.9 kPa-mm. This suggests that more expansion of the teat end increases the area under the loading curve as is to be expected.

Fig. 4.5 shows the mean area under the unloading curve for front and rear teats separately of each of the four cows. This variable was close to significant for the factor cow. This was again different for the same reason that teats of different cows expanded to different diameters. The unloading area for front and rear teats did not differ enough to result in significant differences for location and the interaction between location and cow. Front teats appear to return more energy than the rear ones suggesting that front teats display less viscoelastic behavior than rear teats. Also here the trend of the second cow is reverse. The results in Fig.4.4 and 4.5 generally show that the teats with the larger loading areas produced the smaller unloading areas.

Hysteresis is close to significant between cows (see Table 4.3 and Fig.4.6). This suggests that the energy dissipated into cows' teats differs between cows. The hysteresis was converted to a dimensionless ratio by dividing it by the area under the loading curve and calling it the hysteresis ratio. The results of each of the four cows for front and rear teats separately are shown in Fig. 4.7. The hysteresis ratio was close to significant for the factor location. Rear teats have a higher hysteresis ratio than front teats except for cow no. 2. The location by cow interaction was not significant (see Table 4.3). Fig. 4.7 shows a reversed trend for cow no. 2 suggesting an interaction. The reversed trend of this cow corresponds to that trend for other teat response variables discussed earlier. The hysteresis ratio difference between the front and rear teat of the second cow is not large enough to result in a close to significant interaction.

A larger hysteresis ratio for rear teats could be attributed to larger expansion of rear teats than front teats. Also the longer delay time, higher vacuum at half way opening of the teat, and low vacuum at half way closing of the teat for rear teats contributed to the higher hysteresis ratio.

4.2 EFFECT OF RATE OF LOADING AND UNLOADING

The RLOAD experiment was designed to determine the effect of the rate of step vacuum level changes on teat end diameter changes and particularly on hysteresis. Table 4.4 shows the mean and standard error (SE) of the mean for each step input variable. Small values of

TABLE 4.4

Mean and standard error (SE) of the mean of several step input variables for the three treatments in the RLOAD experiment.

Step input variable	Units	Treatment	Mean	SE of the mean
Step input period,	ms	1,2,3	2062	0.62
Maximum vacuum level,	kPa	1,2,3	30.1	0.03
Minimum vacuum level,	kPa	1,2,3	0.1	0.18
Vacuum level rise time,	ms	1	55	0.97
		2	165	3.91
		3	282	14.11
Vacuum level fall time,	ms	1	54	0.7
		2	145	2.14
		3	345	15.62

SE of the mean for step input period, maximum vacuum level, and minimum vacuum level verify uniformity of application to all the experimental units (three cows with the front right and a rear right teats). The rise and fall times for the first and second treatment were more stable than the third because the vacuum level reaches its maximum quite rapidly and there is less chance of leakage between teat and mouthpiece. The reason for variation is similar to that explained earlier in Section 4.1. The third treatment showed a large variation for another reason. On the third day the vacuum level in the teat chamber did not reach atmospheric pressure for cow 1 while the maximum vacuum level was 29.9 kPa. This resulted in a smaller step change in vacuum level resulting in rise and fall times of 212 ms and 276 ms respectively. This contributed to a larger SE of the mean for rise and fall times for the third treatment.

The experiment required three cows. Cow no.2 of the first experiment (HYSIS) was not used because she was close to the end of her lactation.

Table 4.5 shows the teat response variables for front and rear teats separately of the the cows for each of the three treatments. The results of the analysis of variance for all measured variables are shown in Table 4.6. A visual presentation of the areas under the loading curves and under the unloading curves for front and rear teats separately as a function of treatment is given in Fig. 4.8. The hysteresis ratio for front and rear teats separately as a function of treatment is shown in Fig. 4.9.

According to the statistician from the Department of Statistics, who helped in designing and analyzing the experiments, significant differences (P<=0.05) for some of the variables were not found in an analysis of variance table. However these variables were close to significant and, when plotted, a particular trend shows up as illustrated in Fig. 4.8 and 4.9.

Vacuum level at half way expansion (during loading) of the teat, was close to significant for the factor teat location and it was

TABLE 4.5.

Means of teat response variables for right front (FR) and rear (RR) teat of three cows for experiment RLOAD. The treatments 1,2,and 3 represent three rates of vacuum level changes.

			Teat response variable														
Treatment	Teat location	N	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 (50 ms)	FR	3	28.2	0.7	59	349	141	1005	1059	21.9	18.4	1.19	3.4	98.9	18.3	80.7	81.0
	RR	3	29.8	-0.2	147	474	67	1021	1053	20.5	17.8	1.15	2.7	86.0	11.9	73.8	84.4
2 (150 ms)	FR	3	27.0	4.0	115	534	121	1051	1018	22.0	18.9	1.16	3.1	89.3	22.9	65.8	73.8
	RR	3	28.1	2.4	141	457	151	1073	988	20.9	18.2	1.15	2.7	78.4	18.5	60.2	76.1
3 (300 ms)	FR	3	20.0	6.2	149	498	117	905	1152	21.0	17.7	1.18	3.3	69.4	26.2	42.8	60.3
	RR	3	23.4	6.8	200	528	110	941	1128	20.5	17.7	1.16	2.8	61.9	21.0	41.0	65.1

N : number of observations
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 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

TABLE 4.6.

Results of the analysis of variance for all measured teat response variables of experiment RLOAD.

S : Highly significant (P<=0.01)   s : Significant (P<=0.05)   c : Close to significant (P<=0.10)

Source of variation	Teat response variable														
	VHO	VHC	TRT	TFT	TDT	TLT	TMT	ALD	ASD	TDR	DSP	ARL	ARU	HYS	HYR
Treatment	c	c		c	s								s		S
Cow			c	c				s	s				s		s
Day				c											
Location	c		s					S			c		S		
Treatment*Location				s											

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 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

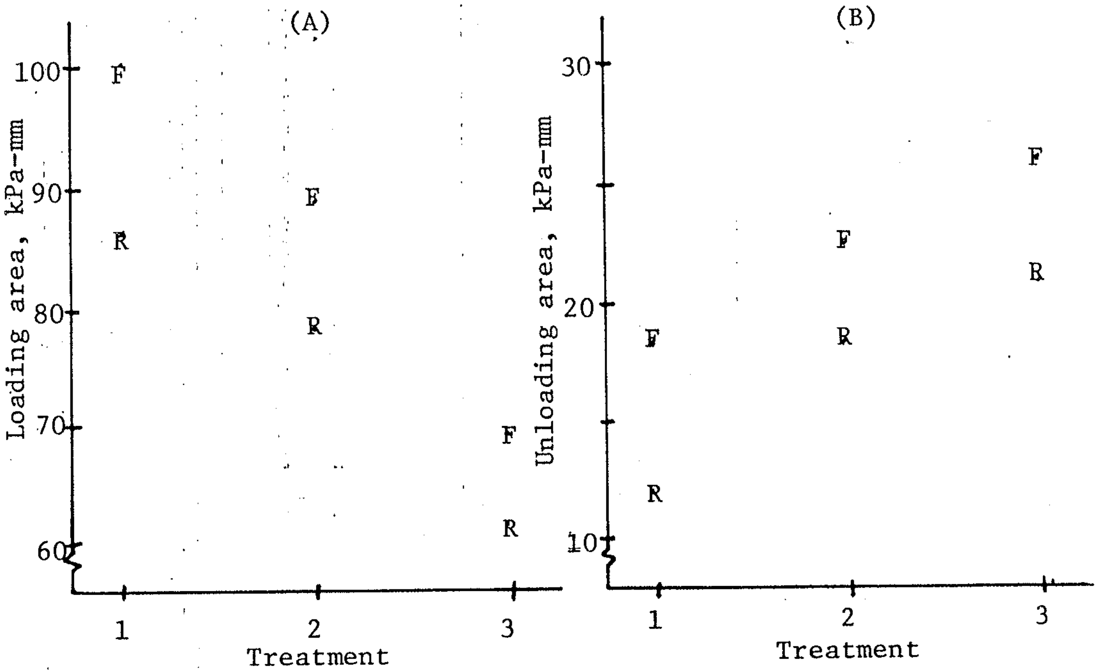

Fig.4.8. Plot showing area under loading curve,(A) and area under unloading curve, (B), both as a function of treatment for front (F) and rear (R) teats of three cows.

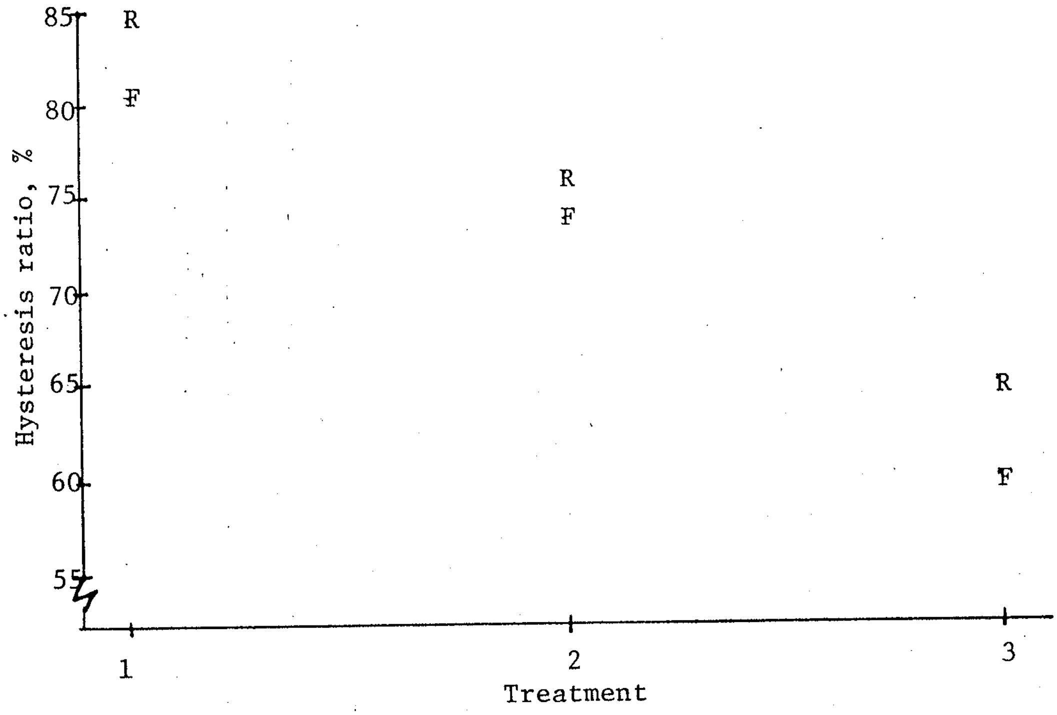

Fig.4.9. Mean hysteresis ratio for front (F) and rear (R) teats of three cows as a function of treatment.

always higher for rear teats (see Table 4.5). It was also close to significant for treatment, but interaction between treatment and location was highly insignificant indicating that location and treatment acted independently. In other words, VHO was higher for rear than front teats for all treatments and there was a decreasing trend for slower changes in vacuum level (see Table 4.5).

Vacuum level at half way contraction (during unloading) of the teat was highly insignificant for location and the interaction of location and treatment but close to significant for treatment. For slower rates of vacuum level changes VHC increased while VHO decreased.

The teat rise time showed significant differences between locations and was close to significant for cow. Front teats expanded in a shorter time than rear teats (see Table 4.5). Also the faster rate of vacuum level changes resulted in shorter rise times for both teat locations (see Table 4.5). The foregoing suggests that the sphincter muscle and teat end tissue of rear teats resist expansion more than front teats. At a slower rate of vacuum level changes, teat end rise times were shorter than vacuum level rise times. Only for treatment 1 are the teat rise times longer than the vacuum level rise times. A fast rate of vacuum level increase can likely open the teat canal fast but might lead to tissue damage or teat end injury. A slower rate of vacuum level changes will open the teat canal slowly and may result in somewhat higher milk flow rate because teat canal open time is increased. An optimum value for vacuum level changes should be used to remove milk thoroughly and rapidly but not impose excessive stress. Reitsma (1977) reported no significant differences in the rise time between front and rear teats.

The teat fall time was somewhat affected by the rate of loading (see Table 4.5). It was close to significant for the factors treatment, cow, and day. The interaction of treatment and location was significant although location was highly insignificant. Therefore the factor location did not behave independent of treatment. For treatment 2 front teats gave higher fall times than rear teats but the opposite took place for treatments 1 and 3 (see Table 4.5). Having approximately the same fall times for both front and rear teats is desirable because in a conventional milking unit all four liners have about the same fall times.

The teat delay rise time (TDT) was significant for the factor treatment. At the fastest rate of vacuum level changes, TDT was the shortest, indicating an earlier teat response to applied changes in vacuum level. This suggests that the teat end tissue and the sphincter muscle around the teat canal respond more quickly at a fast rate of vacuum level changes than at slower rates. Other factors like location, cow, and the interaction of location and treatment were all highly insignificant.

All the factors and interactions for the teat less than half open (TLT) and more than half open (TMT) times were insignificant. The results in Table 4.5 indicate that teats were more than half open for a longer duration in treatment 3, and consequently less than half open for a shorter duration as compared to the other two treatments.

The dimensional changes of the external teat end diameter were analyzed by four variables: (1) average smallest diameter (ASD), (2) average largest diameter (ALD), (3) teat end diameter ratio (TDR), and (4) step change in teat end diameter (DSP). Both the average smallest diameter and the average largest diameter differed significantly between cows. ALD was highly significant between locations unlike ASD. DSP was close to significant for location. Larger expansion and teat end diameter ratio of front teats than rear teats agrees with earlier findings by Reitsma (1977). The higher values of DSP for front teats resulted in higher teat end diameter ratios for front teats. DSP was highly insignificant for the factor treatment. This suggests that teat ends always expand to their maximum value independent of the rate of loading, although rise times tend to change.

The variable of particular interest, hysteresis ratio, showed highly significant differences between treatments and was significant for cows. It was not significant for the factor location but rear teats always had a larger hysteresis ratio than front teats (see Fig.4.9). This was also found in the first experiment (HYSIS).

The mean area under the loading curve is shown in Fig. 4.8 (A). The analysis of variance did not show any significant differences for any of the factors. Also hysteresis was not significant for any of the factors. It is clear from the plot that the energy input to the teat is larger for front than for rear teats. This could be because front teats expanded more in a shorter time than rear ones. Because front teats expand more and in less time than rear teats, their rate of expansion is much higher than that of rear teats. Probably that is a contributing factor to why front quarters tend to milk out before rear ones as indicated by Mein (1984). The rear teats expand less and take more time to expand as indicated by both DSP and TRT.

The energy returned by the teat, as represented by the area under the unloading curve, was more for front teats than rear teats. It was highly significant for location and close to significant for teat location. The two areas under the loading and unloading curves, showed a reversed trend for treatments and were consistent for location. For a faster rate of vacuum level changes, more energy was input (see Fig.4.8A) to the teat and smaller amounts returned (see Fig.4.8B) resulting in larger hysteresis ratios (see Fig. 4.9). About 16% of the energy input to the teat was recovered in treatment no. 1, whereas 25% and 36% in treatment no. 2 and 3 respectively (see Table 4.8). The hysteresis ratio decreases as the rate of air change is decreased (see Fig. 4.9). The hysteresis ratio was larger for rear than front teats suggesting a more viscous behaviour for rear teats as compared to front teats.

4.3 EFFECT OF TIME OF MEASUREMENT

In this experiment a typical value of vacuum level rise and fall time, 150 ms, was used as in the HYSIS experiment. The three cows used in the RLOAD experiment, with one cow added, were used. This fourth cow (no.4 in Table 4.8) had extraordinarily large teats (long and cone shaped with large diameter at upper end of the teat). It was also observed, by feeling, that the walls of this cow's teats were very thin. The measurements were taken before, during, and after milking. The hypothesis of main interest was: do teat responses remain the same when measuring before, during, and after milking? The teat end diameter signal was a straight line for after milking measurements. Therefore, it was not possible to perform an analysis of teat responses after milking. Table 4.7 shows the mean and standard error (SE) of the mean for all the step input variables. The reason why one variable has a larger SE of the mean and another a smaller has already been explained in section 4.1. The step input period was more consistent over days in this experiment than the previous two experiments.

TABLE 4.7

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

The means of the teat responses before (B) and during (D) milking for all the four teats combined of each of the four cows is shown in Table 4.8. The results of the analysis of variance for all measured variables are given in Table 4.9.

The means of all the four teats of each of the four cows are plotted for the variables which showed significant differences between the two times of measurement (before and during milking). The major results are illustrated in Fig. 4.10 through 4.15.

Four independent factors and five interactions were considered (see Table 4.9). A significant interaction indicates that the differences in response to the levels of one factor are different at different levels of another factor.

All the teat response variables except VHC, and TRT were highly significant for the factor cow. The teat rise time differed significantly for the factor cow. These results in Table 4.9 suggest that nearly all teat responses differ considerably between cows and less due to teat location (front and rear), time of measurement (before and during milking), and side (left, right) within a location. The first two cows milked very fast. Cow no.2 required only two to three minutes. Cow no.3, with small teats, milked very slowly. Her teats also felt much harder than those of the other three cows. Cow no.4 with very large cone shaped teats milked at an average flow rate.

The vacuum level at half way expansion (VHO) of the teat was significant for the factor time of measurement. The interaction between cow and location was close to significant for this variable

TABLE 4.8.

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	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

The columns VHO to HYR are printed under the spanning header "Teat response variable".

N : number of observations
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
TDT : 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

TABLE 4.9.

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

S : Highly significant (P<=0.01) s : Significant (P<=0.05) c : Close to significant (P<=0.10)

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 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

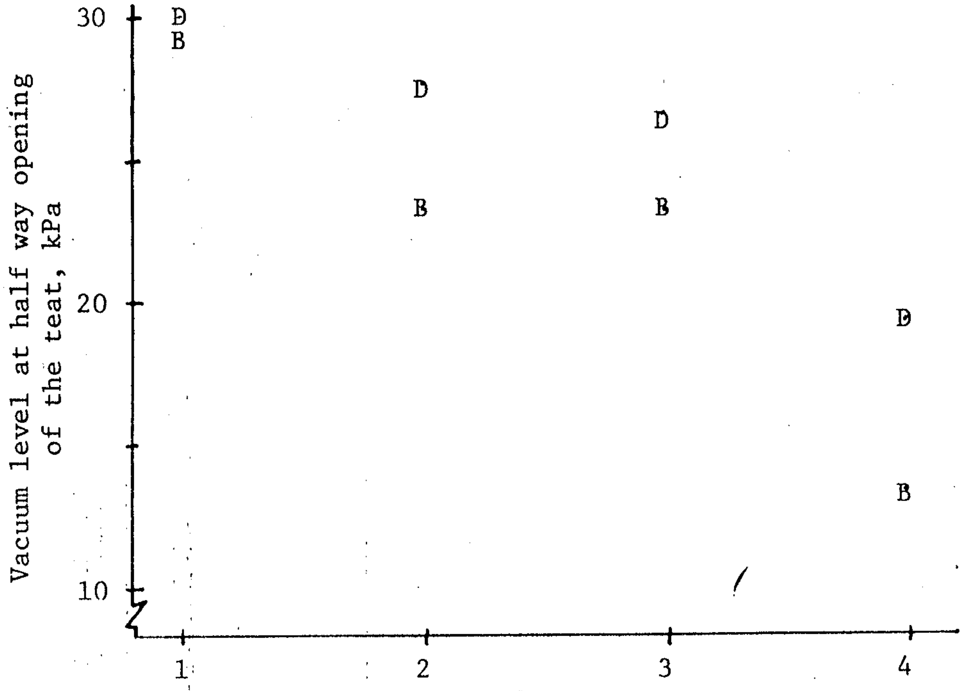

Fig.4.10. Mean vacuum level at half way opening of the teat vs. cow for before (B) and during (D) milking.

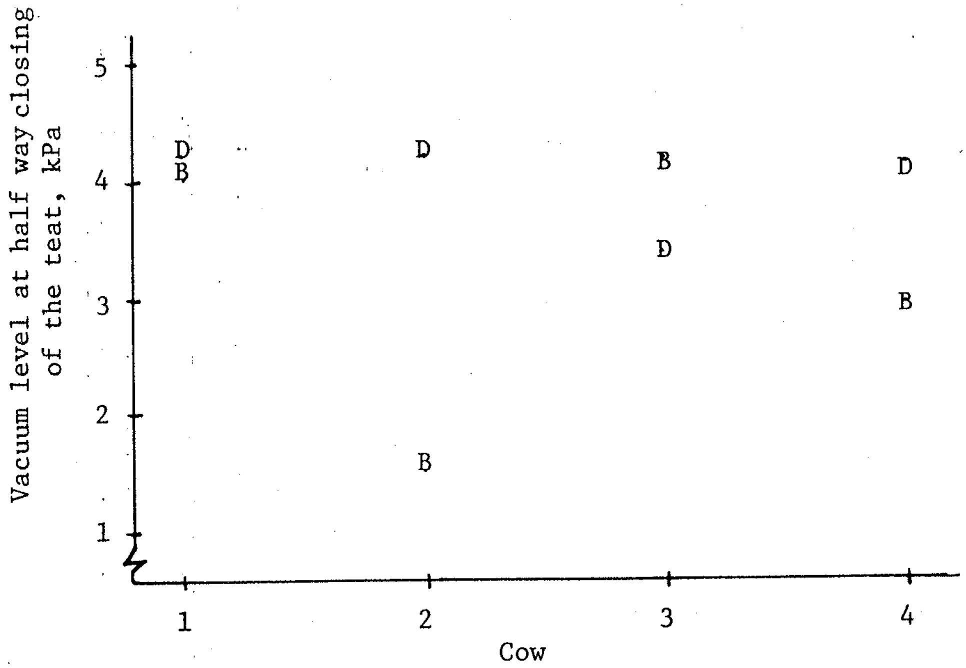

Fig.4.11. Mean vacuum level at half way closing of the teat for before (B) and during (D) milking.

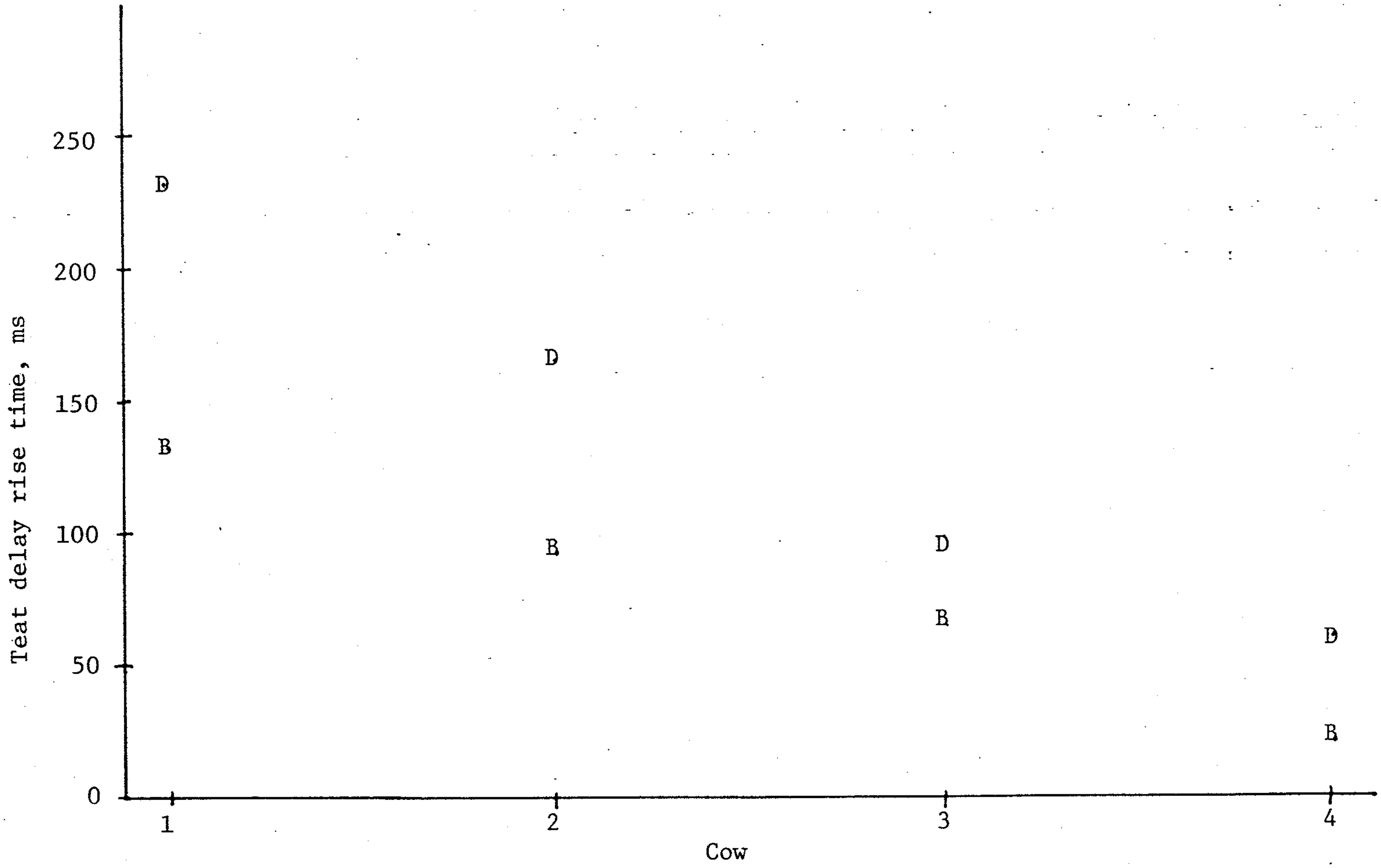

Fig.4.12. Mean teat delay rise time vs. cow for before (B) and during (D) milking.

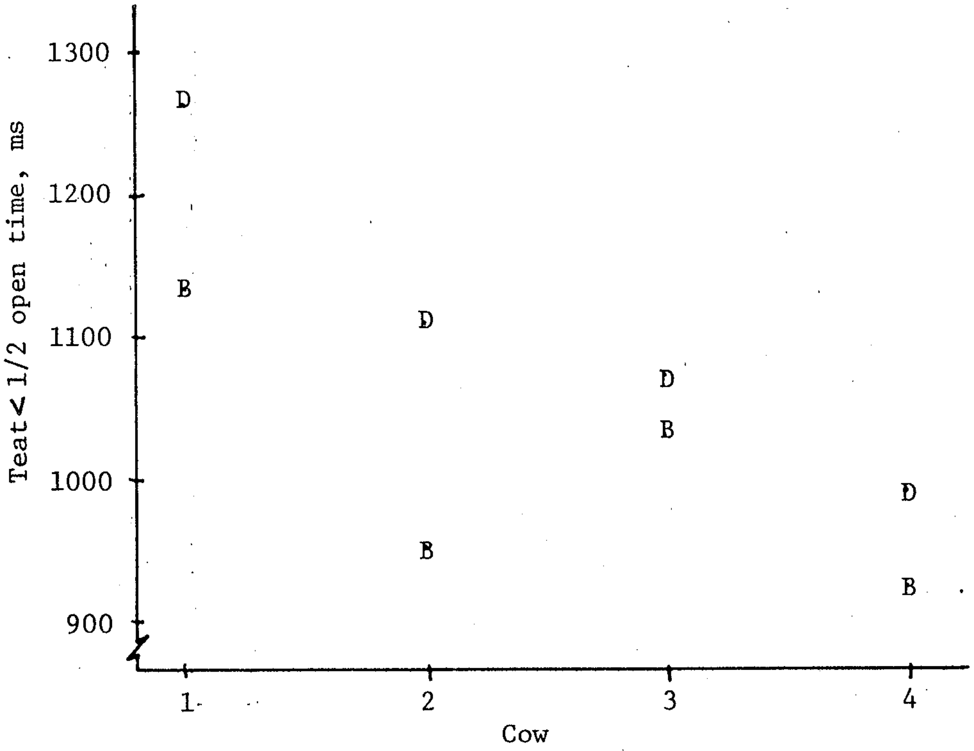

Fig.4.13. Mean teat < 1/2 open time vs. cow for before (B) and during (D) milking.

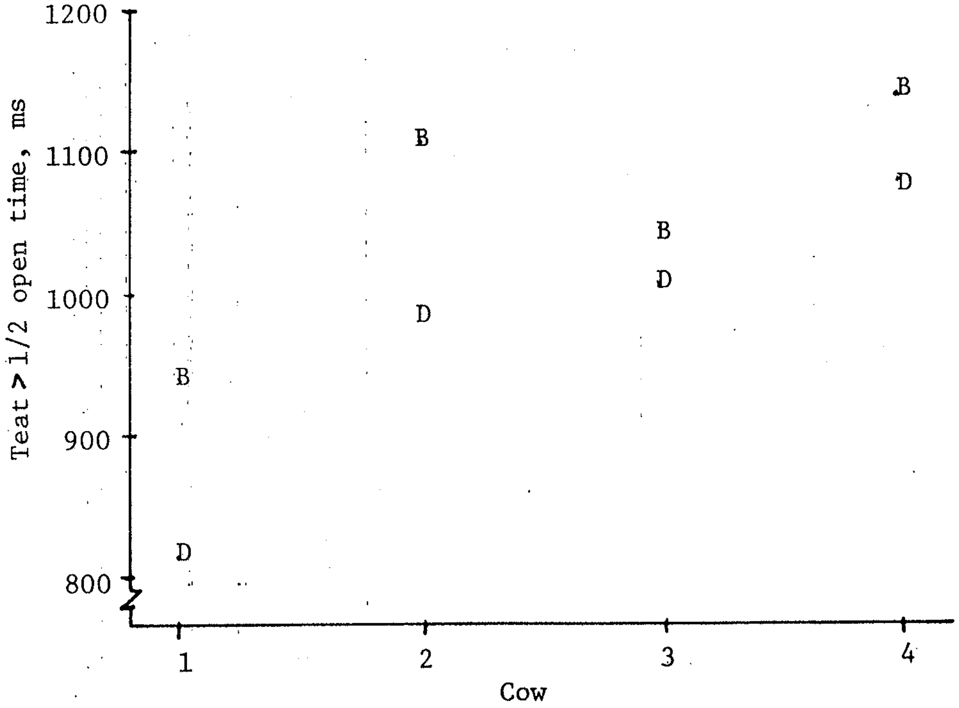

Fig.4.14. Mean teat > 1/2 open time vs. cow for before (B) and during (D) milking.

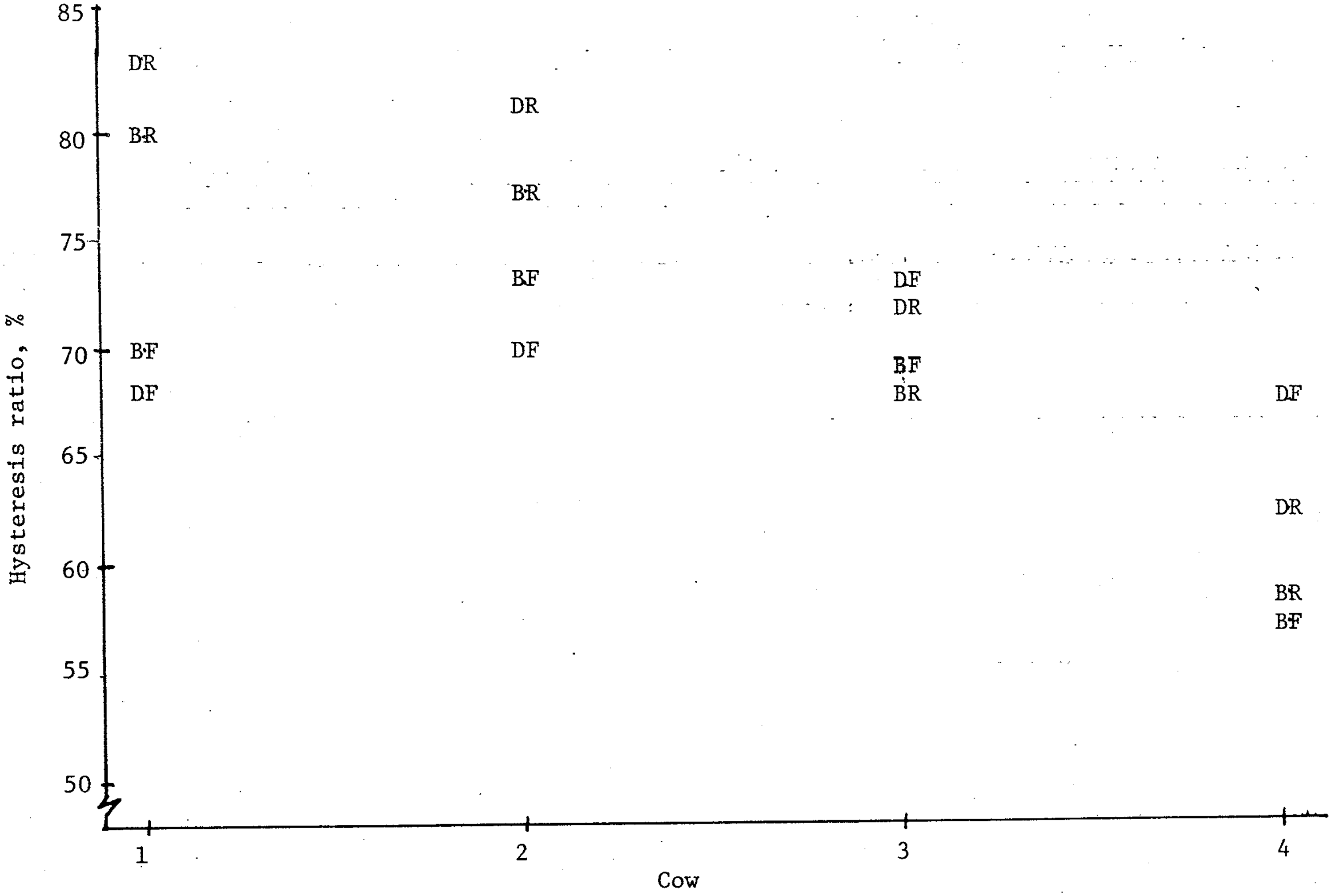

Fig.4.15. Mean hysteresis ratio vs. cow for front (F) and rear (R) teats separately observed before (B) and during (D) milking.

(Table 4.9). The value of this variable is higher during than before milking. This may be due to the reduced pressure inside the teat and udder cistern during milking as compared to that just before milking. The variable vacuum level at half way contraction (VHC) of the teat was highly significant for the factor location and significant for the time of measurement. Two interactions for VHC were significant and two others highly significant (see Table 4.9). Fig. 4.11 shows the cow and time of measurement interaction.

The teat rise and fall times were not significant for the factor time of measurement (see Table 4.9). This indicates that teats take about the same time to expand and contract before and during milking. The teat diameter ratio and step change in diameter were also not significant for the factor of time of measurement. Teats expanded to about the same value before and during milking and the rise and fall times were also about the same for before and during milking. Therefore the rates of teat end expansion and contraction were about the same for before and during milking.

The teat delay rise time (TDT) is highly significant for the factor time of measurement. Fig. 4.12 shows that teat delay rise time is longer during milking than before. The TDT was significant for location whereas its interaction with cow was highly significant. The larger teat delay rise time during milking, as compared to before milking, may be due to congestion developed at the teat end as milking progresses.

The teat less than half and more than half open times are shown in Fig. 4.13 and 4.14. These two variables are highly significant for the factor time of measurement. And these are the only two variables which are also significant for side within location. This suggests that teats within a location (front, rear) have each different times of less than and more than half open. If one of the teats is more than half open for longer duration in a pulsation cycle, it may increase the chances of bacteria getting into the teat canal.

The time for which teat was more than half open was longer before milking than during milking. This pattern is reversed for the time for which teat was less than half open. Teats are half way expanded at higher vacuum levels during milking than before milking as indicated in Fig. 4.10. This leads to the fact that the teat is less than half open for a longer duration during milking than before milking (see Fig. 4.13). The reverse of this applies to the teat more than half open time (see Fig.4.14). Before milking teats are half open at lower vacuum levels (see Fig. 4.11) leading to larger times for teat more than half open before milking as compared to during milking (see Fig.4.14).

Fig. 4.15 shows the hysteresis ratio for each of the cows for front and rear teats separately for before and during milking. The hysteresis ratio was highly significant for the factor cow and location and significant for time of measurement (see Table 4.9). The interaction between cow and location was also highly significant. The significance of individual factors indicates that: (1) hysteresis ratio is different for different cows, (2) differs between front and rear teats in a cow, and (3) also differs between before and during milking. The highly significant interaction between cow and location indicates that hysteresis ratio of front and rear teats is not independent of cows.

4.4 HYSTERESIS OF THE TEAT END

In these studies, the teat end having smooth muscle (sphincter muscle) around the teat canal, showed a pronounced viscoelastic behavior during machine milking. Fig. 4.16 shows a typical hysteresis curve for front and rear teats of a cow. The loading curve of the rear teat indicates little or no change in teat end diameter up to a vacuum level close to the maximum value (30 kPa). Most of the expansion of the teat end took place at this maximum vacuum level. The front teat end started to expand approximately at half of the maximum vacuum level. This suggests that the sphincter muscle around the streak canal of the rear teat end resists expansion more than that of the front teat. This was observed when the rate of vacuum level changes for both teats (front and rear) were the same (150 ms rise and fall times).

Sometimes an irregular change in teat end diameter changes was observed in the hysteresis curves. An example of this is shown for the unloading curve of the front teat in Fig. 4.16. The real cause has not been isolated. Electrical noise didn't appear to be the cause.

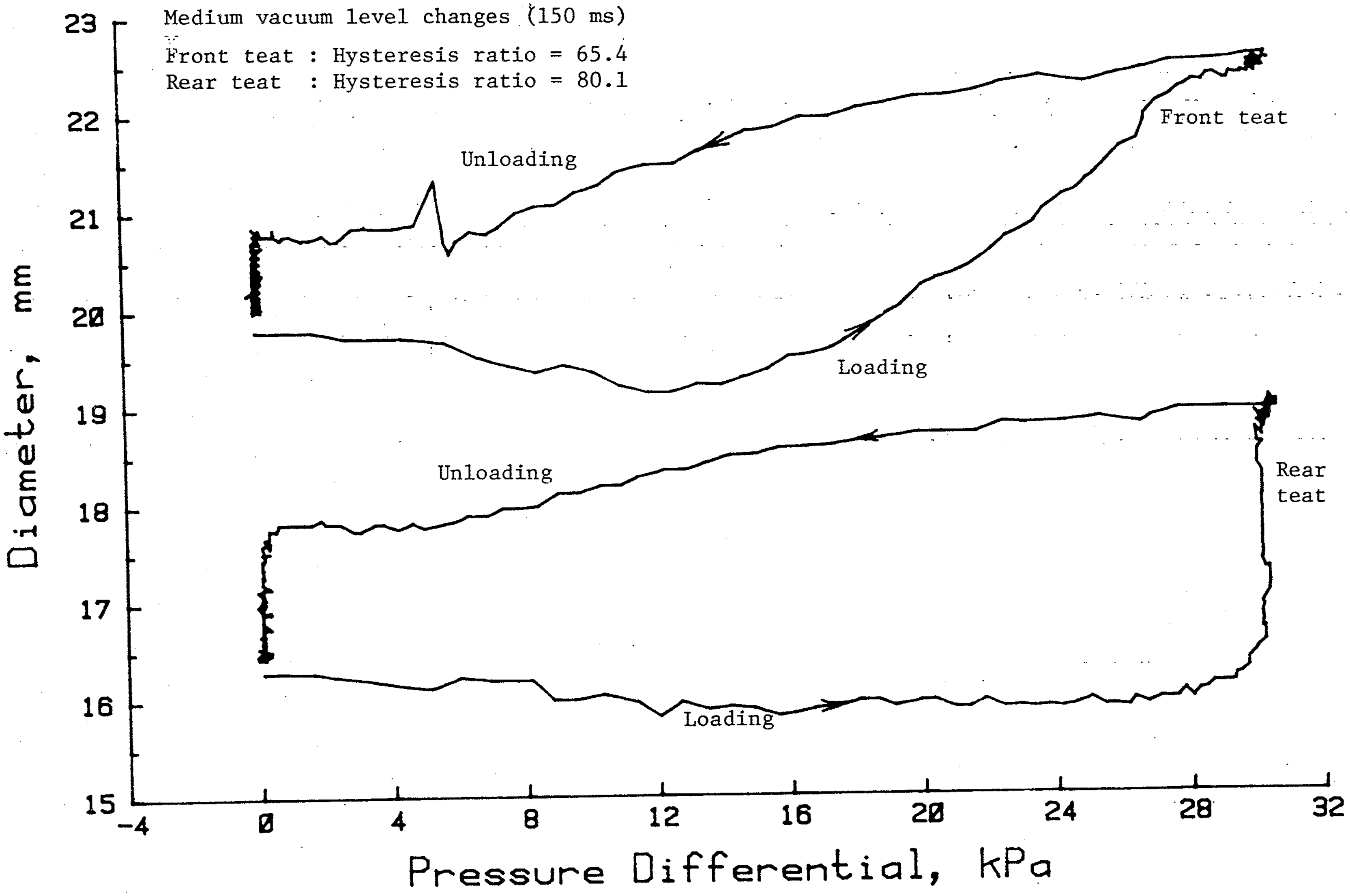

Fig.4.16. Hysteresis curves for front and rear teats of a cow.

Fig. 4.17 shows hysteresis curves of the rear teat of a cow for three different rates of vacuum level changes. Comparing the rate of loading and unloading in Fig.4.17, shows very clearly that hysteresis increases considerably with an increased rate of loading and unloading. At any given vacuum level the diameter values on the unloading curve were greater than those on the loading curve for fast and medium rate of vacuum level changes. These differences were smaller for the slow rate of vacuum level changes (300 ms rise and fall times). This behavior of teat tissue suggests that for vacuum level changes having rise and fall times of 50 and 150 ms teat end expansion starts at a higher vacuum level. At a slow rate the teat end expands smoothly which is likely safer.

Fig. 4.18 shows hysteresis curves for the front teat of a cow before and during milking. Curve B was observed before milking and curve D during milking. The longer teat delay rise time contributed to more hysteresis during milking as compared to before milking. Thiel and Mein (1979) reported that the volume of the teat remained more or less constant during a single milking but volume of the teat tissue increased as the volume of the teat sinus shrank. They reported 50% increase in the teat tissue 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 than before milking. Mein (1984) also reported a reduction of the effective cross-sectional area of the teat canal as congestion develops with time through a pulsation cycle.

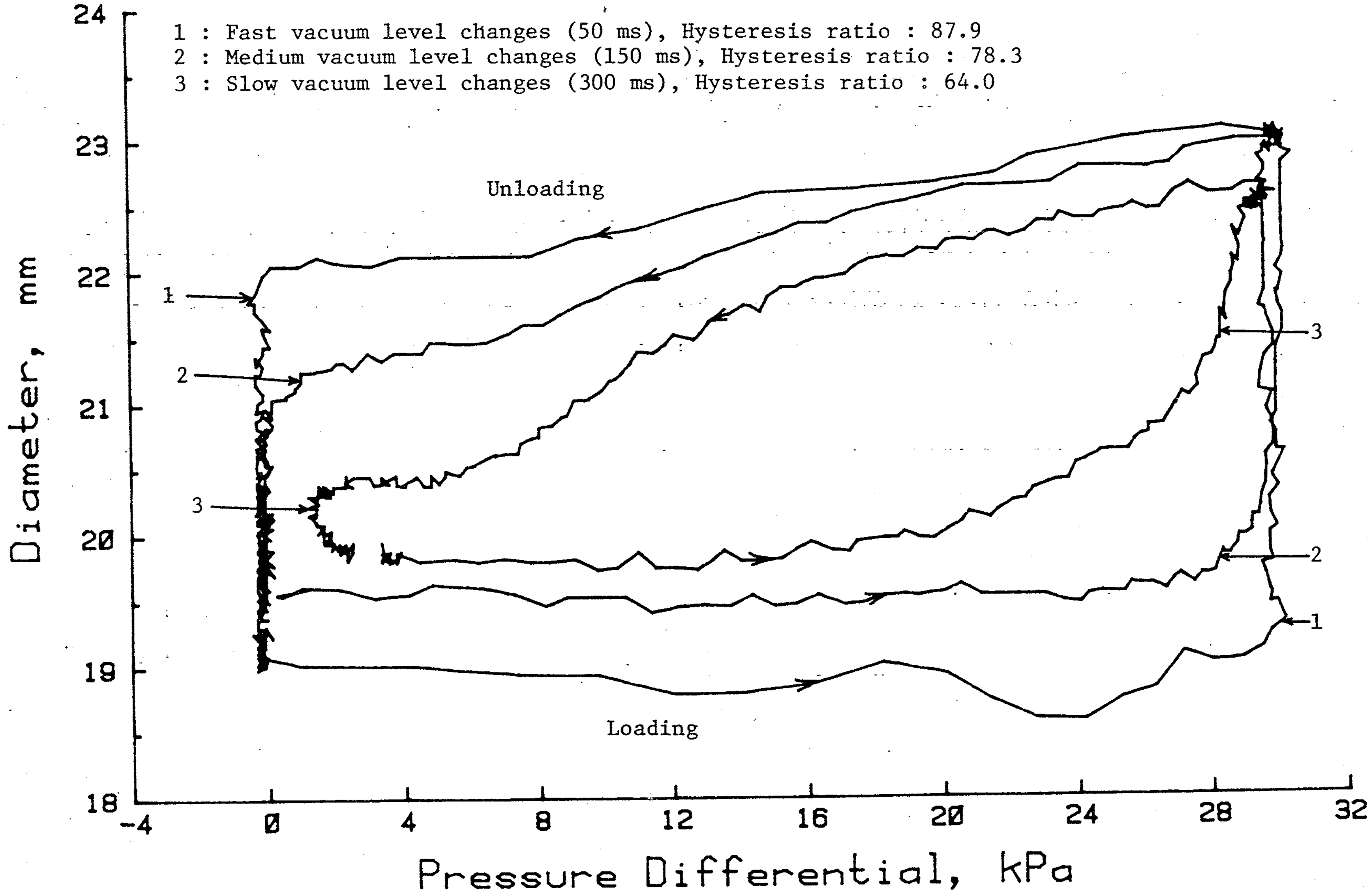

Fig.4.17. Hysteresis curves for a rear teat of a cow for three different rates of loading.

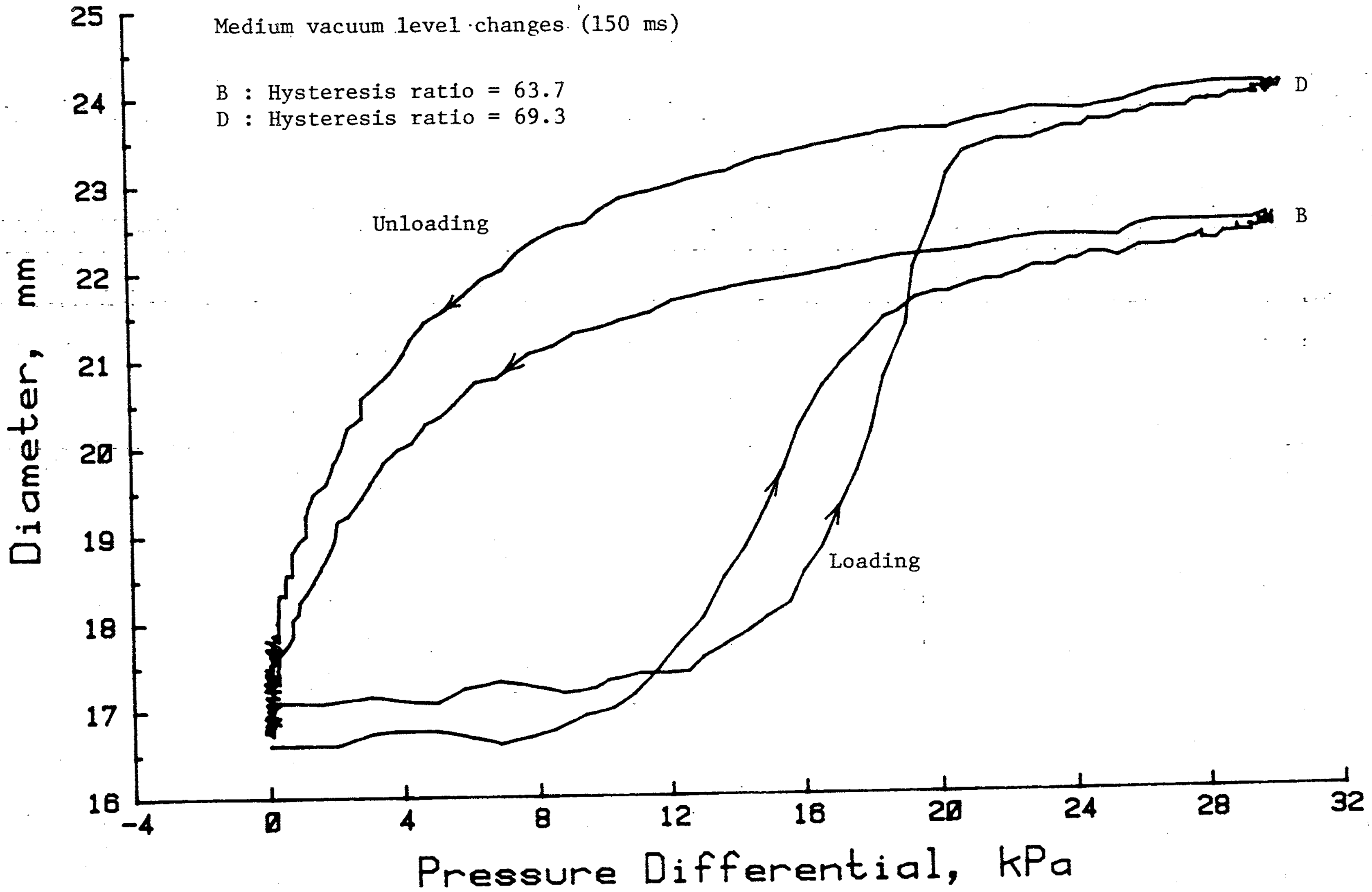

Fig.4.18. Hysteresis curves for front teat of a cow for two different times of measurements, before (B) and during (D) milking.

Greenwald et. al. (1982) reported that in conduit arteries which contain less smooth muscle (McDonald 1974; cited by Greenwald et. al. 1982), muscular activity may nevertheless produce significant changes in diameter and viscoelastic properties. The first experiment, HYSIS, showed differences in the hysteresis ratio of front and rear teats with rear teats having higher values. Perhaps this indicates more muscular activity and more smooth muscle in rear teats.

Landowne and Stacy (1957) reported several factors contributing to the hysteresis loss (energy dissipated as heat). Some depend upon the rate of forcing while others do not. Sometimes the term hysteresis is restricted to time-independent phenomena. The second experiment, RLOAD, clearly indicated more hysteresis at higher rates of loading. The third experiment, TMEAS, showed hysteresis as a time dependent phenomenon with less hysteresis before than during milking.

Chapter V

CONCLUSIONS

Based on the results of this study on hysteresis of the dairy cows' teat, the following are the major conclusions:

1. The dairy cows' teat end displays a large hysteresis ratio (58 to 84%) indicating a strong viscoelastic behavior.
2. Viscoelastic behavior of teats differs significantly between cows and between front and rear teats. Generally rear teats have a larger hysteresis ratio than front teats.
3. Hysteresis ratio depends on the rate (rise and fall times) of applying and releasing a vacuum level of 30 kPa and increases from 63 to 83% when increasing the rate (from 300 to 50 ms rise and fall times).
4. About 15 to 20% of the input energy is recovered at a fast rate of loading while about 35 to 40% is recovered at a slow rate.
5. The hysteresis ratio of the teat end is significantly more during the peak flow rate part of milking as compared to that of just before milking (73 and 69% respectively).
6. Significant differences in teat responses are mainly due to cow differences.

Chapter VI

RECOMMENDATIONS

1. To determine a possible relationship between the incidence of mastitis and teat hysteresis; because hysteresis represents energy loss and it may affect streak canal closure and therefore relate to the incidence of mastitis in dairy cows.
2. To determine the effect of different durations of the atmospheric pressure phase of each loading-unloading cycle on teat hysteresis.
3. To determine the effect of sinusoidal vacuum level changes on teat hysteresis because milk flow rate is frequency dependent.
4. To determine teat hysteresis for different vacuum levels because teat end expansion in response to a step change in vacuum level is a non-linear function of increasing vacuum level.

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