INTRAMAMMARY PRESSURE CHANGES BETWEEN MILKINGS AND DURING MECHANICAL MILKING IN THE COW

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A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Veterinary Physiology

Iowa State University
Of Science and Technology
Ames, Iowa

1965

TABLE OF CONTENTS

I. INTRODUCTION

Many people have theorized that the mechanical milking machine is related to the incidence of bovine mastitis. The most significant contribution, if any, to the incidence of mastitis is due either to the transfer of microorganisms causing mastitis, introduction of microorganisms into the udder or as a traumatic instrument causing injury to the udder of the cow. It is important to understand more fully the changes in IMP (intramammary pressure) during mechanical milking to evaluate the effect of the milking machine on the udder.

The primary objectives of this investigation were as follows:

(1) to develop a method for insertion of intramammary catheters within the teat sinus and gland sinus for measuring IMP.

(2) to measure IMP concomitantly with milking machine vacuum and to demonstrate their relationships.

(3) to measure the IMP between milkings in the absence of udder manipulations.

(4) to observe various physiological aspects of the udder during these experiments.

Several procedures were used for catheter insertion into the mammary gland. The techniques employed were believed to produce a minimal of alteration in the physiology and anatomy of the udder. Techniques for the insertion of intramammary catheters within the teat sinus and gland sinus for measuring of IMP are described. Some of the problems encountered during these procedures as well as their advantages are discussed. Results of IMP changes between milkings and during mechanical milking are presented and evaluated.

II. REVIEW OF LITERATURE

A. Development of the Milking Machine

"The judges greatly regret that there was no entry in class XIV for the best milking machine. He who successfully solves the difficulty will reap a rich reward. The want of such a machine is the one missing link in dairy management. Greater mechanical difficulties have been overcome, and we hope before many years to see the milking machine difficulty practically solved." (1) So wrote the judges in their report on the Trial of Dairy Implements at the Bristol Royal Show in 1878. The prize of 50 pounds which had been offered was offered again in 1882, with the same result. Inventors were not barren of ideas, but none were sufficiently successful to be put into practical use (41).

1. The cannulae milking machine

The earliest devices were cannulae: Blurton in 1836 patented a cannulae machine in which the pail was suspended from the cow; others followed his lead and this idea persisted for many years (41). The simple physics of the problem led to the idea of using vacuum, and two British inventors, Hodges and Brockenden, in 1851, were probably the first to use this (41). Colvin of the U.S.A. extended the idea in 1860 to include a form of teat cup (14).

2. The vacuum milking machine

The next advance in milking machine design was incorporated in the Murchland milking machine. The inventor, William Murchland, was a sanitary engineer who knew little about milking cows before designing his milking machine (29).

The Murchland milking machine used a hand operated vacuum pump which exhausted a 1-inch pipe system extending overhead around the cowshed and provided a stall cock between each pair of cows. A continuous vacuum of 280 mm Hg was applied to the teats. One boy could maintain the necessary vacuum for three girls to operate two or three units (29).

The Nicholson and Gray milking machine appeared shortly after the Murchland. It used a hand or power driven reciprocating vacuum pump connected to a pipeline laid on the floor which had a short vertical branch at each stall. The teat cups were made from cow's horns and each was fitted with a rubber mouthpiece. Continuous vacuum was maintained at 380 mm Hg but fluctuated with each stroke of the pump. The buckets were introduced for individual recording and were provided with graduations for this purpose (27). This machine won 20 pounds and a silver medal at the Doncaster Royal Show in 1891 (27).

3. The pulsator

Dr. Shields of Glasgow took out patents in 1895 and 1896 for a device which he called a "pulsator". He had formed the Thistle Mechanical Milking Machine Company and exhibited his machine at the Darlington Royal Show in 1895, thus, winning a silver medal (41). His idea was to relieve the teats of constant suction, and in fact, to develop the very feature for which the Nicholson and Gray machine had been criticized (41). A mechanically-operated valve on the vacuum pump admitted air to the pipeline with a regular frequency so that the vacuum applied to the teat varied rhythmically or pulsated between 60 and 380 mm Hg. The teat cups were made of rubber and moulded so that under the influence of the pulsating vacuum inside, and the constant atmospheric pressure outside, they squeezed the teats at pulsation frequency (42).

4. The double chambered teat cup

Alexander Gilles, a dairyman in Terang, Australia, in 1903 invented a double chambered teat cup to operate on vacuum alone (41). He applied this principle to the Lawrence-Kennedy machine which had been imported from Great Britain. The pulsator was now used to apply a squeeze to the teat by varying the pressure in the annular chamber instead of directly interrupting the vacuum applied to the teat. Thus was born the Lawrence-Kennedy-Gilles, or LKG milking machine, the first to embody all the principles of machine milking as known today.

In Britain the LKG milking machine continued to develop and another of the features of Gilles patents was introduced. This was the "Gille's Hole," through which a small quantity of air was admitted into the claw-piece or into the teat cups, to assist the movement of milk along the milk line (41).

In 25 years from the invention of the double chambered teat cup and 40 years after the Murchland came on the market, virtually all the present day principles were established. Throughout this period of development there was a continual search for the best method of use and for efficient techniques of cleaning and sterilizing, all of which had an important influence on detail design. Operating conditions of vacuum and pulsation rate, however, have always had a rather vague foundation. The early vacuum levels were probably limited by pump design and capacity (41). The guiding principle was variously stated as the rate at which the calf nurses or the rate at which the cow's heart beats; either one being quite illogical (41). It was not until 1941 that a theory on which milking could be explained was advanced by Ely and Petersen (20) and Miller and Petersen (47) in the United States. Since then research into the problems of design and use of milking machines has developed on an increasing scale.

B. Operation of the Milking Machine

1. Double action principle

With a few exceptions all modern milking machines operate on an orthodox principle which is basically that established by the LKG milker of 1903. In essence, this involves the application of a constant vacuum to the end of the teat, to draw the milk out and convey it to a suitable container, together with a periodic squeeze applied externally to the whole of the teat, to maintain blood circulation. This is known as the double action principle and is that normally used (41).

2. The three phase principle

In the U.S.S.R., where the advent of milking machines is comparatively recent, a "three phase" principle is used exclusively (41).

"Three phase" machines have a normal teat cup assembly, but the clawpiece and pulsator are modified so that the pulsation cycle consists of a release and squeeze, followed by a rest phase in which the inside of the teat cup liner and the pulsation chamber are both at atmospheric pressure. The ratio of the three phases is 45:15:40 (41). No reliable comparative evidence is available, but it appears inevitable that the rate of milking will be slower, other factors being constant (41).

3. The withdrawal of milk

It is necessary to understand clearly the nature of the term "vacuum". Sometimes the rather illogical and impractical term "negative pressure" is used, but in this connection it may be considered to mean vacuum (41). Vacuum is usually measured in terms of inches of mercury, (mm Hg in scientific field) representing the reduction of pressure below atmospheric pressure.

The milk in the udder is generally above atmospheric pressure when the teat cup is applied. The vacuum in the teat cup thus establishes a great pressure differential with respect to the teat sinus and the milk is forced out through the teat canal. The rate at which the milk is removed is dependent on vacuum, pulsation rate and ratio, diameter of the teat canal, elasticity of the teat sphincter, milk ejection, and IMP (5, 12, 16, 24, 41, 47, 51, 64).

C. Domestication and Dairying

1. The domestication of cattle

The domestication of cattle, as a source of food, was an important phase in the advancement of man's civilization. Historically, one should review domestication and dairying. Applied physiology was exhibited by the primitive people in developing the art of milking, particularly with respect to milk letdown.

Domestication was probably first achieved through a symbiotic association between man and wolf, which produced the domesticated dog. Zeuner (96) believes the controlling of the movements of goats or sheep was the next stage of domestication. He states there is archaeological evidence to show that both were domesticated much earlier than the other ruminants. The earliest goat remains date back to 9000-6600 B.C. (96).

Domestic cattle were believed to be present in Western Asia at least 3000 B.C. This evidence was based on skeletal remains. The main early source of archaeological evidence from Europe is the Swiss lake dwellings. Domesticated cattle appear with the earliest Neolithic immigrants, and recent radiocarbon dates indicate that their arrival was about 3000 B.C. (96). All domesticated true cattle are descendents of _Bos primigenius_ and of its Indian subspecies _B.p. namadicus_. Archaeological evidence suggests that the date for the beginning of domestication lies somewhere between 6000 and 4000 B.C. (96).

2. The early milking of cattle

The milk ejection reflex can be initiated under natural conditions by the act of suckling. The reflex may also be evoked by stimulation of the cervix or other parts of the utero-vaginal tract. Lastly, the milk ejection reflex can be stimulated by a conditioned reflex such as nearness of the calf or routine preparation for milking. It is a familiar fact that many cows, even today, and certainly those kept under primitive conditions, will not let down their milk unless the calf is present (11). However, the highly-bred milk cow no longer requires powerful external stimuli but may be conditioned to the mildest of environmental influences. In contrast, in living primitive societies, instances are encountered where the animals appear to require some intense form of stimulation before the milk is released, and pastoral peoples seem to be aware of a whole range of circumstances whereby milk ejection may be evoked, and to which supernatural powers are sometimes allied (96).

It will suffice here to give two extreme examples of eliciting milk ejection for the purpose of obtaining milk. Many primitive tribes took advantage of the animal's physiology and behavior to accomplish this without the aid of magical powers. The Tibetans, for example, maintain that their (Yak) cows can only be milked out after the calves have begun to suckle, and the same opinion appears to be held by many pastoral tribes in Africa and India (11).

An element of magic, however, is seen in the practices of the Waniaturu tribes which are described by Sick (69). "If a cow refuses to be milked, a witch doctor (the mbohangombe) brews a secret concoction with which he smears the hind quarters of the animal around the vulva. There upon, he takes some of the brew in his mouth and holding the lips of the vulva wide apart, blows it vigorously into the vagina. The cow, reacting to these interventions, arches her back and urinates in his face, a circumstance which appears to be of little consequence to the operator. At the same time, the witch doctor drapes a calf's skin over a small boy who has been smeared previously with the concoction and places him before the cow; the animal smells the pelt, licks it and soon submits quietly to the milking routine. Indeed, so accustomed may the cow become to the presence of the child, that she will become restless and bellow loudly if the substitute is not at hand."

D. Anatomy of the Udder

1. Structure of the udder

The udder of the mature cow normally consists of four functional glands and weighs 25 to 60 pounds (exclusive of milk). Variations in size are due to heredity, age, stage of lactation, and amount of secretory and connective tissue. The udder is distinctly divided into right and left halves. While the front and rear quarters are not visibly separated, they are distinct on the basis of milk drainage routes (71).

The interior of the gland has a porous, spongy appearance due to the great number of milk collecting ducts, blood vessels, and lymphatic vessels. The ratio of the secretory tissue to the ductile tissue varies considerably. The secretory tissue consists of many lobules of alveoli served by collecting ducts which empty into the gland sinus (lactiferous sinus) and teat sinus. The alveoli consist of three layers: (1) the basement membrane consisting of thin connective tissue cells, (2) the myoepithelial layer, basket cell type, and (3) the secreting layer of columnar and cuboidal cells.

It is estimated that approximately 40% of the total mammary secretion is stored in natural spaces and the additional 60% is stored by stretching of the udder (71). This elasticity of the udder prevents true measurement of milk secretion rate by either pressure or enlargement of the udder. However, udder capacity estimates as affected by the rate of milk secretion have been studied. Tucker (78) reports that with increased milking intervals the total pounds of milk increased asymptotically. The estimated theoretical udder capacities for five groups of animals in this study were 42.4, 49.9, 55.8, 51.3 and 63.2 pounds of milk, respectively. Milk secretion was estimated to approach zero after 35 hours post milking.

Electron microscopy studies of the three phases of udder glandular activity (proliferation, colostrum formation and lactation) are temporarily well defined during bovine gestation and lactation (23). In early and mid-gestation, proliferation of glandular epithelium is predominant, and secretory activity is minimal. During the colostrum-forming phase, transport of large quantities of serum gamma globulin to the secretion is characteristic. After calving, synthesis of protein and fat is the major feature of lactation (23).

Richardson (67) states that myoepithelial cells are present throughout the mammary tissue and surround the alveoli and smaller ducts. Linzell (36) observed, microscopically, contraction of the myoepithelial cells in mouse mammary tissue. The myoepithelial cells are referred to as the effector organs in milk ejection. Smooth muscle is scattered in interlobular bundles closely associated with the blood vessels (67). However, smooth muscle is not significant in milk ejection from the alveoli.

Each gland has but one true sphincter which is located at the distal end of the teat (71). The canal through this sphincter is from 8 to 15 millimeters long and is known as the papillary duct, lactiferous duct, streak (strich) canal, or teat canal. The teat sphincter normally closes the teat canal to facilitate milk retention. The efficiency of this sphincter is dependent on four integral components. These are (1) elastic connective tissue, (2) smooth muscle, (3) desquamated epithelium within the teat canal, and (4) loose folds of mucous membrane (Furstenberg's rosette) at the proximal end of the teat canal (64).

2. Blood supply of the udder

The blood supply of the udder is very extensive. The abdominal aorta bifurcates to form the paired internal and external iliac arteries. The external pudic artery, a continuation of the external iliac artery, is the major arterial blood supply to the udder. This artery subdivides into many branches to supply the udder. The internal pudic artery, a continuation of the internal iliac, supplies the perineal artery. The perineal artery subdivides and supplies the dorso-caudal aspects of the udder (71, 73). In addition, Linzell (39) has shown that the perineal vein has small semilunar valves which direct the blood flow into the udder.

The venous effluent from the udder has three routes of return: (1) the external pudic veins, (2) the subcutaneous abdominal veins and (3) the lateral surface veins which anastomose with the saphenous vein of the thigh. The presence of the latter route is inconsistent (73).

The arteries and veins of the udder have very extensive anastomoses with their respective components. Swett (73) found that 74% of 157 veins anastomosed on the right side of the udder and 69% of 144 veins anastomosed on the left side of the udder. Swett also reported 12 arterial anastomoses on the left, 15 arterial anastomoses on the right, and 12 transmedian arterial anastomoses in the bovine udder.

3. Nerve supply of the udder

The nerve supply to the udder consists of sensory and sympathetic fibers. St. Clair (68) concluded there was no parasympathetic nerve supply to the mammary gland of the cow since no ganglia were found in the udder.

Recent investigations have entirely failed to substantiate the existence of parasympathetic endings in the mammary glands (34, 35). The sensory nerves are: (1) the inguinal nerve consisting of ventral branches from lumbar spinal nerves 2, 3 and 4, (2) ventral branches of the first 2 lumbar spinal nerves, and (3) the perineal nerve, a branch of the pudic nerve, consisting of fibers from the sacral spinal nerves 2, 3 and 4. Sympathetic innervation of the udder from the mesenteric plexus is incorporated in the nerve trunk of the inguinal nerve (71).

E. Hormonal Control of Milk Ejection

The hormones oxytocin, vasopressin, epinephrine (adrenalin) and norepinephrine (noradrenalin) essentially control milk ejection. Oxytocin and epinephrine play the major role, while vasopressin and norepinephrine are relatively unimportant. Oxytocin enhances milk ejection while epinephrine inhibits this phenomenon.

1. Oxytocin and vasopressin

Oxytocin is an octapeptide, containing eight different amino acids, three being present as amides. All of the amino acids have the L-configuration. Oxytocin isolated from human, beef, hog, and horse pituitaries has the same amino acid composition. The molecular weight of oxytocin is 1,007 (79).

The pituitary gland consists of an adenohypophysis and a neurohypophysis. The neurohypophysis, in particular the neural lobe, which stores oxytocin and vasopressin (antidiuretic hormone) is directly related to milk ejection. The present concept indicates that oxytocin and vasopressin are neurosecretory products which arise in the paired supraoptic and paraventricular nuclei of the hypothalamus. Estimations of the hormone content in the separated supraoptic and paraventricular nuclei of sheep gave the following results: (1) the supraoptic nuclei contained more vasopressin than oxytocin (V:O = 3.3 ± 0.57) and (2) the paraventricular nuclei contained more oxytocin than vasopressin (V:O = 0.66 ± 0.08) (33). In most experiments irrespective of the stimulus employed, the neural lobe released both hormones simultaneously and oxytocin was liberated in much greater quantities than vasopressin (79). However, Theobold (76) concluded from experiments at parturition in the human that oxytocin and vasopressin can be released independently of each other. The oxytocin to vasopressin ratio varied from 4:1 to 100:1. Oxytocin is 5 to 12 times as potent as vasopressin in its oxytocin effect and it appears to have little pressor and antidiuretic effect (18).

Oxytocin has three important functions: (1) to increase uterine contractions, (2) a direct effect on secretory activity and retardation of mammary gland involution, and (3) mediation of milk ejection during milking; the latter effect being essential for complete milking (9, 79).

The initiation of oxytocin release may result from a direct stimulus to the udder and teats or from a conditioned reflex such as feeding at milking time. Oxytocin is released into the blood stream and transported to the mammary gland. Oxytocin then acts upon the myoepithelial cells of the alveoli and adjacent ducts which contract and expel the milk into the collecting ducts for removal (37).

2. Epinephrine and norepinephrine

Epinephrine is a secondary alcohol; the full chemical name is 3,4-dihydroxy-α-phenyl-β-methylaminoethanol. The natural levorotatory form is 15 times more powerful than the dextrorotatory form (8).

The cells of the adrenal medulla elaborate epinephrine and norepinephrine. These hormones are often referred to as the catechol amines. The two hormones are very similar in chemical properties, but the presence of an additional methyl group in epinephrine changes the side chain from a primary amine, norepinephrine, to a secondary amine, epinephrine (79).

The neural stimulus for the discharge of adrenal medullary hormones is acetylcholine, which is liberated by the splanchnic nerve terminals that come in contact with the medullary cells (79). Stimulation of a particular area of the hypothalamus causes mainly epinephrine to appear in the adrenal venous blood; stimulation of another area promotes the appearance of norepinephrine in the venous effluent. These observations indicate that epinephrine and norepinephrine may be released separately by the adrenal medulla and support the concept that the hormones arise from different types of medullary cells.

Epinephrine and norepinephrine are also released as neurohormones by most postganglionic sympathetic nerve endings. The great mass of evidence indicates that norepinephrine is the neurotransmitter at these nerve endings (79).

While these two hormones are similar in many biological respects there are important differences in the nature and degree of their effects. Both hormones increase the heart rate, although epinephrine is more potent in this respect. Both increase systolic blood pressure, whereas only norepinephrine increases diastolic pressure. The hypertensive effect of norepinephrine is a consequence of increased peripheral resistance by vasoconstriction, whereas epinephrine increases the cardiac output (79). It is important to note that in man epinephrine may cause an anxiety state, while norepinephrine does not. However, anticipatory states tend to elevate the release of norepinephrine, and in intense emotional reactions both hormones are elevated.

F. Milk Ejection During Milking

Russian scientists recognize two different mechanisms of milk ejection, reflex milk ejection, and oxytocin stimulated milk ejection. Western scientists adhere only to the latter concept of milk ejection. The discussion here will dwell on these mechanisms of milk ejection with this controversial point in mind. Milk ejection may then be classified as: (1) reflex milk ejection, (2) first oxytocic milk ejection, and (3) second oxytocic milk ejection. Milk ejection can occur without milk removal from the udder. The parameters for measurement of milk ejection in the cow are intramammary pressure and to some extent, milk flow rates.

1. Reflex milk ejection

The reflex milk ejection mechanism appears to consist of a simple reflex arc. The afferent stimuli may consist of manipulation of the teats and udder or a conditioned reflex associated with milking. The effectors of this reflex arc are the smooth muscle fibers of the teats, parenchymatous tissue and larger ducts. The most important smooth muscle fibers concerned with reflex milk ejection surround the larger ducts. Relaxation of these fibers allows milk in the larger ducts to discharge into the gland sinus (95). However, the greatest portion of the milk is retained in the alveoli awaiting the milk ejection response elicited by oxytocin. Reflex milk ejection occurs in the first 10 to 15 seconds after stimulation.

2. Oxytocic milk ejection

The first oxytocic milk ejection usually occurs within one or two minutes after stimulation of the udder by washing with warm water or massaging. Following initial stimulation, the central nervous system releases oxytocin from the neurohypophysis into the blood stream. Oxytocin is then transported to the mammary gland where it causes contraction of the myoepithelial cells and subsequent milk ejection.

The second oxytocic milk ejection follows the same general pattern as the first. Terminal milking constitutes an additional stimulus for release of more oxytocin and hence a repetition of the first milk ejection. The latter phase of milk ejection usually occurs within 4 to 7 minutes after milking commences. However, in a fast milking cow the second release of oxytocin may fail to occur before milking is completed and may not be essential for complete milking.

Milk ejection may be interrupted by a painful stimulus, sudden movement or loud noise. A painful stimulus to the teat does not interfere with milk ejection as readily as a painful stimulus elsewhere. The interruption of milk ejection is presumably brought about by a direct central nervous system inhibition or by the action of epinephrine. Milk flow related to reflex milk ejection was stopped by stimulation of the peripheral end of the external spermatic (inguinal) nerve. Milk flow during oxytocic milk ejection was slowed under these conditions (95). This probably resulted from stimulation of the sympathetic fibers incorporated in the external spermatic nerve.

There has been considerable controversy in the past as to whether an interruption of milk ejection can occur during milking. Linzell (36), upon microscopic examination of living mammary tissue, observed that epinephrine administered intravenously antagonized the action of oxytocin. He also observed that stimulation of the sympathetic nerves of the gland had a similar action. Neither epinephrine nor norepinephrine inhibits the myoepithelium itself when oxytocin is applied topically at the height of vasoconstriction. The peripheral inhibitory action of sympathetic-adrenal activity on milk ejection in the whole animal is most likely due to an intense vasoconstriction preventing adequate access of oxytocin to the myoepithelium (36). The mammary gland blood vessels are very sensitive to epinephrine and norepinephrine (28) and stimulation of the sympathetic nerves can temporarily stop mammary blood flow (56).

The effect of epinephrine on oxytocic milk ejection in the lactating sow has also been examined. Both the duration of ejection and the change in intramammary pressure were used to measure the responses produced. The effects of 0.5 I.U. of oxytocin were suppressed by 200 μg of epinephrine injected just before the oxytocin. Inhibitory action decreased as the period between the injections increased. Two minutes after epinephrine injection the oxytocin response was normal (82). The results obtained by Whittlestone (82) are compatible with the view that epinephrine induced vasoconstriction interferes with the access of oxytocin to the mammary myoepithelium.

Inhibition of oxytocin release by the cerebral cortex during stressful stimuli can also prevent milk ejection (74). While painful stimuli prevented oxytocin release, topical application of 25% KCl, in order to induce cortical spreading depression, caused the disappearance of the inhibition of oxytocin release (74). Partial milk ejection may be induced by short periods of udder stimulation (44). Oxytocin appears to be necessary for milk ejection and thus a normal lactation (46).

G. Intramammary Pressure Changes (IMP)

1. Changes affecting secretion

Milk secretion continues at a normal rate until the intra-alveolar pressure increases to approximately 25 or 30 mm Hg. Thereafter the secretion rate is partially or totally inhibited. Petersen and Rigor (61) concluded from a series of experiments that as pressure increased toward 25 mm Hg, secretion and resorption rates reached a state of equilibrium.

There is no direct linear relationship between udder filling and IMP (80). Turner (80) found that early in lactation the pressure at which milk secretion was suppressed was much higher than at later stages of lactation. In one cow secretion was not affected by 15 mm Hg pressure early in lactation, but was greatly depressed when the pressure reached 30 mm Hg. At the close of lactation, milk secretion was virtually stopped by 15 mm Hg pressure.

2. Changes between milkings

The measurement of IMP between milkings has been studied. In 1926 Tgetgel (75) reported an increase in IMP between milkings. In one cow IMP just after milking was 1 mm Hg and increased to 20 mm Hg 11 hours after milking. IMP before milk ejection was measured in 10 cows and a maximum range of 15.1 to 37.0 mm Hg was found, while the milk yields per milking varied from 6.8 to 17.0 pounds. Smith (71) stated there was no measurable increase in IMP the first hour following milking and thereafter the IMP gradually increased until the next milking. This was probably due to the hydrostatic effect of the accumulated milk in the larger milk ducts and sinuses. Smith further stated that IMP will vary with the shape and quality of the udder and the production of the cow.

Tucker *et al.* (78) measured IMP between milkings and reported 18 to 51 mm Hg before stimulation with total milk yields between 18 and 43 pounds. These measurements were taken with the aid of a manometer, rubber tubing, and a teat cannula. Korkman (31), using a similar apparatus, measured IMP just after milking. In five cows the IMP varied from 0 to 5 mm Hg. Within one hour it reached an average of 8.1 mm Hg which remained constant for the next two hours; after the third hour, IMP increased rapidly. Korkman stated that udder manipulations connected with teat cannula insertion may result in some milk ejection and, therefore, a high IMP reading. Mielke (44) reported a slight rise in IMP within 40 to 120 seconds after teat cannula insertion and a second rise when the udder was stimulated further. Kitts *et al.* (30), using electronic recording devices, measured IMP on twelve lactating cows. These cows produced between 20 and

75 pounds of milk per day. IMP immediately after complete milking varied from 2 to 13 mm Hg. Prior to the next milking and before udder stimulation, IMP varied from 9 to 29 mm Hg.

3. Changes during milking

Zaks (95) reported that IMP decreased at the onset of udder stimulation. It was assumed that the decrease in pressure resulted from relaxation of specific mammary gland tissues preparatory to receiving milk during milk ejection.

Whittlestone (83) showed that first-milk-ejection pressures were between 30 and 40 mm Hg. After the milk was drained (via cannula), additional massage and stimulation caused a second milk ejection associated with a small rise and fall in pressure. The second pressure increase was between 15 and 30 mm Hg, which was considerably lower than the first.

The increase in IMP following milk ejection and a subsequent decrease in pressure with milk removal have been reported by several workers (30, 63, 71). However, the changes in IMP that occur in the bovine udder during mechanical milking are not clearly understood.

Reports on mechanical milking of the excised bovine udder have shown the development of vacuum within the teat and gland sinuses after milk removal. Vacuum levels within the teat sinus were equal to those of the milk line and were assumed to result from an extension of the milk line vacuum (59, 63). Other workers found no conclusive evidence for vacuum extension into the udder since it was believed that the teat sphincter did not open except during milk removal (41).

In summary, the IMP changes during mechanical milking have been reported to have four characteristic phases: (1) a decrease in pressure due to relaxation of the mammary gland tissue, (2) an increase in pressure (30 to 40 mm Hg) due to the first milk ejection, (3) a later increase in pressure (15 to 30 mm Hg) due to the second milk ejection, and (4) in some instances a vacuum, similar to the vacuum within the inflation, after cessation of milk flow.

III. EXPERIMENTAL PROCEDURES

A. Materials and Methods

1. Experimental animals

Eight Holstein cows, four in first lactation, three in third lactation and one in the seventh lactation, were used for IMP studies during mechanical milking. Eleven lactating Holstein cows varying in age, stage of lactation and production were used for IMP studies between milking (Table 1). Three lactating Holstein cows were used to study teat sphincter contractions.

2. Surgical procedures for catheterization of the teat and gland sinuses

Two different catheterization procedures were used to facilitate pressure measurements from the teat and gland sinuses. Surgical installation of catheters was conducted under general anesthesia. The first procedure consisted of two flanged polyvinyl[1] catheters (o.d. 0.080 inch, i.d. 0.054 inch, Figure 1a) which were surgically placed in the teat and gland sinuses. Placement was accomplished by carefully passing a needle (0.10 inch x 12 inch) through the teat canal, teat sinus, gland sinus, and then to the exterior through the wall of the udder. After the catheter was passed upward through the needle, the latter was removed through the wall of the udder. The catheter was drawn into the udder until the flange contacted the inner wall of the gland sinus (Figure 2). The catheter was anchored to the skin with nylon suture.

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[1] Vinyl (Medical grade), Becton, Dickinson & Company, Rutherford, New Jersey.

In the second procedure, a polyvinyl[1] "insertion cannula" (o.d. 0.375 inch, i.d. 0.250 inch, Figure 1d) was placed through the lateral wall of the udder into the gland sinus. Placement of the "insertion cannula" was accomplished by passing a large metal trocar and cannula (Figure 1c) through the gland sinus wall. The trocar was removed and the "insertion cannula" was passed through the metal cannula; the latter was then removed. The "insertion cannula" was anchored to the subcutaneous fascia and skin with nylon suture. This cannula permitted passage of polyvinyl recording catheters (o.d. 0.080 inch, i.d. 0.054 inch, Figure 1b) into the teat and gland sinuses for recording. The recording catheters were "fixed" in a rubber stopper (Figure 1b) and inserted as a unit through the "insertion cannula" (Figure 3). A rubber stopper was used to occlude the cannula between recordings. Placement of the catheters was verified by radiography or palpation.

A modification of the insertion cannula was adopted in the latter experiments in which the cannula was made from gum rubber tubing[2] (o.d. 0.375 inch, i.d. 0.250 inch, Figure 4a). Two rubber flanges (dia. 1 inch) were vulcanized[3] 0.5 inch apart on rubber tubing (o.d. 0.50 inch, i.d. 0.375 inch) to form a "keeper" (Figure 4b). Surgical placement of the insertion cannula was accomplished in the following manner: an incision was made at the base of the teat to allow passage of a gloved finger and a

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[1] Nalgon tubing, Nalge Company, Inc., Rochester, New York.

[2] Rubber tubing, Davol Rubber Company, Providence, Rhode Island.

[3] Vulcanized in an oven at 140° C for 1 hour.

large needle (Figure 4c). The surgeon probed the large collecting ducts and passed the needle upward through the large collecting duct and exteriorized the needle through the wall of the udder. The rubber insertion cannula was attached to the needle and pulled into place. The "keeper" was placed over the insertion cannula and anchored to the skin with nylon suture (Figure 5). The rubber insertion cannula and keeper were siliconized[1] to reduce tissue reaction.

Local and systemic antibiotics were administered for three days post-operatively following major surgical procedures as described above. Further intramammary infusion with antibiotics was employed when necessary.

In four experiments the teat canal was occluded with a purse string suture (0.30 mm nylon), 8 mm above the end of the teat; this was accomplished under local anesthesia. Teat canal ligation prevented milk vacuum extension into the teat sinus. Thus, the effect of inflation collapse and dilation upon teat sinus pressure could be evaluated.

3. Cannulation procedure for continuous recording between milkings

Cannulae 36 inches long were made from polyethylene tubing[2] (o.d. .067 inch, i.d. .047 inch) by forming a small retainer ring one inch from the tip. The tip was sealed and several small holes were drilled near the tip. This cannula thus served as a teat cannula and a connecting tube to the pressure transducer (Figure 6). The cannulae were water filled to provide a hydraulic system for pressure measurements.

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[1] Siliclad, Clay Adams, Inc., New York 10, New York.

[2] Intramedic, Clay Adams, Inc., New York 10, New York.

4. Microballoons for measuring teat sphincter contractions

Microballoons were made from polyethylene tubing (o.d. .048 inch, i.d. .030 inch) by heating and carefully blowing to form a small bubble in the tubing. The balloons were then liquid filled and sealed at one end. A small flange was formed on the sealed end to hold the microballoons in place during recording. Insertion of the microballoons was accomplished by using small alligator forceps.

5. Recording systems and milking equipment

Recording equipment consisted of a direct writing recorder,[1] pressure transducers,[2] and a low level junction box.[3] Transducers were placed at the same height as the base of the teats for recording from intramammary catheters. Transducers were connected to the intramammary catheters and the milking machine by polyvinyl tubing (o.d. 0.080 inch, i.d. 0.054 inch, length 48 inches). A pneumatic system (recording site to transducers) was used in preference to a hydraulic system, the latter caused excessive reverberations, for recording during mechanical milking.

The dynamic response characteristics of different size and length of polyethylene tubing were determined with air and fluid-filled systems. The input wave for testing was from the pulsator line of the milking machine. The milking machine was operated at 50 cycles/minute and a pulsator ratio of 50:50.

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[1] Model 350, Sanborn Company, Waltham, Massachusetts.

[2] Model 267 B, Sanborn Company, Waltham, Massachusetts.

[3] Sanborn Company, Waltham, Massachusetts.

A magnetic floor type milking machine[1] (pulsator ratio 50:50) equipped with molded narrow bore natural rubber inflations[2] was used throughout this study except for quarter milking. A quarter milk collecting system[3] replaced the standard milk collecting system during quarter milking (Figure 7). The milking machine vacuum was maintained at 250, 312, 400 or 500 mm Hg for different experiments and it was measured from the pulsator line and milk line (Figure 2).

B. Results

1. Dynamic response characteristics of polyethylene tubing

The dynamic response characteristics of polyethylene tubing to an input wave were nearly identical for all sizes and length studied (Figures 8 and 9).

The rise time varied with different sizes and lengths of tubing, but was not consistent with respect to tubing size or length (Table 2). There were more reverberations noted in the fluid filled system. The smaller and longer tubing appeared to attenuate these reverberations.

2. IMP changes during mechanical milking

a. Milking machine vacuum maintained at 312 mm Hg Twenty-four recordings were obtained from 12 different quarters of five cows milked at 312 mm Hg vacuum. All pressures are reported as the range observed from

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[1] DeLaval Separator Company, Poughkeepsie, New York.

[2] 05, DeLaval Separator Company, Poughkeepsie, New York.

[3] Quarter milking unit designed by Dr. J. S. McDonald and built at the National Animal Disease Laboratory, Ames, Iowa.

these 24 recordings. IMP prior to milk letdown were negligible (0 to 8 mm Hg). Washing the udder stimulated milk letdown within 20 to 90 seconds and resulted in an increased pressure (35 to 55 mm Hg). Pressures within the gland and teat sinuses were similar when both contained milk. The pressure decreased during milking; near the end of milk flow a slight vacuum developed within the udder (0 to 5 mm Hg).

When milk flow ended, teat sinus vacuum abruptly increased to a maximum with each inflation dilution (216 to 312 mm Hg). A residual teat sinus vacuum (48 to 120 mm Hg) persisted after inflation collapse (Figure 10 a,b) and could be varied by pulling down or pushing up on the teat cup (Figure 10 c). The vacuum within the gland sinus (8 to 35 mm Hg) resulted in a visible collapse of the sinus wall above the base of the teat.

After milk removal the teat canal was ligated. The teat cup was replaced on the teat and machine milking continued. Under these conditions the following changes were noted (Figure 10 d): (1) during normal teat cup suspension, teat sinus vacuum pulsated from 0 to 200 mm Hg, (2) pushing up on the teat cup resulted in a positive pressure of 30 mm Hg after inflation collapse, and (3) conversely, pulling down on the teat cup resulted in a residual vacuum of 30 mm Hg.

In repeated experiments similar results were obtained with recording or flanged intramammary catheters.

b. <u>Milking machine vacuum maintained at 250, 312, 400 and 500 mm Hg</u> Following the initial IMP studies at 312 mm Hg vacuum further experimentation was conducted at vacuums of 250, 312, 400, and 500 mm Hg vacuum. The same general trends were observed with the residual vacuum and peak vacuum levels varying in accordance with the vacuum applied. The average values are shown (Table 3).

3. IMP changes between milkings in the cow

The IMP immediately after milking and teat cannulation varied from 0 to 15 mm Hg. Apparently manipulation and cannulation of the teats resulted in partial milk ejection. The IMP could then be adjusted to less than 8 mm Hg by the removal of 30 to 200 ml of milk via the teat cannula.

The daily production of the cows in this study ranged from 20 to 83.3 pounds. The data showed a gradual increase in IMP over the entire recording period. An average of the quarter IMP for 12 hours is shown (Figure 11). In 9 of 11 cows the IMP did not exceed 12 mm Hg 12 hours after milking.

Two cows showing the highest IMP had 13 to 18 and 10 to 22 mm Hg at 12 hours with a total milk yield of 48.1 and 36.3 pounds, respectively (Table 4). The IMP showed the greatest increase between 10 and 12 hours after milking. The cow that showed the lowest IMP had 6 to 8 mm Hg with a total production of 31.9 pounds. Thus, the IMP recorded between milkings was not entirely dependent on milk production as evidenced by the variation in milk production without a proportional change in IMP.

The relationship between quarter milk production and IMP after udder stimulation (washing) was varied (Figure 12). The correlation between quarter milk production and IMP after stimulation was as follows:

Condition	Correlation
Total - no correction for cow or quarter	0.585
Right front quarter	0.429
Left front quarter	0.246
Right rear quarter	0.638
Left rear quarter	0.730

4. Teat contractions during continuous IMP recordings

During the continuous recording of IMP between milkings teat contractions were evident in three of the eleven cows. The number of teats contracting varied from one to three on each cow with the contractions persisting throughout most of the recording period. An example of the record during teat contractions is shown (Figure 13).

During udder stimulation and prior to milk ejection a sharp decrease in IMP was noted in two cows. This period of udder relaxation persisted for a very short time and was followed by normal milk ejection (Figure 14).

5. Teat sphincter contractions

During one experiment the milking machine was stopped, but the teat cups were left on the teats to observe the teat and gland sinus vacuum as it gradually returned to zero. During the slow decline in vacuum, small periodic changes were noted in the teat sinus vacuum. One would suppose a teat sphincter contraction as a possible mechanism for the altered vacuum changes. This cow which possibly showed teat sphincter contractions also exhibited estrus on the day of recording IMP changes during milking.

Subsequently, teat sphincter contractions were recorded in the bovine during the estrus period and within 36 hours following diethylstilbesterol administration (75 mg, im). These contractions did not occur during the anestrous period. Simultaneous electromyograms were also obtained from the teat sphincter area (Figure 15).

The recordings showed the occurrence of a rhythmic contraction of the teat sphincter every 15 to 40 seconds during its active phase. Pressure of contractions varied from 10 to 30 mm Hg. Spontaneous teat sphincter contractions occurred after an external stimulus (loud noise, person entering the room) during the active phase. Epinephrine (iv) by infusion abolished the teat sphincter contractions for 13 minutes (Figure 16). Thereafter, the contractions slowly returned to their previous rate.

C. Discussion

1. Dynamic response characteristics of recording system

The dynamic response characteristics of polyethylene tubing in the system tested and utilized in this series of experiments show that tubing 48 inches long with an inside diameter of 0.034 inch would reproduce the experimental events satisfactorily. There was minimal waveform distortion with tubing 2 inches and 48 inches long and 0.115 inch and 0.034 inch inside diameter. The fluid filled system presented excessive reverberations with the longer lengths of tubing tested.

The rise time varied by 38 msec, but was not dependent on tubing size or length but varied according to the variability of the pulse generator (pulsator). The fastest rise time recorded was 12.8 msec (Table 2). The rise time of the recorder galvanometer and driver amplifier was 5 msec;[1] thus the high frequency response of the recorder was adequate to reproduce the event. From these data a maximum tubing length of 48 inches with an internal diameter of .047 inch or larger was selected for recording the highest frequency events.

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[1] Specifications, Sanborn Company, Waltham, Massachusetts.

2. IMP changes during mechanical milking

a. Milking machine vacuum maintained at 312 mm Hg IMP were low prior to milk letdown. These pressures were measured from cows with indwelling flanged catheters or recording catheters left in the udder between milkings. This permitted IMP measurements before teat and udder manipulations and subsequent milk letdown. Therefore, intramammary pressures of 0 to 8 mm Hg may be more indicative of the pressure prior to udder stimulation and milk letdown than an average of 20 to 30 mm Hg usually reported (30, 31, 75). The decline in IMP during milking was similar to that observed by Whittlestone (83).

After milk flow ceased, records of pulsator and teat sinus vacuum changes were similar, although the vacuum level was usually less within the teat sinus. One might assume that the vacuum changes within the teat sinus, corresponding to the pulsator line vacuum changes, were due to extension of milk line vacuum through the teat canal when the inflation was expanded. However, this is only one factor in teat sinus vacuum changes. After milk removal and ligation of the teat canal, pressure changes within the teat sinus were different from those seen with a patent teat canal. The following differences were noted: (1) during routine teat cup suspension, the vacuum change with each pulsation was not as great; (2) vacuum returned to zero with each pulsation (*i.e.*, no residual vacuum remained); (3) decreased tension (pushing upward) on the teat cup resulted in a positive pressure after inflation collapse; and (4) increased tension (pulling down) on the teat cup resulted in a residual vacuum in the teat sinus.

These results indicate that vacuum changes within the teat sinus during mechanical milking result from two factors: (1) dilation and collapse of the teat sinus and inflation concomitantly, and (2) extension of milk line vacuum through the teat canal into the teat sinus during inflation dilation. The author believes that the gland sinus does not exhibit marked vacuum changes because of annular ring closure at the end of milk flow.

Increased residual vacuum caused by increasing the tension on the teat cup during machine stripping may result in greater teat damage. Peterson[1] (62) observed extensive mucosal hemorrhages in the teat sinus of most teats when they were subjected to prolonged machine stripping with increased tension on the teat cups. Little injury was noted from prolonged machine stripping if the teat cups were pushed upward. Extensive mucosal hemorrhages were probably due to an increased residual and total vacuum within the teat sinus caused by increasing the tension on the teat cup as well as overmilking.

Residual teat sinus vacuum may be relieved after teat cup removal through equilibration with the gland sinus or through the teat canal. Vacuum may be partially relieved when the weight of the cluster is removed from the teat and the tissues return to their normal position. If the vacuum is relieved via the teat canal, the possibility exists for aspiration of microorganisms into the teat sinus. Many factors account for the introduction of microorganisms into the bovine mammary gland via the teat

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[1] Peterson, K. J., Department of Veterinary Medicine, Oregon Agr. Exp. Station, Corvallis, Oregon. Udder injury associated with overmilking. Private communication. 1964.

canal. Vacuum created within the udder by the milking machine, when coupled with other factors, may be quite important in the development of udder infections.

These studies are in agreement with the observations of Petersen (59) and Pier et al. (63) in regard to IMP changes in the bovine udder during mechanical milking. In addition, from our observations the following conclusions are made: (1) after the end of milk flow, residual vacuum develops within the teat sinus and remains after inflation collapse; (2) a slight residual vacuum develops within the gland sinus at the end of milk flow; and (3) pressure changes within the teat sinus are apparently due to inflation action upon the teat and extension of milk line vacuum through the teat canal.

b. Milking machine vacuum maintained at 250, 312, 400 and 500 mm Hg

After establishing a characteristic profile of IMP changes at 312 mm Hg, various milking machine vacuum levels were studied with respect to the criteria previously established. The most striking difference noted was the increase in residual vacuum and peak vacuum within the teat sinus when the milking machine vacuum was increased. There appears to be an increased incidence of udder infections when the higher milking machine vacuums are used routinely for milking (48, 49). One may theorize more extensive udder injury in the latter case.

3. IMP between milkings in the cow

The IMP varied considerably after the teat cannulae were inserted into the teats following milking. While considerable care was exercised in complete milking the IMP probably varied because of partial milk ejection associated with teat cannulation.

One should recall the IMP of 0 to 8 mm Hg prior to udder stimulation observed when teat sinus catheters were left in place. In this case no udder manipulation was necessary to connect to the recording system.

Korkman (31) and Kitts *et al.* (30) have made reference to the partial milk ejection noted with teat cannulation procedures using a single channel recording device. The author elected to use a continuous recording system, *i.e.*, a four-channel recording instrument and immediate teat cannulation after milking to avoid the problem previously encountered, *viz*, partial milk ejection during the recording period. The data from the IMP studies between milkings show a slow rise in IMP up to six hours and the greatest rise at 10 to 12 hours after milking. However, IMP difference did not exceed 12 mm Hg, *i.e.*, from initial IMP at the start of recording period to the end of the recording period. Some investigators have adjusted the pressure transducer height to balance the initial IMP to zero. However, in our experiment an IMP of less than 8 mm Hg was arbitrarily selected as a starting point.

Two cows which had IMP measurements between milkings without udder stimulation were repeated but with periodic udder stimulation (20 sec massage every 2 hours). In this series of experiments the 20-sec massage caused a 3 to 5 mm Hg increase in IMP within 2 minutes from the sixth hour to the end of the recording period. The IMP decreased slightly following partial milk ejection. The entire response to stimulation of the udder and corresponding rise in IMP appeared as a step function increase of the latter.

IMP at the end of the recording period was found to be comparable to previous findings in this laboratory. The author believes that in most studies of similar nature that repeated teat cannulation resulted in milk ejection during the recording period. Thus, the IMP reported were higher than those observed in this study.

It is interesting to note that without udder stimulation and partial milk ejection between milkings the difference of change of IMP for a given period is usually nearly constant. Another important point, seldom referred to, is that the cisternal milk may be very small in quantity prior to milk ejection at milking time. Thus, the author believes that the IMP measured in the teat sinus does not reflect the pressures developed in the alveoli and small collecting ducts of the udder, but rather it reflects a degree of filling of the udder. Remember that a stimulus of short duration during the first 5 or 6 hours following milking causes little or no change in IMP as measured in the teat sinus. However, after that time one will notice a small increase in IMP with an udder stimulation of short duration. Therefore, after 5 or 6 hours of milk secretion the alveoli and small collecting ducts are filled and begin to expand with continued milk secretion and impinge upon the free space of the teat and gland sinuses and the larger collecting ducts. In this case the cisternal pressures will increase without a corresponding change in the volume of milk contained therein.

The rapid decrease in IMP during udder washing which was noted in two cows is similar to the phenomenon noted by Zaks (95). He states that there may be a reflex relaxation of the udder in preparation for the large volume of milk which follows milk ejection. Perhaps this phenomenon occurs routinely to some extent but is masked by the milk ejection reflex.

The correlation between quarter IMP after milk ejection and quarter milk production was rather low. The correlation between production and IMP may be low because of the indefinite boundaries of udder capacity. These indefinite boundaries are variable storage space, tissue elasticity and perhaps contractile elements of the udder. The correlation of IMP to production was higher for the rear quarters due to the rear limbs being a partial but definite boundary on their respective quarters. The number of data is rather low to be of any statistical significance.

4. Teat and teat sphincter contractions

Rhythmic contractions of the smooth muscle of the reproductive system has been observed, *e.g.*, fallopian tubes, uterus and vas deferens. Recent research has shown a rhythmicity of the teat wall of the bovine (58). The origin of these contractions may be myogenic or neurogenic.

Regardless of origin, the presence of smooth muscle contractions within the teat wall or teat sphincter appears to be an interesting and surely important physiological event.

a. Teat contractions during continuous IMP recordings In our experiments it was interesting to note that the teat contractions were of random nature and did not occur in all teats. No correlation of contractions was noted with respect to right and left or front and rear teats. In two of the three cows, teats which did not exhibit contractions were previously infected. Only one of the three cows showing teat contractions was chronologically near normal estrus. Thus, from known facts, the teat contractions appear to be of random nature. The physiological significance of these teat contractions remains obscure.

b. Rhythmic contractions of the teat sphincter The teat sphincter contractions observed were definitely influenced by the hormonal nature associated with the estrus cycle.

These contractions appear to be of a rhythmic nature but influenced by the central nervous system. This was noted when an external stimulus caused an immediate teat sphincter contraction. Infusion of epinephrine or oxytocin abolished the teat sphincter contractions temporarily. One might have expected oxytocin to enhance the contractions as seen in the myometrium. Since parasympathomimetic or sympathomimetic drugs seem to abolish the contractions and there is evidence of CNS influence on the contractions, one might assume an intriguing and complex control involved. This phenomenon of teat sphincter contractions should be studied more extensively.

IV. SUMMARY

Surgical techniques have been developed for the placement of catheters to measure and record IMP during mechanical milking in the live, intact cow. Simultaneous pressure recordings were made from the teat sinus, gland sinus, milk line and pulsator line during mechanical milking. Data from 24 recordings on 12 different quarters of five cows with a milking machine vacuum of 312 mm Hg (12.5 inches) were evaluated. Further evaluations were conducted with 250, 312, 400 and 500 mm Hg milking machine vacuum.

IMP was low before udder stimulation (0 to 8 mm Hg) in the initial studies. IMP in eleven cows between milkings was comparatively low in the absence of udder stimulation. Within 20 to 90 seconds after udder stimulation, intramammary pressure increased to 35 to 55 mm Hg. Pressures within the gland and teat sinuses were similar when both contained milk.

After the end of milk flow, the pulsating teat sinus vacuum increased to a maximum with each inflation dilation. When the rubber inflation collapsed against the teat, a residual teat sinus vacuum remained. Ligation of the teat canal abolished the residual vacuum seen during routine machine milking.

Teat contractions were observed during continuous recording of IMP between milkings. Teat sphincter contractions were observed during estrus of the cow. The complexity of the origin and significance of the teat sphincter contractions have not been elucidated.

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VI. ACKNOWLEDGMENTS

The writer expresses appreciation to Dr. R. W. Dougherty, Leader, Physiopathological Investigations, National Animal Disease Laboratory, for assistance and encouragement in planning of this study, for assisting with the experimental surgery and for reviewing the manuscript; to Dr. Melvin J. Swenson, Head, Department of Veterinary Physiology and Pharmacology for his advice, encouragement, and support in planning the experiments and in reviewing the manuscript; to Dr. J. S. McDonald, Bacteriological Investigations (Mastitis), National Animal Disease Laboratory, for cooperation and assistance with experimental surgery and recording; to Mr. Ralph Glazier for preparation of figures in this report; to Mr. Herb M. Cook for assistance with recording during this study; and last, but not least, to the perseverance of my wife and family throughout this period.

This work was carried out under the Government Employees Training Act, Public Law 85507.

VII. APPENDIX A. FIGURES

Figure 1. Intramammary catheters, cannulae, and trocar

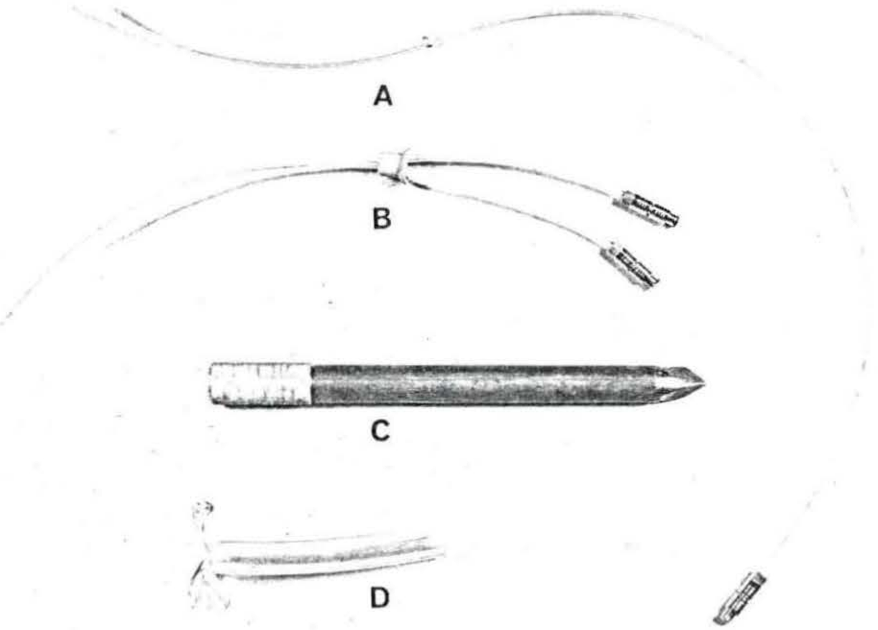
(A) Flanged intramammary catheter

(B) Recording catheters and rubber stopper

(C) Trocar and metal cannula

(D) Polyvinyl insertion cannula

Figure 2. Flanged catheters within the udder and recording sites in the milk line (M.L.) and pulsator line (P.L.)


A
B
C
D

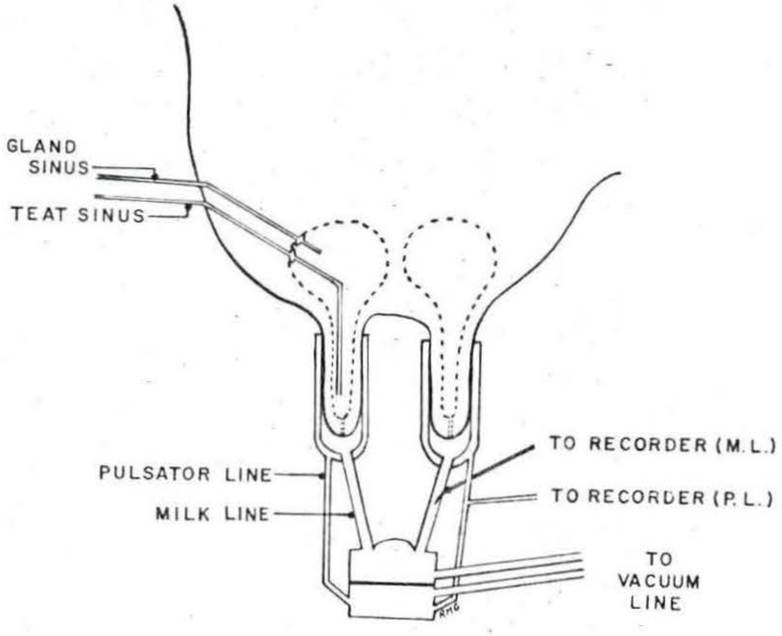

GLAND SINUS
TEAT SINUS
PULSATOR LINE
MILK LINE
TO RECORDER (M.L.)
TO RECORDER (P.L.)
TO VACUUM LINE
RHG

Figure 3. Insertion cannula and recording catheters within the udder

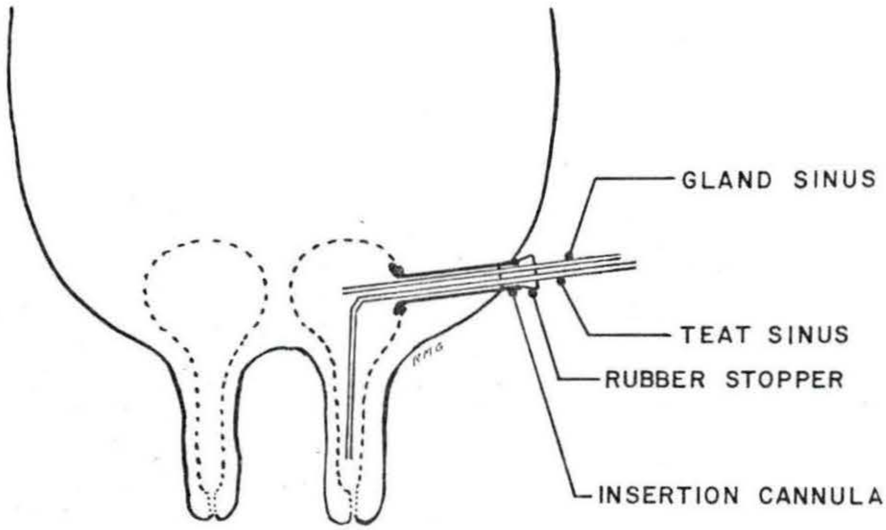
Figure 4. Rubber insertion cannula, keeper and needle

(A) Rubber insertion cannula

(B) Rubber keeper

(C) Cannula inserting needle

[Scale -- 1 inch = 3 inches]


GLAND SINUS
TEAT SINUS
RUBBER STOPPER
INSERTION CANNULA
RMG

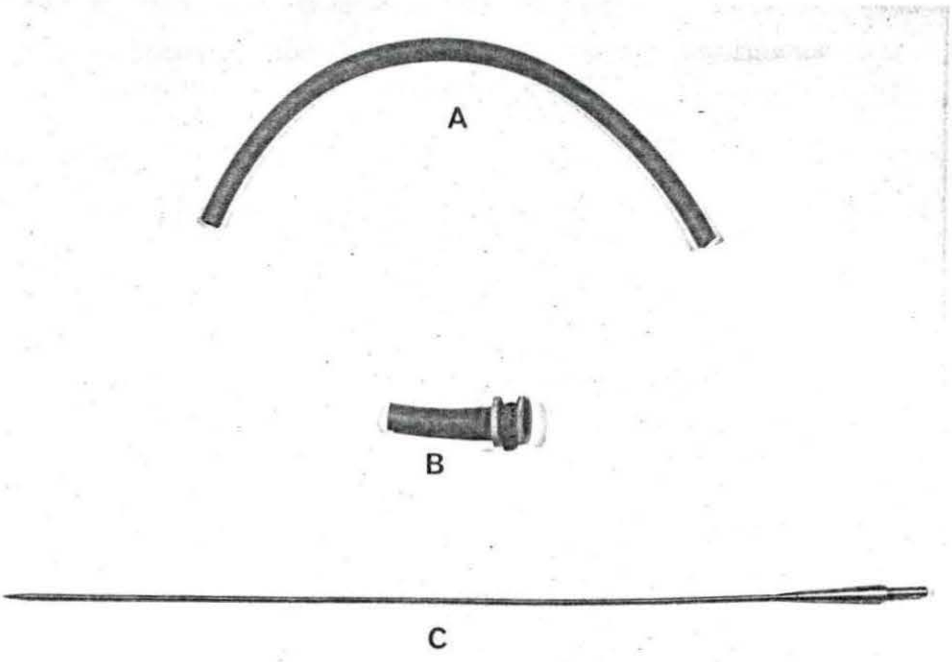
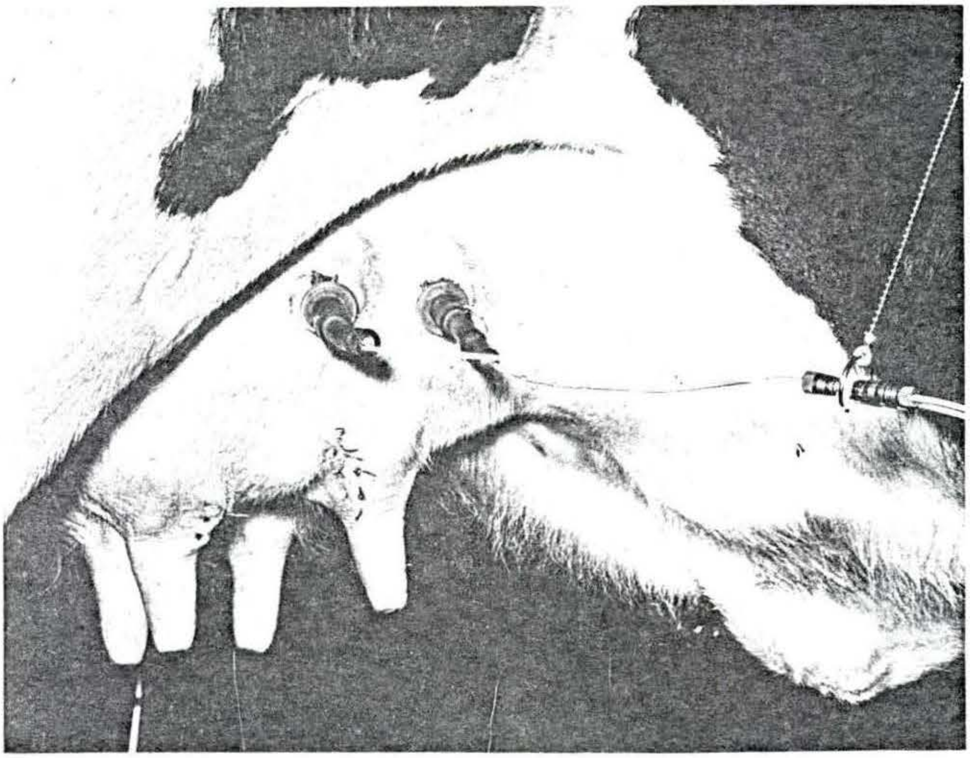

A
B
C

Figure 5. Rubber insertion cannulae placed in the udder

Figure 6. A view showing the teats cannulated for continuous intramammary pressure recordings



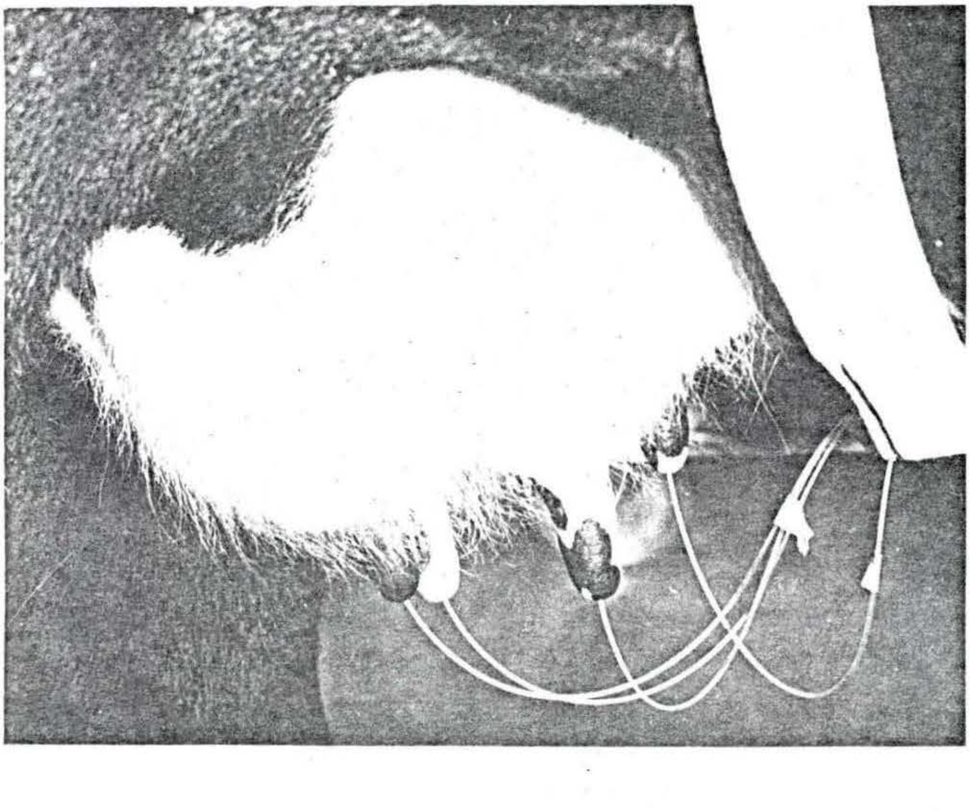


Figure 7. Quarter milking system used for quarter milking; A and C from front quarters, B and D from rear quarters

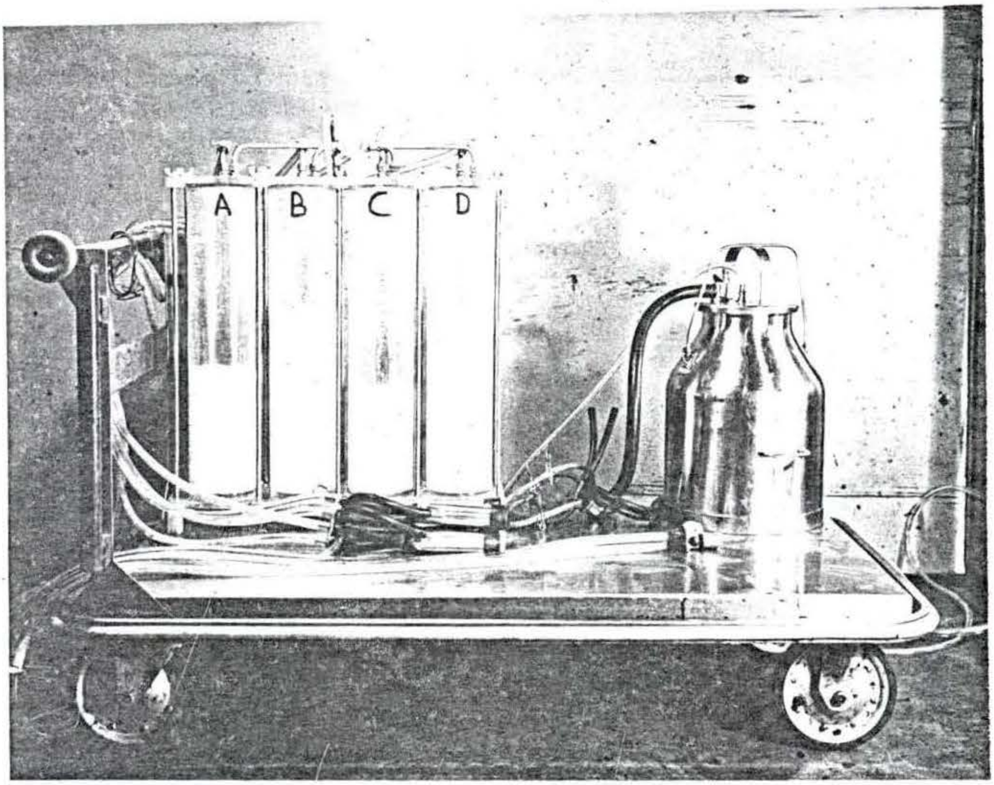

A
B
C
D

Figure 8. Response characteristics of different size and length of polyethylene tubing (fluid filled)

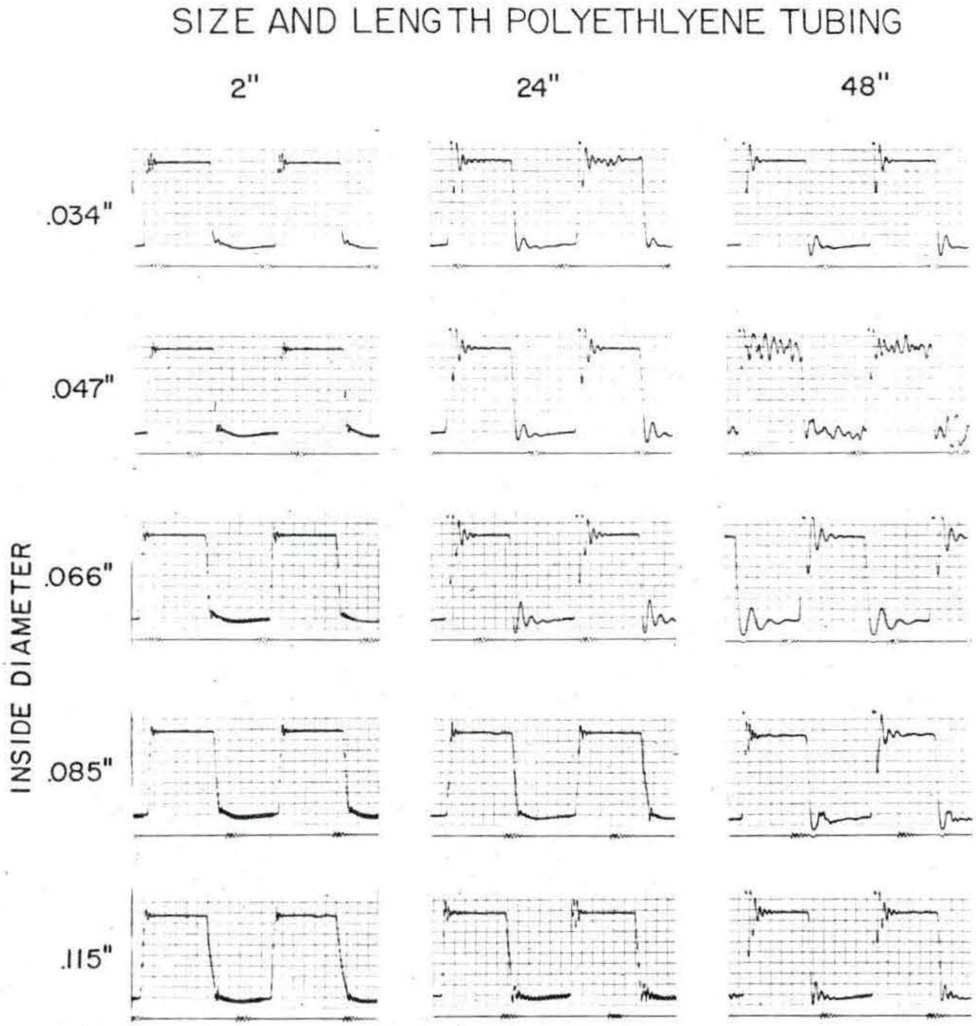

SIZE AND LENGTH POLYETHLYENE TUBING
2"
24"
48"
INSIDE DIAMETER
.034"
.047"
.066"
.085"
.115"

Figure 9. Response characteristics of different size and length of polyethylene tubing (air filled)

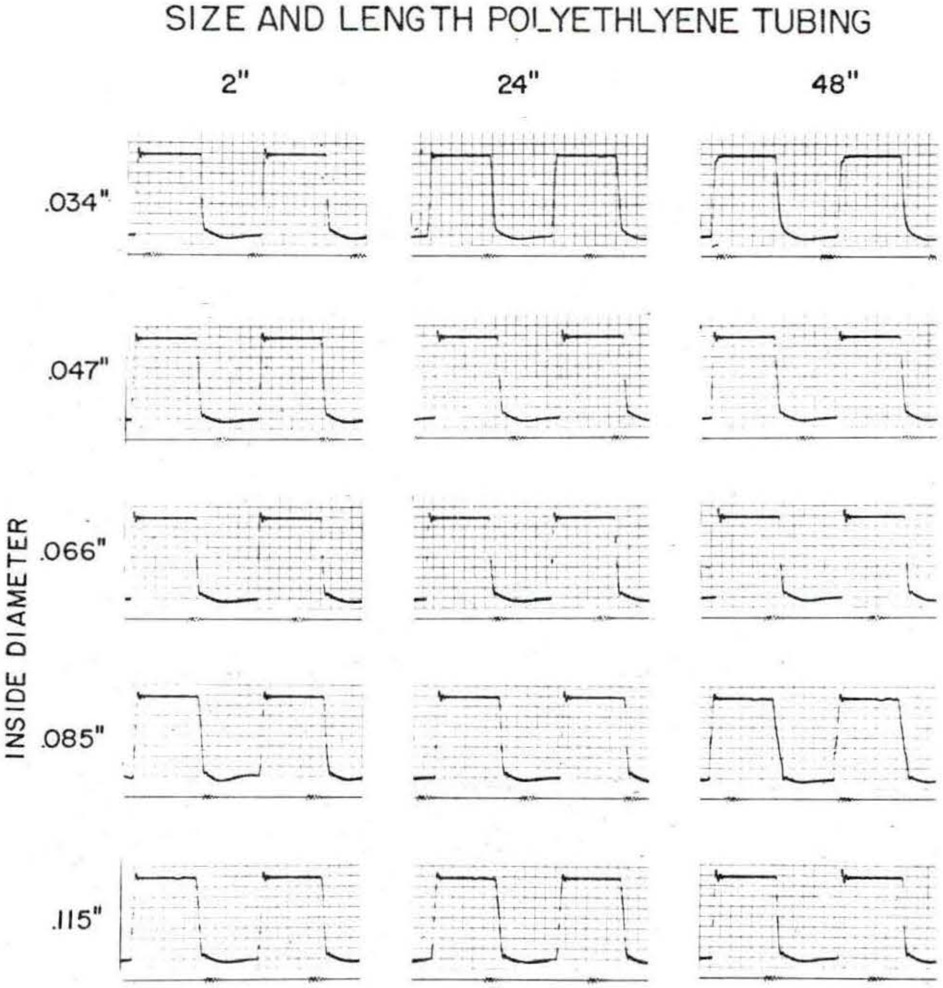

SIZE AND LENGTH POLYETHLYENE TUBING
2"
24"
48"
INSIDE DIAMETER
.034"
.047"
.066"
.085"
.115"

Figure 10. Recordings of typical pressure changes during mechanical milking

(A) Sequence of pressure changes during routine milking

(B) Expanded segment of the teat sinus pressure at the end of milk flow

(C) Pressure changes within the teat sinus as a result of teat cup manipulation (patent teat canal)

(D) Pressure changes within the teat sinus as a result of teat cup manipulation (ligated teat canal)

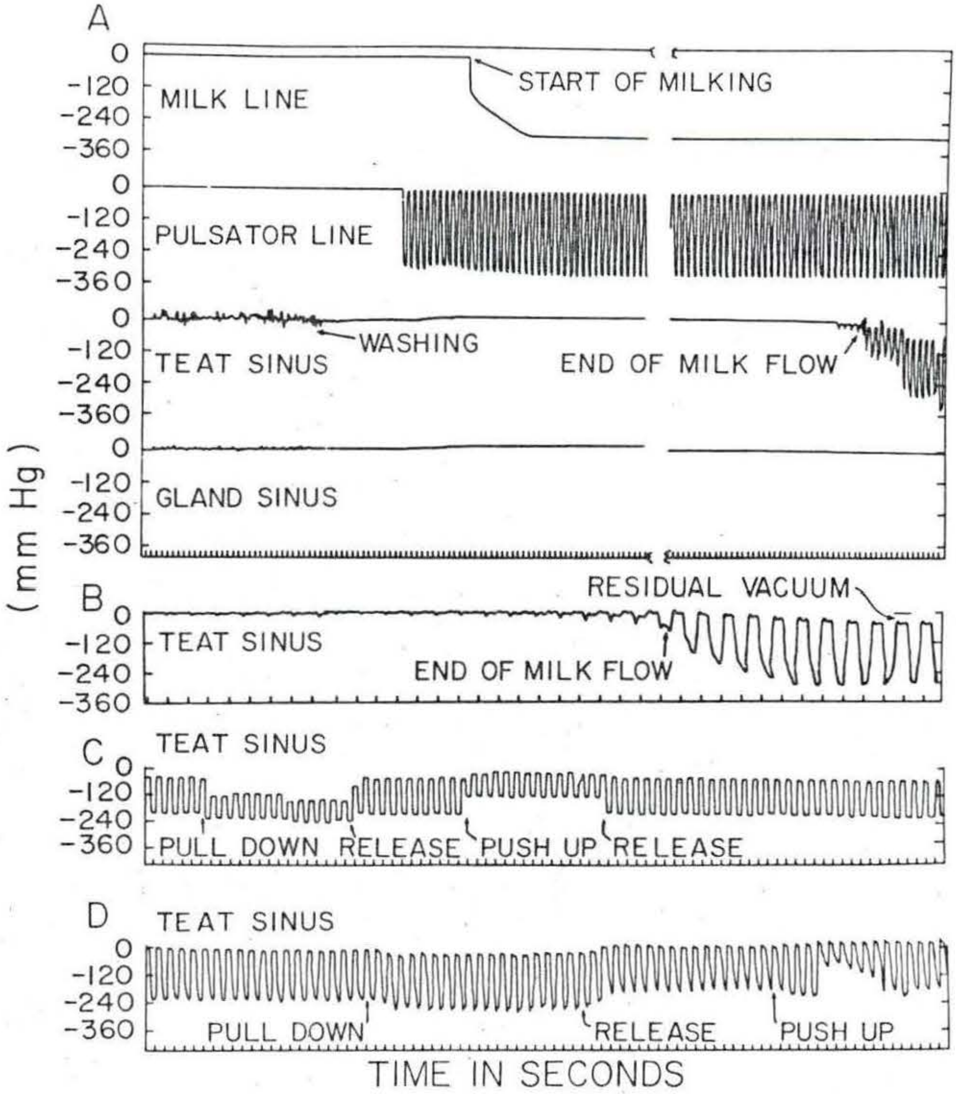
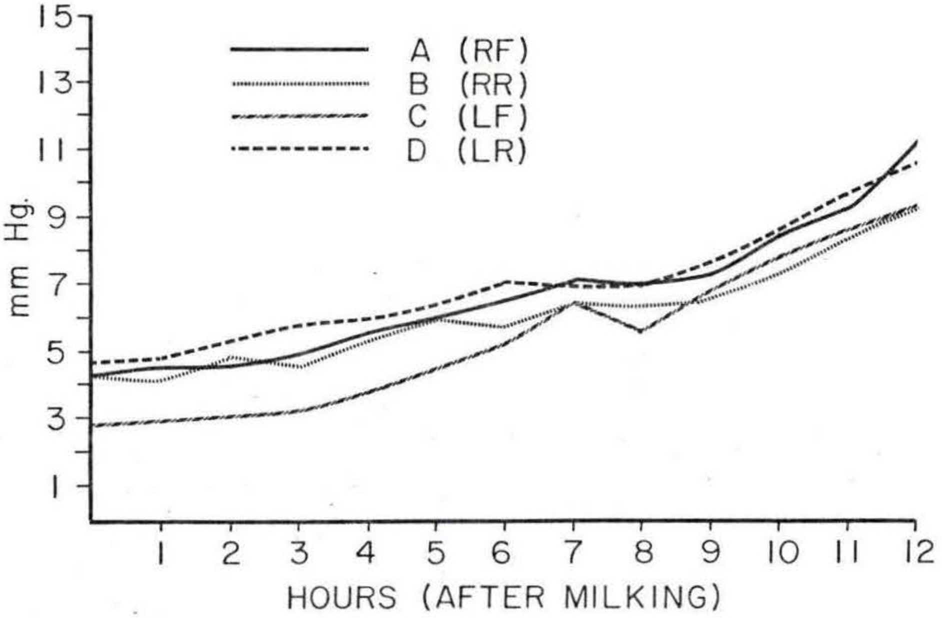

A
MILK LINE
START OF MILKING
PULSATOR LINE
TEAT SINUS
WASHING
END OF MILK FLOW
GLAND SINUS
(mm Hg)
0
-120
-240
-360
B
TEAT SINUS
RESIDUAL VACUUM
END OF MILK FLOW
C
TEAT SINUS
PULL DOWN
RELEASE
PUSH UP
RELEASE
D
TEAT SINUS
PULL DOWN
RELEASE
PUSH UP
TIME IN SECONDS

Figure 11. Average quarter intramammary pressures between milkings in 11 cows

Figure 12. Relationship of quarter milk production and intramammary pressure after stimulation


15
13
11
9
7
5
3
1
mm Hg.
1
2
3
4
5
6
7
8
9
10
11
12
HOURS (AFTER MILKING)
A (RF)
B (RR)
C (LF)
D (LR)

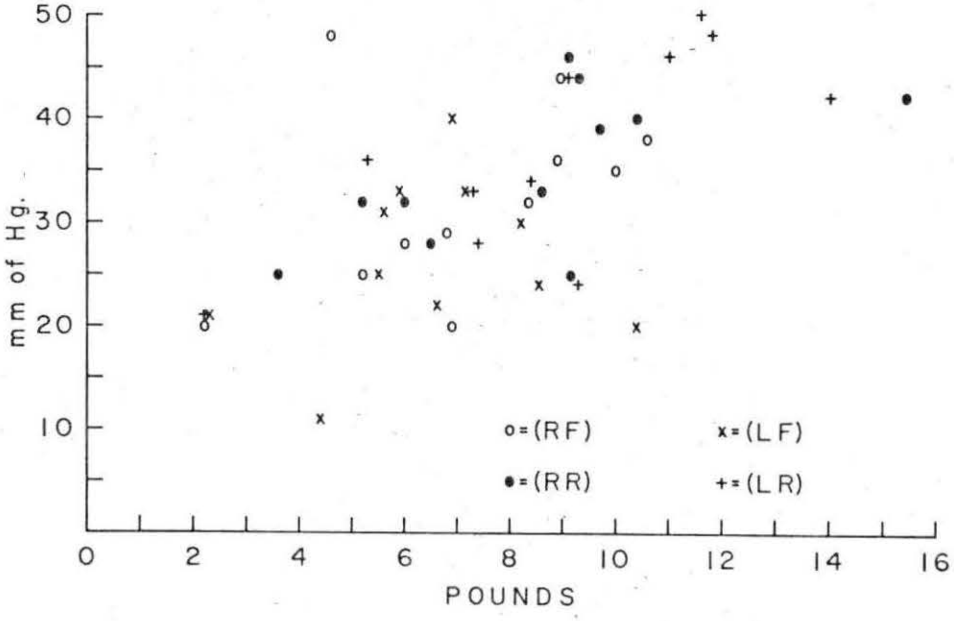

50
40
30
20
10
mm of Hg.
0
2
4
6
8
10
12
14
16
POUNDS
o = (RF)
x = (LF)
● = (RR)
+ = (LR)

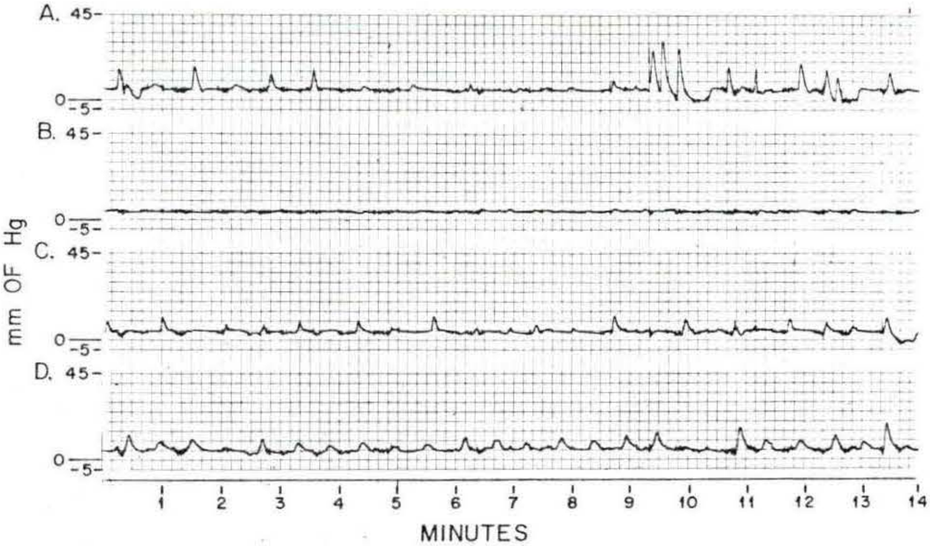
Figure 13. Teat contractions on two cows recorded during intramammary pressure studies between milkings

(A) Right front quarter

(B) Right rear quarter

(C) Left front quarter

(D) Left rear quarter


A. 45-
0
-5-
B. 45-
0
-5-
C. 45-
0
-5-
D. 45-
0
-5-
mm OF Hg
1
2
3
4
5
6
7
8
9
10
11
12
13
14
MINUTES

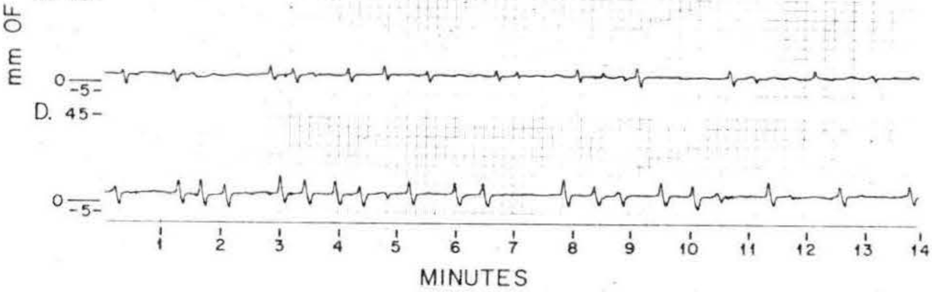
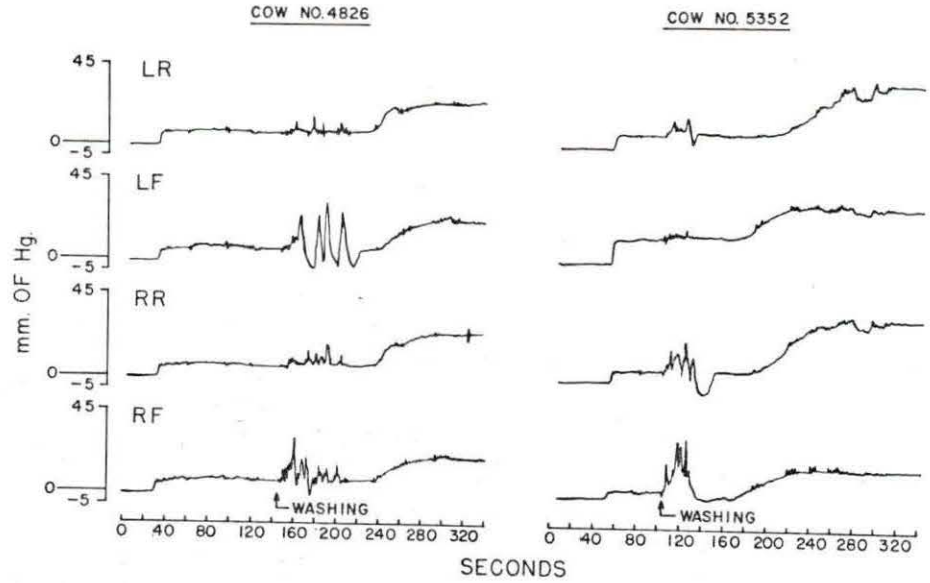

A. 45-
0
-5-
B. 45-
0
-5-
C. 45-
0
-5-
D. 45-
0
-5-
mm OF Hg
1
2
3
4
5
6
7
8
9
10
11
12
13
14
MINUTES

Figure 14. Decreased intramammary pressure and teat contractions associated with udder washing and subsequent milk ejection

Figure 15. Teat sphincter contractions and simultaneous electromyogram


COW NO. 4826
COW NO. 5352
mm. OF Hg.
45
LR
0
-5
45
LF
0
-5
45
RR
0
-5
45
RF
0
-5
WASHING
WASHING
0 40 80 120 160 200 240 280 320
0 40 80 120 160 200 240 280 320
SECONDS

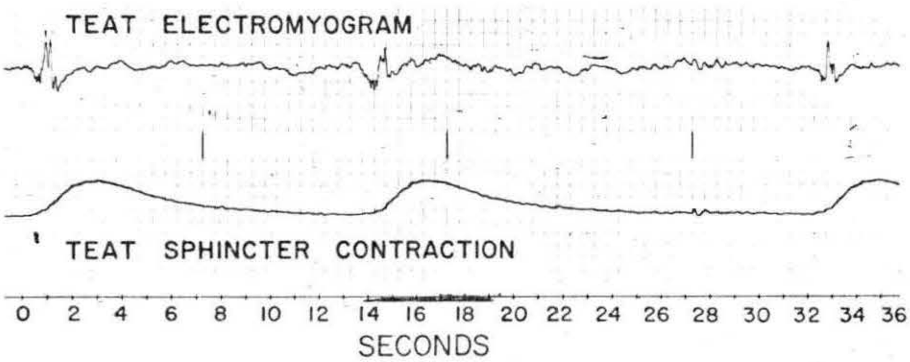
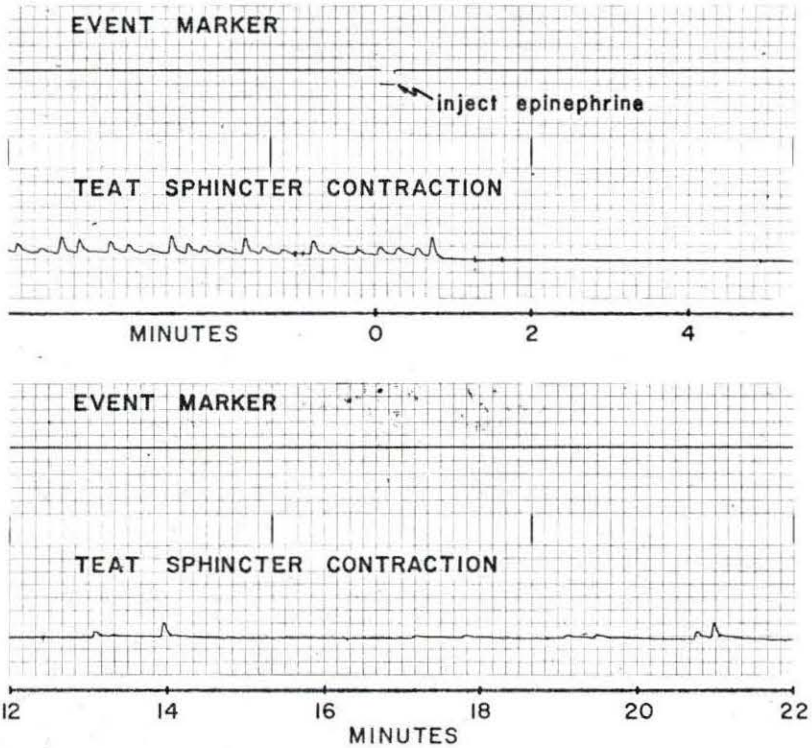

TEAT ELECTROMYOGRAM
TEAT SPHINCTER CONTRACTION
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
SECONDS

Figure 16. Teat sphincter contractions abolished following iv injection of epinephrine into the jugular vein


EVENT MARKER
inject epinephrine
TEAT SPHINCTER CONTRACTION
MINUTES
0
2
4
EVENT MARKER
TEAT SPHINCTER CONTRACTION
12
14
16
18
20
22
MINUTES

VIII. APPENDIX B. TABLES

Table 1. Age, lactation, and production of cows used in IMP studies between milkings

		Lactation		Production
Cow	Age (yrs)	Number	Month	(Daily lb)
4819	5	3	5	34.2
4826	5	3	4	55.0
4833	5	3	5	48.0
4928	4	3	1	60.7
4929	4	3	2	61.5
4932	4	3	2	83.3
4939	4	3	6	63.1
4950	4	3	1	62.9
5076	3	2	2	64.1
5353	3	2	5	25.1
5352	3	2	5	20.0

Table 2. Rise time (msec) for dynamic response of polyethylene tubing

Tubing (i.d.) Size (inch)	2 in Air	2 in Fluid	24 in Air	24 in Fluid	48 in Air	48 in Fluid
.034	16.0	12.8	30.4	24.0	28.8	14.4
.047	24.0	16.0	17.6	20.8	22.4	14.4
.066	19.2	24.0	17.6	16.0	16.0	22.4
.085	35.2	25.6	25.6	22.4	35.2	16.0
.115	32.0	32.0	26.7	17.6	41.6	16.0

Table 3. Average teat sinus vacuum (mm Hg) developed at different milking machine vacuums (mm Hg)

Milking machine vacuum	Teat sinus	
	Residual vacuum	Peak vacuum
250	70	165
312	90	265
400	125	330
500	365	455

Table 4. Intramammary pressures and quarter milk production in two cows showing the highest intramammary pressures

	Intramammary pressure (mm Hg)							
	Cow #4932				Cow #5076			
	R.F.	R.R.	L.F.	L.R.	R.F.	R.R.	L.F.	L.R.
Initial	5	6	5	6	7	5	2	4
1 hour	4	5	5	6	7	4	1	3
2	5	6	4	6	7	4	1	3
3	5	6	5	7	6	4	1	4
4	5	7	5	8	9	5	2	6
5	6	6	5	8	9	5	3	6
6	6	5	4	9	9	5	5	6
7	7	5	4	5	9	7	5	6
8	8	7	6	7	11	7	4	7
9	9	8	8	8	12	9	6	8
10	12	10	9	10	16	13	8	10
11	14	13	11	15	17	14	9	11
12	18	17	13	18	22	17	10	12
	--	--	--	--	--	--	--	--
Production (lbs)	8.3	15.4	10.4	14.0	8.9	9.7	8.7	9.0