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Effect of liner design, pulsator setting, and vacuum level on bovine teat tissue changes and milking characteristics as measured by ultrasonography

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Friesian-type dairy cows were milked with different machine settings to determine the effect of these settings on teat tissue reaction and on milking characteristics. Three teat-cup liner designs were used with varying upper barrel dimensions (wide-bore WB= 31.6mm; narrow-bore NB= 21.0mm; narrow-bore NB1=25.0mm). These liners were tested with alternate and simultaneous pulsation patterns, pulsator ratios (60:40 and 67:33) and three system vacuum levels (40, 44 and 50kPa). Teat tissue was measured using ultrasonography, before milking and directly after milking. The measurements recorded were teat canal length (TCL), teat diameter (TD), cistern diameter (CD) and teat wall thickness (TWT).

Teat tissue changes were similar with a system vacuum level of either 50kPa (mid-level) or 40kPa (low-level). Widening the liner upper barrel bore dimension from 21.0mm ($P<0.01$) or 25.0mm ($P<0.001$) to 31.6mm increased the magnitude of changes in TD and TWT after machine milking. Milk yield per cow was significantly ($P<0.05$) higher and cluster-on time was reduced ($P<0.01$) with the WB cluster as compared to the NB1 cluster. Minimum changes in teat tissue parameters were achieved with system vacuum level of 40kPa and 50kPa using NB and WB clusters, respectively. Similar changes in teat tissue and milk yield per cow were observed with alternate and simultaneous pulsation patterns. Widening pulsator ratio from 60:40 to 67:33 did not have negative effects on changes in teat tissue and had a positive effect on milk yield and milking time. Milk liner design had a bigger effect on teat tissue changes and milking characteristics than pulsation settings.

Key words

Cattle,
Machine milking,
Teat tissue,
Pulsation,
Milk liner,
Ultrasonography.

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Introduction

Changes in teat thickness are minimal when milk is removed *via* a catheter inserted in the teat canal (Hamann and Mein, 1990) or by hand (Gleeson *et al.*, 2002). Therefore, an increase in thickness values after machine milking can be interpreted as a response of the teat tissue to the machine milking action.

Physiological and pathological changes in the circulatory system associated with milking may decrease the efficacy of the defense systems. Zecconi (1992) observed higher infection rates of quarters and more ducts colonised in teats, where teat end thickness changed by >5% than with teats showing less congestion. This decreased efficiency may be prolonged after

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Abbreviations

NB: narrow bore tapered liners (21.0mm to 18.0mm)
NB1: narrow bore tapered liners (25.0mm to 21.0mm)
WB: wide bore tapered liners (31.6mm to 21.0mm)
TCL: teat canal length
TD: teat diameter
CD: cistern diameter
TWT: teat wall thickness
TL: teat length
4x1: simultaneous pulsation
2x2: alternate pulsation



FIGURE 1: Teat placed in a condom with the probe in vertical position against the teat wall.

milking at higher system vacuum levels (Hamann *et al.*, 1993). Teat thickness changes of 15% were shown when system vacuum level in bucket milking plants was increased from 40 to 50kPa. It has also been shown that full teat tissue recovery after machine milking may take many hours (Gleeson *et al.*, 2002). This recovery time may also be influenced by milking systems using different liner types, which have been shown to result in varying degrees of teat canal penetrability (O'Brien, 1988). Liner designs commonly used in Ireland with wide upper barrel bore dimensions (31.6mm tapered to 21.0mm) give higher milk yield (Gleeson and O'Callaghan, 2001) with reduced liner slips (O'Callaghan, 2001) than narrow bore type liners. Liners with wide upper barrel bore also have a higher cavity vacuum (O'Callaghan, 1998) and a higher teat-end vacuum (O'Callaghan, 2001) compared to narrow-bore liner types. Higher teat-end vacuum will increase peak milk flow-rate (Gleeson and O'Callaghan, 1999) but may also increase teat congestion or oedema. The physical properties of liners, such as wall thickness, mounting tension and rubber hardness, will also alter the cyclic pressure applied to the teat (Hamann and Mein, 1996). Therefore, liner design is an important factor in determining the effectiveness of pulsation.

Increasing pulsator ratio was demonstrated to induce a progressive increase in teat thickness, as did pulsation rate (Hamann *et al.*, 1993). Experiments by Craig *et al.* (1991) and O'Callaghan (1998) have shown that a wide pulsator ratio results in faster milking than a narrow pulsator ratio. The interaction between liner design, vacuum conditions at the teat-end and pulsation

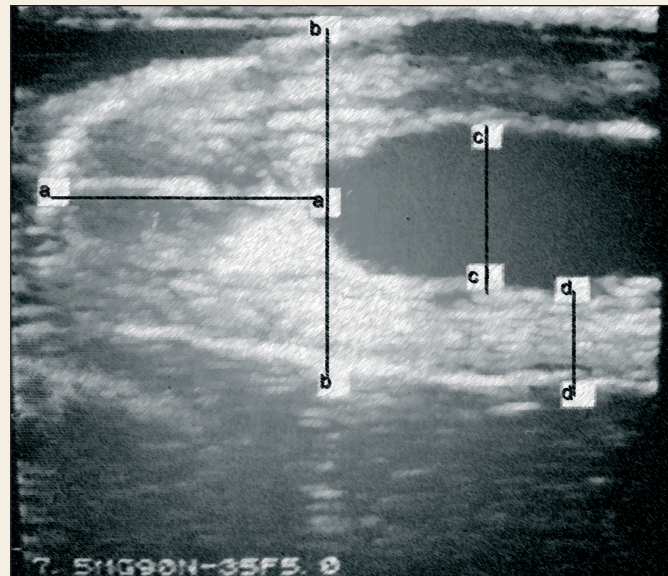


FIGURE 2: Measurement of teat canal length (a), teat diameter (b), cistern diameter (c), and teat wall thickness (d).

characteristics can influence the level of teat tissue reaction. Therefore, it is necessary to evaluate the effects of combinations of machine settings on the physiological status of teat tissue.

Changes in teat tissue induced by different milking systems have previously been measured using a simple spring-loaded calliper instrument or a modified electronic caliper device (Hamann *et al.*, 1988). An alternative measurement technique is ultrasonography, which is non-invasive and is employed extensively in animal measurements. Banting (1998) used this technique for the examination of the bovine mammary gland for inflammation and fibrotic reactions of the udder. Spencer *et al.* (1996, 1997), Neijenhuis *et al.* (1999) and Gleeson *et al.* (2002) used this method to measure changes in bovine teat tissue after machine milking. Spencer *et al.* (1996) suggested that there was more variability with cutimeter measurements than with ultrasonic measurements. Neijenhuis *et al.* (1999) also concluded that ultrasonography was a good research instrument to monitor changes in teat tissue caused by machine milking. Ultrasonography allows measurement of a wide range of teat tissue parameters, including canal length, cistern diameter, teat wall thickness and teat diameter. In this paper we report the effects of liner design, pulsator settings, and pulsation characteristics with different system vacuum levels on machine-induced changes in teat tissue as measured using the ultrasonic technique.

Materials and methods

Teat tissue measurement procedures

An Aloka 500v-ultrasound scanner with a 7MHz linear probe was used to measure changes in teat tissue on cow's teats. A plastic ring at the opening supported a Femidom-condom; this allowed it to be held in place with one hand, filled with warm water and placed around the cow's teat (Figure 1). A film of

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FIGURE 3:
Calibrated
tube in which
the teat was
placed to
measure teat
length.

lubricating gel was placed on the probe head to improve contact with the condom. The probe was manipulated until a clear image of the teat appeared on the screen. When the picture was obtained, the image was frozen on screen. Images of teats were stored on videocassette and these were subsequently measured on screen. A purpose-designed software program was used to automatically record to file the distance between two points, which were marked using a ball mouse.

The teat parameters measured included teat canal length (TCL), teat diameter (TD), cistern diameter (CD), and teat wall thickness (TWT). TD was measured across the distal end of the teat canal; CD and TWT measurements were made at 10mm from this point (Figure 2). Teats were washed with warm running water and dried with paper towels before the pre-milking measurement.

Values recorded for each teat parameter were taken on the left-sided front and rear teats of cows directly after milking and 15 minutes after milking. Post-milking values were compared to pre-milking values and the results presented as the mean changes (increases or decreases) in measurements. Teat length (TL) was measured using a calibrated transparent tube, into which the teat was placed (Figure 3). The ultrasonic method and procedure was outlined in detail by Gleeson *et al.* (2002).

Liners designs and vacuum level - Experiment 1

Six Friesian dairy cows were milked, with three milking systems and two cluster types, using a Latin Square design experiment (6 x 6). Cows were milked for three days per treatment, with day one used as an adjustment day. The cows were milked in a 14-unit, 80-degree side-by-side milking parlour, using 13.5mm-id long milk tubes, to a single 72mm-id milk-line situated at either 1.5m above the cow standing (mid-level) or situated below the cow standing (low-level). The three milking systems had vacuum levels of 40kPa (low-level), 44kPa (low-level) and 50kPa (mid-level) and used a simultaneous pulsation pattern. Cluster one (WB) consisted of wide bore (31.6 to 21.0mm) tapered liners; it had a claw volume of 150ml and a cluster weight of 3.1kg. The second cluster type (NB) consisted of narrow bore (21.0 to 18.0mm) liners; it had a claw volume of

323ml and a cluster weight of 1.65kg. The claw-piece designs were those normally supplied by manufacturers with these liner types. The WB cluster was used in experiments 1, 2 and 3 and the NB cluster was used in experiments 1 and 2. Clusters were manually removed when milk flow-rate ceased in the cluster claw-piece. The pulsator ratio setting was 68:32 and the pulsation rate was 60c/minute here and in subsequent experiments. Cows were milked at intervals of 17h (overnight) and 7h (daytime). Milk yield (kg) was recorded for each individual cow using Dairymaster Weigh-all electronic milk meters (E.P. Harty, Causeway, Co Kerry).

Pulsator ratio and pulsation pattern (mid-level) - Experiment 2

Eight Friesian dairy cows were milked, with four milking treatments and two cluster types, using a Latin Square design experiment (8x8). Cows were milked for three days per treatment with day one used as an adjustment day in the same milking facility and using the mid-level milk-line as outlined for Experiment 1. The system vacuum level setting was 49kPa. The milking treatments consisted of pulsator ratio settings of 67:33 and 60:40 and simultaneous (4x1) and alternate (2x2) pulsation patterns. Pulse chamber 'a' and 'c' were similar for all treatments. Clusters were manually removed when milk flow-rate dropped to 0.2kg/minute as indicated by a light from the milk-meter software program. Milking characteristics, including milk yield (kg) and milking time (seconds), were recorded using the electronic milk meters at the morning milking, as outlined for Experiment 1.

Pulsation pattern (low-level) - Experiment 3

Eight Friesian-type dairy cows were milked with four milking treatments using a Latin Square design experiment (4x4) for three days per treatment with day one used as an adjustment day. Cows were milked in the milking facility as outlined for experiment 1 using a low-level milk-line situated below the cow standing and with a system vacuum level setting of 44kPa. The milking treatments consisted of the WB cluster used in experiment 1 and 2 and a narrow-bore liner type with an upper barrel dimension of 25.0mm tapered to 21.0mm at the bottom (NB1). A claw-piece with a volume of 275ml and a cluster weight of 1.65kg as recommended by the cluster manufacturer was used with the NB1 liner type. These cluster types were operated with 4x1 and 2x2 pulsation patterns and a pulsator ratio setting of 67:33. Individual cow milk yield (kg) and milking time (seconds) were recorded using electronic milk-meters at the morning milking.

Statistical analysis

Measurements recorded for teat tissue, milk yield and milking time were subjected to analysis of variance test using Genstat (Genstat 5 Release 3.2, 1995). The analysis for teat tissue measurements was performed on the mean values of left-sided

TABLE 1: Effect of plant vacuum levels (40, 44 and 50 kPa) on mean teat tissue changes (mm)*, and mean milk yield (kg) with WB and NB clusters - Experiment 1

Vacuum level - kPa	40 low-level		44 low-level		50 mid-level		
Cluster Type	NB	WB	NB	WB	NB	WB	s.e.d
Canal length	3.18	3.45	3.46	3.33	3.51	3.73	0.41
Canal length (15min)	2.73	3.42	3.10	4.05	3.03	3.37	0.45
Teat diameter	0.21 ^b	1.26 ^a	0.67 ^{ab}	1.55 ^a	0.52 ^b	0.19 ^b	0.47
Teat diameter (15min)	-0.03 ^d	1.22 ^a	0.70 ^{ad}	1.50 ^a	0.68 ^d	0.06 ^d	0.32
Cistern diameter	-7.33	-8.01	-7.03	-8.85	-7.73	-7.75	0.52
Cistern diameter (15min)	-6.67 ^b	-7.82 ^a	-6.42 ^b	-8.40 ^a	-7.10 ^b	-7.62 ^{ab}	0.40
Wall thickness	2.63	3.65	2.86	4.38	2.94	3.43	0.34
Wall thickness (15 min)	2.30 ^b	3.43 ^a	2.78 ^b	3.90 ^a	2.95 ^b	3.20 ^b	0.24
Teat length	11.62	8.75	11.17	5.17	10.42	9.12	1.83
Teat length (15 min)	4.50	2.92	4.67	0.67	4.42	2.50	1.43
Mean milk yield (kg)	18.05	17.27	17.05	18.15	18.38	17.58	0.63

s.e.d.: standard error difference

* Tissue changes were recorded directly after milking and 15 minutes later.

Values with different superscripts, within rows, differ significantly, ^{ab} P<0.05, ^{ac} P<0.01, ^{ad} P<0.001.

front and rear teats for two morning recordings for each group for each period.

Results

Experiment 1

There was a significant interaction shown between vacuum level and cluster design for some teat parameters measured. A higher (P<0.05) increase in TD occurred with the WB cluster at a vacuum level of 44kPa (low-level) compared to measurements taken with a vacuum level of 50kPa (mid-level). These differences were still evident 15 minutes after cluster removal. The minimum changes in TD with WB were found at a vacuum level of 50kPa and with NB at a vacuum level of 40kPa (Table 1). There were no significant interactions between vacuum level and cluster type for TCL or TL or mean milk yield. However,

teats tended to be longer after milking with the NB cluster compared to the WB cluster. The largest decrease (P<0.05) in CD and a corresponding increase (P<0.05) in TWT occurred with WB clusters at a plant setting of 44kPa (15 minutes after milking). There were no significant differences in changes to TCL, CD or TL between the three vacuum levels (Table 1a). However, higher changes in TD (P<0.01) occurred with a vacuum level of 44kPa as compared to the other two system vacuum levels. WB clusters increased TCL (P<0.01), TD (P<0.05), TL (P<0.01) TWT (P<0.001) and decreased CD (P<0.01) directly after milking; when compared to changes in teat tissue with NB clusters, these changes remained significant for all teat parameters fifteen minutes after milking. Changes in TWT was also higher (P<0.001) with the WB cluster directly after milking and fifteen minutes after milking. This increased

TABLE 1a: Effect of cluster type and plant vacuum level (kPa) on mean teat-tissue changes (mm) directly after milking and 15 minutes later - Experiment 1

	Cluster type			Plant vacuum level			
	WB	NB	s.e.d	40	44	50	s.e.d
Canal length	3.50	3.38	0.24	3.31	3.59	3.42	0.29
Canal length (15min)	3.61 ^a	2.95 ^c	0.26	3.07	3.57	3.20	0.32
Teat diameter	0.46 ^a	1.00 ^b	0.27	0.73	1.11	0.35	0.33
Teat diameter (15min)	0.45 ^a	0.98 ^b	0.18	0.60 ^a	1.10 ^b	0.37 ^a	0.22
Cistern diameter	7.37 ^a	8.20 ^c	0.30	-7.67	-7.94	-7.74	0.37
Cistern diameter (15min)	7.95 ^a	6.73 ^d	0.23	-7.25	-7.41	-7.36	0.28
Wall thickness	3.82 ^a	2.81 ^d	0.19	3.14	3.62	3.18	0.24
Wall thickness (15 min)	3.50 ^a	2.68 ^d	0.14	2.69	3.34	3.06	0.17
Teat length	11.07 ^a	7.68 ^c	1.06	10.19	8.17	9.77	1.30
Teat length (15 min)	2.03 ^a	4.53 ^c	0.82	3.71	2.67	3.46	1.01
Mean milk yield (kg)	17.66	17.83	0.36	17.66	17.60	17.98	0.44

s.e.d.: standard error difference

Values with different superscripts, within rows, for cluster type and plant vacuum differ significantly, ^{ab} P<0.05, ^{ac} P<0.01, ^{ad} P<0.001.

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TABLE 2: Effect of pulsator ratio (60:40 and 67:33) and pulsation pattern (alternate =2x2, simultaneous = 4x1) with WB and NB clusters on teat tissue changes (mm), mean milk yield (kg) and mean milking time (seconds) with mid-level milking - Experiment 2

Pulsator ratio	60:40	60:40	60:40	60:40	67:33	67:33	67:33	67:33	
Pulsation pattern	2 x 2	4 x 1	2 x 2	4 x 1	2 x 2	4 x 1	2 x 2	4 x 1	
Cluster type	WB	WB	NB	NB	WB	WB	NB	NB	s.e.d
Canal length	2.98	3.16	2.72	2.47	2.39	2.69	2.80	3.14	0.41
Teat diameter	1.47	1.76	- 0.36	- 0.09	1.10	1.04	0.40	0.04	0.38
Cistern diameter	- 7.96	- 7.38	- 7.99	- 7.44	- 7.96	- 9.17	- 6.99	- 8.12	0.68
Wall thickness	3.56	3.30	2.90	2.50	3.40	4.40	2.60	2.90	0.26
Teat length	10.37	10.44	10.53	9.22	9.60	11.00	9.60	8.50	1.50
Milk yield	16.93	17.02	16.45	15.36	17.62	17.26	16.35	16.39	0.42
Mean milking time	495	488	650	629	484	468	581	572	25.8

thickness in TWT corresponded with a reduction shown in CD. The milk yield harvested was similar for WB and NB cluster types. Changes in teat tissue measurements recorded post-milking tended to reduce fifteen minutes after cluster removal.

Experiment 2

The teat tissue changes and milking characteristics as a result of machine milking with eight treatments, including two pulsator ratios, two pulsation patterns and two cluster types, in a mid-level plant are outlined in Table 2. There were no significant differences between treatments for any of the teat parameters measured. The largest increase in TD occurred with the treatment containing WB clusters, 60:40 ratio and a 4x1 pulsation pattern and the minimum changes in TD were observed with NB clusters using similar pulsator ratio and pulsation pattern. However, a lower milk yield was harvested per cow using the latter system. The highest ($P<0.06$) milk yield (17.62kg) recorded per cow was obtained with the combination of WB clusters, 67:33 pulsator ratio and a 2x2 pulsation pattern, whilst the lowest milk yield (15.36kg) was obtained with the

treatment comprised of NB clusters, 60:40 pulsator ratio and 4x1 pulsation pattern. The shortest cluster-on time (468 seconds) per cow was observed with the treatment incorporating WB, a ratio of 67:33 and a 4x1 pulsation pattern and the longest cluster-on time (650 seconds) was observed with the treatment comprising of NB, a pulsator ratio of 60:40 and 2x2 pulsation pattern. The biggest reduction in CD with a corresponding largest increase in TWT occurred with the treatment comprised of WB, 67:33 pulsator ratio and 4x1 pulsation pattern.

There were significant cluster x ratio interactions in relation to changes in TD ($P<0.01$) and CL ($P<0.05$) and ratio x pattern interactions for changes to TWT ($P<0.001$) and CD ($P<0.01$); there were no interactions evident for cluster x ratio, cluster x pattern or for ratio x pattern (Table 2a). Widening the pulsator ratio from 60:40 to 67:33 had no effect on TCL or TD and tended to increase the changes in CD and resulted in a significant increase in TWT ($P<0.001$). The mean cow milk yield was also higher ($P<0.05$) with the pulsator ratio of 67:33. Cluster-on time was significantly shorter ($P<0.01$) at 527 seconds per cow with a pulsator ratio setting of 67:33 compared

TABLE 2a: Interaction of cluster type, pulsator ratio, pulsation pattern on teat tissue changes (mm), mean milk yield (kg) and mean milking time (seconds) with mid-level milking - Experiment 2

	Cluster type			Pulsator ratio			Pulsation pattern			Cluster x ratio	Cluster x pattern	Ratio x pattern
	WB	NB	s.e.d	60:40	67:33	s.e.d	2x2	4x1	s.e.d	P-value	P-value	P-value
Canal length	2.81	2.78	0.20	2.83	2.76	0.20	2.72	2.87	0.48	0.03	0.65	0.38
Teat diameter	1.34 ^a	-0.00 ^d	0.19	0.70	0.65	0.19	0.65	0.69	0.19	0.01	0.67	0.20
Cistern diameter	-8.12 ^a	-7.64 ^d	0.34	-7.70	-8.06	0.34	7.73	8.03	0.34	0.13	0.97	0.01
Wall thickness	3.65 ^a	2.70 ^d	0.13	3.03 ^a	3.32 ^b	0.04	3.09	3.27	0.13	0.16	0.14	0.00
Teat length	10.34	9.46	0.78	10.14	9.66	0.78	10.02	9.79	0.78	0.66	0.22	0.61
Mean milk yield	17.21 ^a	16.14 ^d	0.21	16.44 ^a	16.91 ^b	0.21	16.84	16.51	0.21	1.00	0.36	0.42
Mean milking time	484 ^a	608 ^d	12.94	565.5 ^a	526.6 ^c	12.94	552.8	539.3	12.94	0.07	0.87	0.95

s.e.d: standard error difference

Values with different superscripts, within rows, for cluster type, pulsator ratio and pulsation pattern differ significantly, ab $P<0.05$, ac $P<0.01$, ad $P<0.001$.

TABLE 3: Effect of pulsation pattern (alternate = 2x2, simultaneous = 4x1) with WB and NB cluster types on mean teat tissue changes (mm), milk yield (kg) and milking time (seconds) with low-level milking - Experiment 3

	2 x 2	4 x 1	2 x 2	4 x 1	s.e.d
	N.B1	W.B	W.B	N.B1	
Canal length	2.59	2.54	2.75	2.34	0.31
Teat diameter	- 0.03 ^a	0.65 ^c	1.00 ^c	- 0.20 ^a	0.29
Cistern diameter	- 6.87	- 7.50	- 7.30	- 6.88	0.95
Wall thickness	2.34	3.08	3.36	2.43	0.45
Teat length	8.47	10.84	9.31	9.53	0.99
Mean milk yield	13.79 ^b	15.09 ^b	14.1b	12.72 ^a	0.76
Mean milking time	517 ^a	595 ^c	444 ^a	674 ^c	58

s.e.d: standard error difference
Values with different superscripts, within rows, differ significantly, ^{ab} P<0.05, ^{ac} P<0.01.

to a cluster-on time of 566 seconds per cow with a ratio of 60:40. There was no significant difference in teat tissue changes or milking characteristics between pulsation patterns. When teat tissue changes were compared, increases in TD, CD and TWT associated with the WB clusters were significantly greater than those associated with NB clusters (P<0.001). Significantly higher (P<0.001) milk yield (17.21kg) and lower (P<0.001) cluster-on time (484 sec) per cow, were shown with WB, compared to NB with a milk yield of 16.14kg and a cluster-on time of 608 seconds per cow. There were no differences in changes to CL or TL between cluster types.

Experiment 3

The teat tissue changes and milking characteristics as a result of machine milking with alternate or simultaneous pulsation patterns with either WB or NB1 cluster types in a low-level milking plant are outlined in Table 3. WB increased TD with either simultaneous or alternate pulsation patterns compared to NB1 with either pulsation setting (P<0.01). There was no difference between treatments for changes in TCL and TL, but treatments containing WB tended to have larger increases in

CD and TWT compared to treatments using NB1. A significantly lower milk yield per cow (P<0.05) was recorded with NB1 clusters and a 4x1 pulsation pattern compared to the other treatments. The longest cluster-on time per cow (P<0.05) was recorded with both WB and NB clusters using a 4x1 pulsation pattern compared to clusters with a 2x2 pulsation pattern. Cluster x pulsation pattern interactions were not observed (Table 3a). There were no differences shown in teat tissue changes or milk yield between pulsation patterns. However, a longer cluster-on time was observed with 4x1 pulsation pattern compared to the 2x2 pattern (P<0.01). Larger changes to TD (P<0.001) and TWT (P<0.05) were observed with WB compared to NB1. Milk yield per cow was significantly higher (P<0.05) and cluster-on time per cow was lower for WB (P<0.01) compared to the NB1 cluster.

Discussion

System vacuum levels of 50kPa (mid-level) and 40kPa (low-level) gave similar changes in teat tissue after machine milking. While previous studies have shown that vacuum level can have a great effect on teat thickness changes (Hamann *et al.*, 1993), it was the interaction with cluster type that had the largest effect on changes to the teat diameter in this study. With system vacuum levels of 40kPa and 50kPa using NB and WB clusters, respectively, minimum changes were achieved in the teat tissue parameters measured. Both these system vacuum settings would result in claw vacuum levels within the ISO-guidelines (1996) of 32 to 40kPa measured during peak flow-rate. Widening the upper barrel bore of a milk-liner from 22.0 or 25.0 to 31.6mm and a system vacuum level of 44kPa (low-level) increased the magnitude of teat tissue changes after milking, particularly TD. Higher teat-end vacuum associated with the WB liner type (O'Callaghan, 2001) and the higher system vacuum setting of 44kPa in a low-level milking system may explain the significant changes in teat tissue that have occurred. This result would also agree with the findings of Hamann (1992) that widening barrel bore would result in increased teat thickness. The increase in thickness may also be due to teats expanding after entering the

TABLE 3a: Interaction of cluster type and pulsation pattern on teat tissue changes (mm), mean milk yield (kg) and mean milking time (seconds) with low-level milking - Experiment 3

	Cluster type			Pulsation pattern			Cluster x pattern
	N.B1	W.B	s.e.d	2x2	4x1	s.e.d	P-value
Canal length	2.46	2.65	0.22	2.67	2.44	0.22	0.95
Teat diameter	-0.12 ^a	0.83 ^d	0.21	0.49	0.22	0.21	0.69
Cistern diameter	-6.90	-7.40	0.67	-7.09	-7.19	0.67	0.89
Wall thickness	2.38 ^a	3.22 ^b	0.32	2.85	2.75	0.32	0.59
Teat length	9.00	10.08	0.71	8.89	10.19	0.71	0.75
Milk yield	13.25	14.60	0.54	13.95	13.90	0.54	0.08
Milking time	596	520	41.2	481 ^a	635 ^c	41.2	0.94

s.e.d: standard error difference

Values with different superscripts, within rows, differ significantly, ^{ab} P<0.05, ^{ac} P<0.01, ^{ad} P<0.001.

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liner to fill the barrel of the liner as suggested by O'Callaghan (2001). Widening the upper barrel bore of a milk-liner can also result in a significant reduction in CD after milking with a corresponding increase in TWT. This reduction is probably due to more complete milk evacuation. With all teat parameters measured, changes in teat tissue tended to reduce towards their pre-milking values 15 minutes after milking. However, it has been shown that full recovery of teat tissue can take many hours (Gleeson *et al.*, 2002). Using either alternate or simultaneous pulsation patterns in mid-level or low-level milking systems had similar effects on teat tissue changes and on milk yield per cow. However, shorter milking times were observed with an alternate pulsation pattern and narrow-bore liners in a low-level milking system than with a simultaneous pulsation pattern and wide-bore liners. O'Callaghan (1998) showed that a higher teat-end vacuum occurs during the milking phase with the WB cluster in conjunction with simultaneous pulsation compared to the NB cluster in conjunction with an alternate pulsation pattern. This higher vacuum, in conjunction with higher vacuum at the teat-end in a low-level milking system, may result in more teat penetration into the liner during milking and may result in longer cluster-on times and higher TD changes. Widening the pulsator ratio from 60:40 to 67:33 in a mid-level milking system did not have negative effects on teat tissue and had a positive effect on cow milk yield and milking time. Previous studies by Hamann and Mein (1996) showed increased teat thickness changes when the 'b' phase was increased from 40% to 70% in conjunction with changes in the 'a' phase of the pulsator. Changing the 'a' value of the pulsator graph has also been shown to change milking time (O'Shea *et al.*, 1983). In this study, the pulse chamber phases 'a' and 'c' remained constant with the 'b' phase increasing from 42% to 49%. In this study, cluster-on time was reduced with a pulsator ratio setting of 67:33 as compared to a ratio of 60:40. This result would agree with the findings of Craig *et al.* (1991) and O'Callaghan (1998) that machines with a wide pulsator ratio would milk faster than those with a narrow pulsator ratio. The teat tissue changes and milking characteristics observed for clusters and pulsation patterns in a low-level milking system were similar to those observed for these components in a mid-level milking system. All pulsation treatments applied had TD changes within the $\pm 5\%$ level as suggested by Hamann and Mein (1996) as an indicator of the effectiveness of pulsation.

In a previous study by Hamann *et al.* (1993) teat length was reduced significantly by milking; whereas in all three experiments reported here, the mean teat length increased after machine milking. The increase in teat length after milking may be due to the increased cluster weight and higher cow milk yield with increased machine-on time.

The results of this study would agree with the findings of Brandsman (1968) that liner design has a bigger effect on milking characteristics than pulsation characteristics or vacuum level and liner design also appears to have a bigger effect on teat tissue changes than other machine settings.

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