
Milk Removal: The Key to Maintaining Milk Production and a Tool to Enhance Efficiency

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1. Introduction

Manipulation of the lactation curve by increasing peak milk production and (or) lactation persistency has consistently been a focus of both researchers and dairy producers. One of the key findings that has enabled manipulation of lactation performance is that the milk yield of dairy cows is responsive to demands of offspring or milk removal; hence milk production can be increased by frequent milking or suckling. Early studies illustrated the galactopoietic effect of frequent milking during the entire lactation, with three times daily milking increasing milk yield by up to 20% relative to twice daily milking. Research using nurse cows revealed a long-term increase in milk production when cows and heifers were allowed to suckle a calf during the first 8 to 10 wk of lactation (Everitt & Phillips, 1971; Edmunds, 1977; Fulkerson, 1981). The results of these experiments laid the groundwork for current research, which has identified a time during early lactation wherein the mammary gland of dairy cows is especially receptive to the stimulus of frequent milking. More recently, it has been established that frequent milk removal (three or more times daily) for a short duration within the first three weeks of lactation can increase milk production through the remainder of lactation (Hale et al., 2003; Dahl et al., 2004b; Wall & McFadden, 2007b). Since the establishment of the galactopoietic effect on milk production, several experiments have been conducted to identify the factors that regulate the milk yield response. These reports have documented consistent responses to increased milking frequency; however, questions remain about the mechanisms involved in regulation of milk production efficiency.

1.1. Frequent milking or suckling increases milk production

As previously indicated, frequent milking of dairy cows has emerged as an effective management tool for dairy farmers to increase milk production efficiency. Although it is a

relatively novel management practice, the original interest and research in this area dates back to the late 1800's (Hills, 1890; 1898). Despite considerable variation in the magnitude of the milk yield response, it was recognized long ago that thrice-daily milking (3X) increased milk production relative to twice-daily milking (2X), and that frequent milking could be a profitable management tool if costs associated with the extra milkings are outweighed by the value of additional milk obtained (Riford, 1922; Dahlberg, 1924). Cows milked 3X generally produced about 20% more milk than those milked 2X, and milk production could be increased another 7% by milking four times daily (4X) instead of 3X (Woodward, 1931). Modern-day adjustment factors used to compare milk production of cows milked 2X to those milked 3X range from 12-14%, depending on the parity of the cow (VanRaden et al., 1999).

Much of the work on frequent milking for the entire lactation was conducted during the 1980s and 1990s, when there was great interest in switching milking regimes from 2X to 3X in order to increase milk production efficiency (Table 1). A typical response to 3X milking is illustrated in Figure 1, which shows the lactation curves of cows milked 2X or 3X for the entire lactation (re-drawn from Amos et al., 1985). Three-times daily milking increased milk production both at peak and through the entire lactation. Persistency of the lactation curve was also slightly increased, but this effect disappeared after approximately 180 DIM. In summaries of DHIA records, the increase in milk production with 3X was 13, 12, and 16% compared to 2X (Allen et al., 1986; Gisi et al., 1986; Smith et al., 2002). These reports were obtained from mostly Holstein herds, or combined Holstein and Jersey herds. Culotta and Schmidt (1988) suggested that smaller dairy breeds do not respond as well to frequent milking as larger breeds. Consistent with that hypothesis were observations of Campos et al. (1994), that relative to 2X, 3X increased milk production by 17.3 and 6.3% in Holsteins and Jerseys, respectively. In contrast, Copeland (1934) observed an impressive 21 and 19% increase in milk and fat production, respectively, from Jerseys milked 3X compared to those milked 2X. In addition, they reported a correlation (+.64) between the amount of milk cows produced prior to frequent milking and the magnitude of the response to frequent milking (Copeland, 1934). This led to speculation that higher producing cows better responded to increased milking frequency than did lower producing cows. The existence of such a relationship, however, has not been established. To the contrary, Erdman and Varner (1995) and Stockdale (2006) reviewed the literature on frequent milking, and reported no correlation between previous milk production and the response to changes in milking frequency. Instead, those researchers concluded that there was an incremental milk yield response. Relative to 2X, this fixed milk yield response was -6.2, +3.5 and +4.9 kg/d for once daily milking (1X), 3X, or 4X, respectively (Erdman & Varner, 1995). In agreement with this, Peel et al. (1979) estimated that the post-suckling increase in milk production of cows suckled for as little as one week during early lactation was 4.3 kg/d. They went so far as to provide the readers with the following equation to allow prediction of the milk yield response to various suckling regimes:

$$\text{Increase in milk yield (\%)} = 4.3 \pm 0.8 \text{ (mean } \pm \text{S.E.)} \times \text{number of weeks suckled.}$$

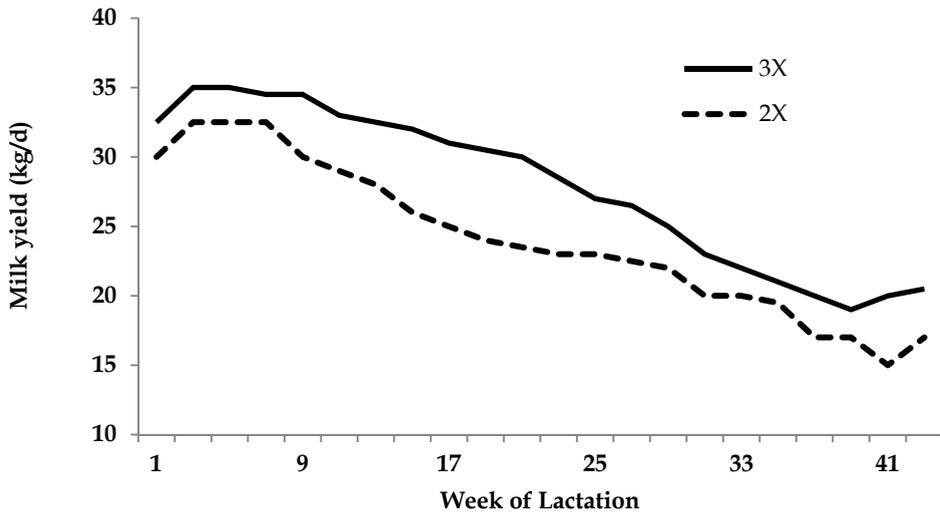


Figure 1. The effect of frequent milking on milk production of dairy cows. Lactation curves of multiparous cows milked twice (2X) or thrice (3X) daily for the entire lactation (re-drawn from Amos et al., 1985).

Reference	Parity	Breed	Duration of FM	Change in milk yield ^b (2X vs. 3X ^c)	Change in milk yield (2X vs. 4X)
Riford, 1922	≥ 1	Holstein; Guernsey	Unknown	+ 4.6 kg/d	
Woodward, 1931	≥ 1	Holstein	Full lactation	+ 20%	
Copeland, 1934	≥ 1	Jersey	Through late lactation	+ 21%	
Rao and Ludri, 1984	≥ 2	Brown Swiss x Sahiwal	50 to 130 DIM ^d	+ 1.34 kg/d	+ 1.73 kg/d
DePeters et al., 1985	≥ 2	Holstein	Full lactation	+ 17%	
	1	Holstein	Full lactation	+ 6% (NS)	
Amos et al., 1985	≥ 2	Holstein	Full lactation	+ 18.5%	
	1	Holstein	Full lactation	+ 25.2%	
Allen et al., 1986	≥ 2	Holstein	Full lactation	+ 13.4%	
	1	Holstein	Full lactation	+ 19.4%	
Gisi et al., 1986	≥ 2	Holstein	Full lactation	+ 12%	
	1	Holstein	Full lactation	+ 14%	
Barnes et al., 1990	1	Holstein	Full lactation	+ 14%	
Campos et al., 1994	1	Holstein	Full lactation	+ 17.3%	

Reference	Parity	Breed	Duration of FM	Change in milk yield ^b (2X vs. 3X ^c)	Change in milk yield (2X vs. 4X)
	1	Jersey	Full lactation	+ 6.3%	
Klei et al., 1997	≥ 1	Holstein	Full lactation	+ 10.4%	
Smith et al., 2002	≥ 1	Holstein	Full lactation	+ 16%	

^aReports on frequent milking or suckling during early lactation or on half-udders are represented in tables 3 and 5.

^bNumbers in columns represent the increase in milk yield observed with increased milking frequency.

^c2X = twice daily milking; 3X = thrice daily milking; 4X = four times daily milking.

^dDIM = days in milk

Table 1. Summary of selected literature reports on the effects of frequent milking (FM) on milk yield of dairy cows^a

Importantly, the increase in milk yield in response to frequent milking or suckling is not specific to dairy cows; milk production was increased with frequent milking or suckling of other dairy ruminants, including goats (Wilde et al., 1986), sheep (Geenty & Davison, 1982; Negrao et al., 2001; Nudda et al., 2002), and buffalo (Dash et al., 1976), as well as various cross breeds (Little et al., 1991; Krohn, 2001; Sidibe-Anago et al., 2008; Alvarez-Rodriguez et al., 2010).

1.2. Effects of frequent milking or suckling on milk composition and cow health

Reported effects of frequent milking on milk composition, somatic cell count (SCC) and herd health have been inconsistent. Many researchers have observed no effect of frequent milking on milk composition (Poole, 1982; Rao & Ludri, 1984; Amos et al., 1985; DePeters et al., 1985; Gisi et al., 1986), whereas some have observed a decrease in fat percentage (Allen et al., 1986; Smith et al., 2002). Due to the increase in milk production in response to frequent milking, however, there is often an increase in the total yield of fat and protein (Klei et al., 1997; Dahl et al., 2004b). With respect to SCC, some reports have indicated an association between frequent milking and decreased SCC, and these authors concluded that frequent milking may improve mammary health (Poole, 1982; Armstrong et al., 1985; Smith et al., 2002; Dahl et al., 2004b). Others have reported no effect of frequent milking on SCC (Waterman et al., 1983; DePeters et al., 1985; Gisi et al., 1986; Bar-Peled et al., 1995; Klei et al., 1997; Hale et al., 2003; Patton et al., 2006; Wall & McFadden, 2007a; Shields et al., 2011; Wright et al., 2011). The inconsistencies in the above reports may be the result of variations in timing and methods of sampling across experiments. Suckling of cows during early lactation has consistently been associated with a decrease in SCC and a decrease in the incidence of clinical mastitis, in some cases by up to 50% or more (Walsh, 1974; Edmunds, 1977; Little et al., 1991; Krohn, 2001). In fact, Walsh (1974) suggested that the increase in milk production elicited by suckling was probably due to the additional stimulus of the gland as well as the markedly improved mammary health of suckled animals.

Discrepancies also exist in the reported effects of frequent milking on reproductive performance and herd health. Some researchers have observed decreased reproductive

performance in 3X cows compared to 2X cows (Ludwin, 1942; Armstrong et al., 1985; DePeters et al., 1985; Smith et al., 2002), whereas others have observed no effect (Poole, 1982; Amos et al., 1985; Gisi et al., 1986) or an improvement (Allen et al., 1986) in reproductive performance with 3X. Armstrong et al. (1985) suggested that any negative effects of frequent milking on herd health or reproductive performance may be associated with poor herd management. Well-controlled field studies using standardized sampling procedures will be necessary to verify the impact of milking frequency on milk composition, SCC and herd health, as well as identifying the interaction between frequent milking and herd management on these factors.

Similarly, suckling of a calf during early lactation of the cow is associated with increased weight loss and an increase in the days to first estrus (Margerison et al., 2002). In most cases, however, the delay in resumption of estrous cyclicity is offset by an increase in conception rate (Little et al., 1991; Krohn, 2001). Consequently, the effects of suckling on reproductive performance appear to be negligible, or in some cases positive (Table 2). In addition, Perez-Hernandez et al. (2002) reported that exposure of cows to a teaser bull decreased the effects of suckling on days to first estrus. Therefore, in agreement with the suggestion by Armstrong et al. (1985), simple changes in management - when feasible - can be used to overcome any potential negative impact of frequent milking or suckling regime on reproductive performance. Table 2 summarizes the findings of Little et al. (1991), who looked at lactation and reproductive performance of cows allowed to suckle calves for the first 90 days of lactation.

	Suckled & machine milked	Machine milked
Total milk production (kg)	1,894.10	1,644.60
Lactation length (d)	341	305
Dry matter feed intake (kg/d)	13.25	13.14
Days to estrus	101	41
Services per conception	1.3	1.9

Table 2. Productivity characteristics of crossbred cows subjected to suckling compared to machine-milked herdmates. Cows were allowed to suckle their calves for the first 90d of lactation and were also machine milked twice daily for the entire lactation (Little et al., 1991).

In addition to the increase in milk yield, suckling during early lactation has also been associated with an increase in lactation length (Everitt & Phillips, 1971; Little et al., 1991; Krohn, 2001). This is particularly relevant since some producers are interested in incorporating an extended lactation management scheme into their herd. Extended lactation offers the benefit of decreased health risk to the cow because there is less exposure to risk of metabolic disease, which highest during the transition period. This, in turn, decreases costs to the producer associated with treating sick cows and veterinary expenses. The use of frequent milking or suckling offers a tool for increasing lactation persistency during

extended lactations. Indeed, Sorensen et al. (2008) reported that the use of increased milking frequency makes an extended lactation cycle economically viable for the producer, in addition to an observed improvement in the health of the cow.

1.3. Effects of suckling on calf health and performance

There are health benefits of keeping the calf with the cow and allowing the calf to suckle. Edmunds (1977) suggested that suckling calves generally perform better than those raised on milk replacer. Little et al. (1991) reported an increase in growth rate from birth to weaning of 0.2 kg/d for calves that were allowed to suckle vs. those that were raised on milk replacer. Similar observations were made by Alvarez-Rodríguez et al. (2010). In some cases, however, there is wide variation in the daily weight gain of suckling calves, especially if there are multiple calves on a single cow. Therefore, depending on the suckling scheme used, calves allowed to suckle don't always have higher growth rates than calves raised on milk replacer (Krohn, 2001). In a review of the literature, Edmunds (1977) reported that suckling calves had superior daily weight gain, a decrease in scours, and minimal incidence of other diseases compared to bucket-reared herdmates. The author suggested that this was a result of decreased stress associated with separation from the cow, since suckling calves are allowed almost constant contact with their mothers.

An interesting study conducted by Bar-Peled et al. (1997) reported on the performance of first lactation heifers that were allowed to suckle as calves, and compared them to heifers that were reared on milk replacer. Their findings are summarized in table 3, and have major implications regarding the effects of suckling on performance as adults; suckling clearly improved production efficiency in several areas.

	Suckled	Milk replacer
Body weight at conception (kg)	358.6	327.2
Average daily gain (kg)	0.82	0.68
Age at conception (d)	394	426
Conception rate (%)	83.4	74.2
Calving age (d)	669	700
Milk production (kg/300d)	9624	9171

Table 3. Productivity characteristics of heifers that were allowed to suckle as calves compared to herdmates raised on milk replacer. Heifers were allowed to suckle as calves for the first six weeks of life. Herdmates were raised on milk replacer (Bar-Peled et al., 1997).

1.4. The effect of parity on the response to frequent milking

It has been reported that the milk production response to frequent milking was more pronounced in animals with smaller udder capacity, such as heifers (Woodward, 1931; Copeland, 1934; Lush & Shrode, 1953). Copeland (1934) speculated that this may be a

function of increased udder pressure associated with less udder capacity. In agreement with this, Allen et al. (1986) observed that relative to 2X, 3X increased milk production by 13.4 and 19.4% in cows and heifers, respectively. In the previous year, however, another group reported that mature cows respond better to frequent milking than primiparous cows (DePeters et al., 1985). Of the studies that measured the milk yield response in heifers separately, most reported that heifers responded to frequent milking similarly to or better than multiparous cows. Therefore, no relationship has been established between parity and the magnitude of the milk yield response to frequent milking. To the contrary, we observed that that relative to multiparous cows, heifers respond similarly to increased milking frequency during early lactation (Wright et al., 2011). Similar observations have been made on the response of primi- vs. multi-parous cows to suckling during early lactation (Everitt & Phillips, 1971).

1.5. Economic impact of frequent milking or suckling

Several research groups have characterized the economic impact of frequent milking. Factors contributing to the profitability of frequent milking were labor, herd size, herd health, management, feed costs, and milk price (Armstrong et al., 1985; Culotta & Schmidt, 1988; Maltz et al., 2003). Rao and Ludri (1984) reported that 3X increased net income by 21% relative to 2X. More recently, we estimated a net increase of approximately \$93/cow/yr when cows were milked 4X for the first 3 wk of lactation and milked 2X thereafter (Table 4; Wall & McFadden, 2007b). With respect to suckling, McKusick et al. (2001) estimated an increase in net income of \$25 per ewe/suckling lamb pair in a mixed rearing system (in which ewes are suckled *and* machine milked until lambs are weaned) relative to ewes solely machine milked and lambs raised on milk replacer. The increase in profitability of suckling management systems comes from eliminating the expenses associated with purchase of milk replacer, and also the increase in milk production of the dams after the suckling period. This, combined with the observation of Bar-Peled et al. (1997) that suckling calves perform better as adults, indicates multiple areas of economic gain with a suckling regime. Therefore, when there are no negative effects on animal health or reproductive performance, frequent milking or suckling has the potential to be a very profitable management tool.

2. Frequent milking or suckling during early lactation: a window of opportunity

An exciting development for both dairy producers and dairy scientists was the finding that the timing of implementation can influence the milk yield response to frequent milking. During middle and late lactation, frequent milking increased milk production; however cessation of frequent milking resulted in an immediate decrease in milk yield to pre-treatment levels (Elliott, 1961; Morag, 1973a, b; Svennersten et al., 1990). During early lactation, however, frequent milking for a short duration can stimulate milk production and the effect persists through the remainder of lactation, even after less frequent milking is resumed. This effect was originally observed in experiments designed to determine the

milk yield loss associated with the use of nurse cows. Using identical twin cows, Everitt and Phillips (1971) discovered that suckling by calves in addition to machine milking during the first 8 to 10 weeks of lactation was associated with increased milk production after weaning and throughout the remainder of lactation in both primi- and multiparous cows (Figure 2). Shortly after this report, similar observations were made in both cows (Edmunds, 1977; Moss & O'Grady, 1978; Thomas et al., 1978; Fulkerson, 1981) and heifers (Fulkerson et al., 1978; Peel et al., 1979). Pearson et al. (1979) assigned cows to 3X for the first 143 d of lactation, followed by 2X thereafter. Although they did not report the full lactation curves, they measured milk yield for the entire lactation and reported that relative to 2X, cows that were milked 3X for the first 143 d of lactation produced more milk through 280 DIM (Pearson et al., 1979). Subsequently, it has been observed in numerous experiments that frequent milking during early lactation was associated with both acute and persistent increases in milk production (Table 5). These findings presented an opportunity for dairy producers; that an initial investment in labor could increase milk production efficiency for the remainder of lactation. Poole (1982) speculated that the practice might not be adopted, however, because producers would be discouraged by the partial decrease in milk production upon cessation of frequent milking, despite the significant carry-over effect.

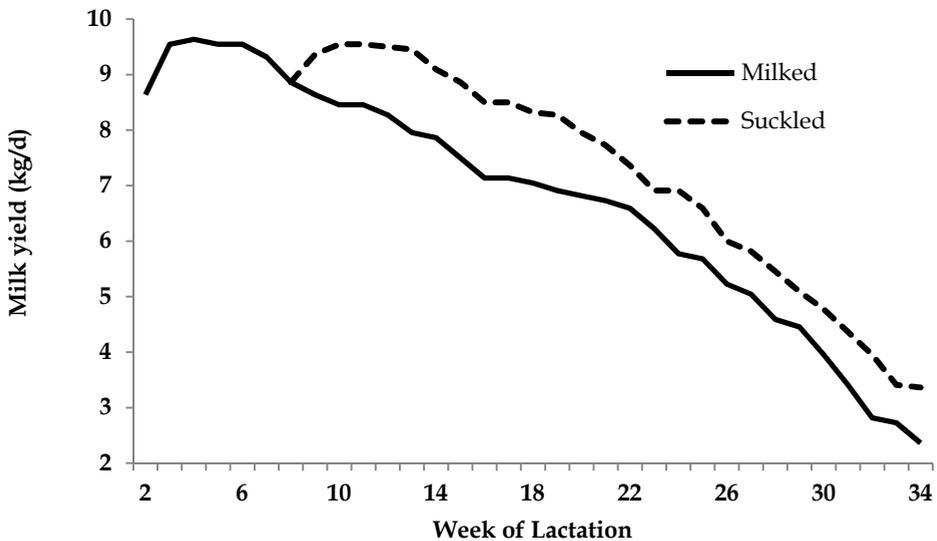


Figure 2. The effect of suckling during early lactation on milk production of dairy cows. *Ad libitum* suckling for the first 8 weeks of lactation increases milk production through late lactation (re-drawn from Everitt and Phillips, 1971). Cows were either milked 2X during the entire lactation (solid line), or were suckled by calves until 8 weeks of lactation, followed by 2X milking thereafter (dashed line).

Milking routine ^b	Feed cost during FM ^c	Feed cost after FM ^d	Labor ^e	Miscellaneous cost ^f	Extra milk income/cow/yr ^g	Total net income/cow/yr	100-cow herd ^h
4X 1 to 21	\$19.28	\$98.00	\$84.00	\$0.50	\$294.75	\$92.94	\$9,293.60
4X 1 to 14	\$12.86	\$100.75	\$56.00	\$0.34	\$210.29	\$40.33	\$4,032.85
4X 7 to 21	\$12.86	\$98.00	\$56.00	\$0.34	\$239.33	\$72.12	\$7,212.35

^aCows were assigned to unilateral frequent milking (twice daily milking of the left side, four times (4X) daily milking of the right side) for days 1 to 21, 1 to 14, or 7 to 21 of lactation (n = 10 cows per treatment). The differential milk yield response was adjusted to a whole-udder basis, and additional milk yield per cow was estimated (Wall & McFadden, 2007b).

^bFour times daily milking for days 1 to 21, 1 to 14 or 7 to 21 of lactation, followed by twice daily milking for the remainder of lactation.

^cAdditional feed to support increased milk production during frequent milking (FM), estimated at \$0.92/cow/d.

^dAdditional feed to support increased milk production after frequent milking, estimated at \$0.39/cow/d.

^eAdditional labor associated with extra milkings and animal handling during 4X milking, approximately \$4/d

^fCost associated with extra milkings, including inflation replacement, teat dip, and towels; approximately \$0.025/d

^gExtra milk income is based on \$12/cwt.

^hTotal net annual income for a 100-cow operation.

Table 4. Potential economic return of milking four-times daily during early lactation.^a

Reference	Treatment duration ^d	Parity	Change in milk yield (kg/d; 2X vs. 3X)	Change in milk yield (kg/d; 2X vs. 4X)	Change in milk yield (kg/d; 3X vs. 6X)
Pearson et al., 1979	1 to 150	≥ 2	+ 2.2		
Poole, 1982	1 to 140	≥ 2	+ 4.4 (acute)		
			+ 1.84 (pers.)		
		1	+ 2.17 (acute)		
			+ .65 (pers.)		
Bar-Peled et al., 1995	1 to 42	≥ 2			+ 7.3 (acute)
					+ 5.1 (pers.)
Sanders, 2000	1 to 42	≥ 2			+ 6.0 (acute)
					+ 3.7 (pers.)
		1			+ 1.7 (acute)
Hale et al., 2003	1 to 21	≥ 2		+ 8.6 (acute)	
				+ 2.6 (pers.)	
Dahl et al., 2004b	1 to 21	≥ 2			+ 14 (acute)
					+ 3.7 (full lactation)

^aReports on frequent milking during the entire lactation or on half-udders are represented in Tables 1 and 6.

^bNumbers in columns represent the increase in milk yield observed with increased milking frequency

^c2X = twice daily milking; 3X = thrice daily milking; 4X = four times daily milking; 6X = six times daily milking.

^dNumbers in columns represent days in milk.

^ePers. = the persistent increase in milk production after cessation of frequent milking.

^fAcute = the increase in milk production during frequent milking.

Table 5. Summary of select literature reports on the effects of frequent milking during early lactation on milk yield of dairy cows^a

In an attempt to minimize additional costs associated with frequent milking, and to investigate the response of dairy cows to frequent milking or suckling during a short interval of time in early lactation, Bar-Peled et al. (1995) compared 3X to 6X or 3X+suckling for the first 6 wk of lactation, followed by 3X of all cows. Relative to cows milked 3X during the entire lactation, 6X and 3X + suckling acutely increased milk production by 7.3 and 14.7 kg/d, respectively (Bar-Peled et al., 1995). Cessation of frequent milking or suckling was associated with a partial decline in milk production; however, a carry-over effect was observed in 6X cows (+5.1 kg/d relative to 3X; Bar-Peled et al., 1995). In a similar experiment, Sanders et al. (2000) observed an acute increase of 6 kg/d and a carry over response of 3.7 kg/d in 6X cows relative to 3X cows. In heifers, the acute response to 6X was lower in magnitude (+1.7 kg/d), and no carry over effect was observed (Sanders et al., 2000).

A summary of literature reports on the effect of suckling during early lactation on milk production is presented in Table 6. The results of subsequent experiments have further narrowed down the 'window' during early lactation wherein frequent milking can increase milk production for the remainder of lactation. Hale et al. (2003) assigned cows to 2X or to 4X for the first 3 wk of lactation, followed by 2X. Four times daily milking was associated with an acute increase of 8.8 kg/d and a carry over effect of 2.6 kg/d for the remainder of lactation. A treatment interval of 1 to 21 DIM was also used in a field study by Dahl et al. (2004b), who observed similar effects of frequent milking during early lactation. In contrast, VanBaale et al. (2005) assigned cows to 3X or 6X for the first 7, 14, or 21 d of lactation and reported that 6X did not increase milk production relative to 3X. Their observations were inconsistent with previous reports, and the authors speculated that facility logistics may have influenced their results because 6X cows were housed farther away from the milking parlor and spent a considerably longer time away from their pen than 3X cows (VanBaale et al., 2005). With the exception of one negative report (VanBaale et al., 2005), and one abstract (Fernandez et al., 2004), it is generally accepted that frequent milking increases milk yield, and that frequent milking or suckling during early lactation can increase milk production for the remainder of lactation (see Tables 5 and 6). The mechanistic basis for the milk yield response to frequent milking, however, is poorly understood. Even less understood are the mechanisms involved in the persistent effect on milk yield of frequent milking during early lactation.

Reference	Treatment Duration (DIM)	Parity	2X vs. 1X + suckle	2X vs. 2X + suckle	3X vs. 3X + suckle
Everitt and Phillips, 1971	1 to 70	2+		(+) 1.2 kg/d (pers. ^a)	
		1		(+) .87 kg/d (pers.)	
Walsh, 1974	1 to 100	2+		(+) 11.3% (acute ^b)	
				(+) 7.7% (pers.)	
Moss and O'Grady, 1978	1 to 56	2+		(+) 3.3 kg/d	
					(no pers.)
Thomas et al., 1978	1 to 56	2+		(+) 1.68 kg/d (acute)	

Reference	Treatment Duration (DIM)	Parity	2X vs. 1X + suckle	2X vs. 2X + suckle	3X vs. 3X + suckle
				(+) 1.77 kg/d (pers.)	
Fulkerson et al., 1978	1 to 56	1	(+) 16% (full lactation)		
Pearson et al., 1979	1 to 150	2+			
Peel et al., 1979	1 to 28	1	(+) 13% (pers.)		
Fulkerson et al., 1981	1 to 7	2+	(+) 9% (pers.)		
Teeluck et al., 1981	1 to 90	2+	(+) 2.2 kg/d	(+) 3.33 kg/d	
Poole, 1982	1 to 140	2+			
Little et al., 1991	1 to 94	5	(+) 15% (full lactation)		
Bar-Peled et al., 1995	1 to 42	2+			+ 14.7 kg/d (acute)

^aPers. = the persistent increase in milk production after cessation of suckling, if reported

^bAcute = the increase in milk production during suckling

Table 6. Summary of select literature reports on the effects of suckling during early lactation on milk yield of dairy cows

3. Local regulation of the milk yield response to frequent milking

Shortly after the report in the 1930s that frequent milking increased milk production, several studies utilized unilateral frequent milking (UFM) to investigate the effect. Half-udder designs are extremely powerful because they eliminate variation between animals due to environment, nutrition, and genetics. In addition, both udder halves are theoretically exposed to the same systemic factors, hence responses to frequent milking are strictly at the level of the mammary gland. A summary of the milk yield response to frequent milking in selected half-udder experiments is presented in Table 7. The early reports provided strong evidence for local regulation of milk production, and increases in milk yield from 8.4 to 32% in the frequently-milked udder half were observed (Ludwick et al., 1941; Cash & Yapp, 1950; Agarwala & Sundaresan, 1955; Claesson et al., 1959). Morag (1973b) reported that the increase in milk production in response to UFM occurs within 24 h, and the magnitude of the response was independent of previous milk production. In addition, heifers respond to UFM; Hillerton et al. (1990) milked udder halves 2X or 4X for 4 wk during mid-lactation. In both cows and heifers, milk production of 4X udder halves increased by 10.4% relative to 2X udder halves (Hillerton et al., 1990).

Reference	Stage of Lactation	Duration of UFM	Parity	Change in milk yield (%; 2X vs. 3X)	Change in milk yield (2X vs. 4X)
Cash & Yapp, 1950	-	Full lactation	≥ 2	+ 32	
Agarwala & Sundaresan, 1955	Early	25 d intervals	≥ 2	+ 8.4	
Hillerton et al., 1990	Mid-late	28 d	≥ 1		(+) 10.4%
Knight et al., 1992	Mid	14 d	1		(+) 14%

Reference	Stage of Lactation	Duration of UFM	Parity	Change in milk yield (%; 2X vs. 3X)	Change in milk yield (2X vs. 4X)
Knight, 1992	Early	42 d	≥ 1	+ 10.4	
Norgaard et al., 2005	Mid	7 d	≥ 1		(+) 18%
Wall & McFadden, 2007a	1 DIM ^d	21 d	≥ 2		(+) 3.5 kg/d (acute ^e)
					(+) 1.8 kg/d (pers. ^f)
Wall & McFadden, 2007b	1 DIM	14 d	≥ 2		(+) 3.7 kg/d (acute)
					(+) 1.2 kg/d (pers.)
	7 DIM	14 d	≥ 2		(+) 2.9 kg/d (acute)
					(+) 1.5 kg/d (pers.)
Wright et al., 2011	1 DIM	21 d	1		(+) 2.8 kg/d (acute ^e)
					(+) 0.9 kg/d (pers.)
Shields et al., 2011	1 DIM	21 d	≥ 2		(+) 3.4 kg/d

^aReports that did not use half-udders are represented in Tables 1 and 5.

^bNumbers in columns represent the increase in milk yield observed with increased milking frequency.

^c2X = twice daily milking; 3X = thrice daily milking; 4X = four times daily milking.

^dDIM = days in milk.

^eAcute = the increase in milk production during frequent milking.

^fPers. = the persistent increase in milk production after frequent milking, if reported.

Table 7. Summary of select literature reports on the effects of unilateral frequent milking (UFM) on milk yield^a

As mentioned previously, an emerging theme in these experiments has been that the effects of frequent milking during early lactation on milk production persist even after a lower milking frequency is resumed (Bar-Peled et al., 1995; Hale et al., 2003; Dahl et al., 2004b). Although this persistent milk yield response has been consistently observed (Table 5), it was unknown whether the response was regulated by hormones, by local factors within the mammary gland, or by the combination of the two. To investigate this question, we used a half-udder model and assigned cows to UFM (4X of the right udder half, 2X of the left udder half) for d 1 to 21 of lactation, followed by 2X for the remainder of lactation (Wall & McFadden, 2007a). When the half-udder milk yields were adjusted to the equivalent of a whole udder basis, the acute and long-term milk yield responses to frequent milking that we observed were consistent with those reported by Hale et al. (2003). Therefore, our results indicated that both the acute and persistent effects of frequent milking during early lactation are regulated by local factors within the mammary gland. This is illustrated in Figure 3A and B. Figure 3A (re-drawn from Bar-Peled et al., 1995) shows the milk yield response of multiparous cows to 6X for the first 6 wk of lactation, followed by 3X. We observed a similar effect using a half-udder experiment (Figure 3B), and the milk yield response lasted through 270 DIM. This finding presents some intriguing questions and research opportunities. First, what are the local factors that regulate milk production capacity of the mammary gland? Once the factor(s) have been identified and pathways understood, how can we refine our approach to maximize milk production efficiency of dairy cows? Now that it is established that the factors are indeed local, the problem has become relatively simplified. Extremely

powerful, within cow experiments that are less sensitive to the influence of environment, genetics and nutrition can now be designed to ask such mechanistic questions.

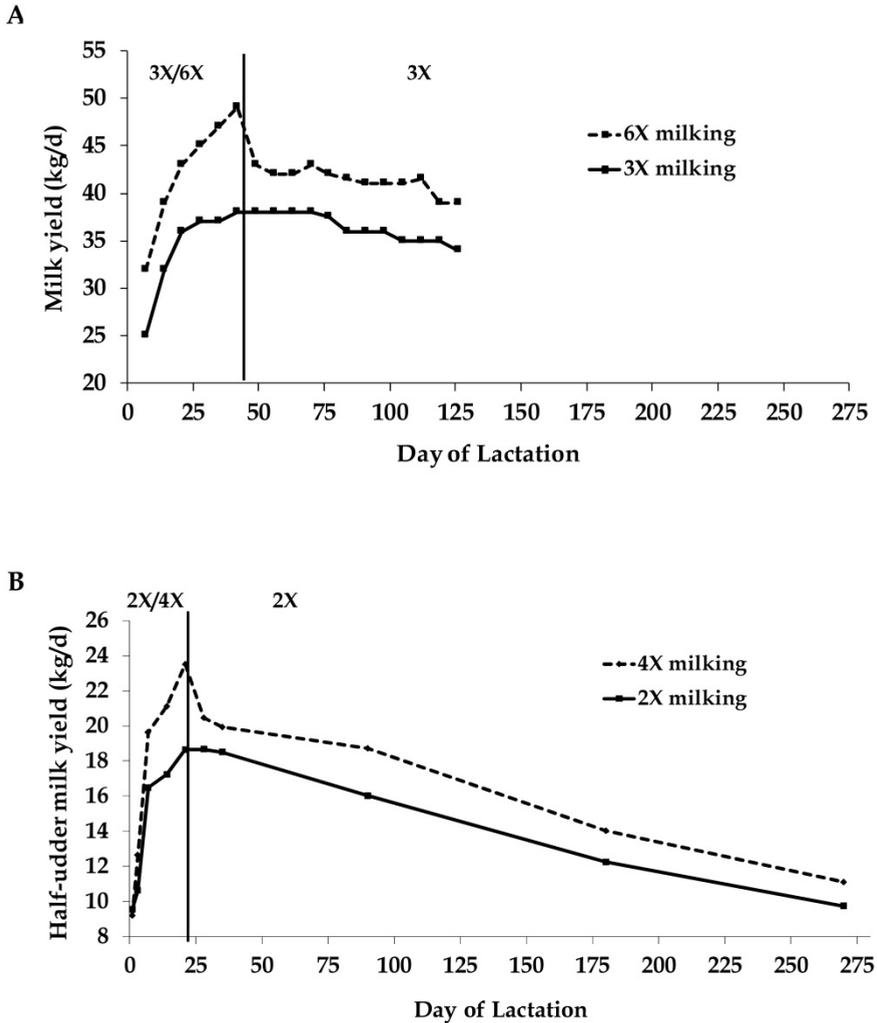


Figure 3. A. Six-times daily milking for days 1 to 42 of lactation increases milk production through late lactation (re-drawn from Bar-Peled et al., 1995). B. Unilateral four-times daily milking for days 1 to 21 of lactation increases milk production for the remainder of lactation (Wall and McFadden, 2007).

On the road to refinement, one theme that has transpired is the existence of a 'window' of time wherein the mammary gland is especially responsive to frequent milking. The duration of this window has been shortened from the first 10 wk of lactation (Moss & O'Grady, 1978; Thomas et al., 1978) to the first 6 wk of lactation (Bar-Peled et al., 1995; Sanders et al., 2000), and shortened further still to the first 3 wk of lactation (Hale et al., 2003; Dahl et al., 2004b;

Wall & McFadden, 2007a). It was unknown whether a shorter duration or altered timing of frequent milking during early lactation would still elicit a persistent effect on milk production; however, since any costs associated with extra labor are increased only during frequent milking, it was of great interest to shorten the duration of frequent milking if a persistent increase in milk yield could still be observed. To answer this question, we assigned cows to UFM (4X of the right udder half, 2X of the left udder half) for d 1 to 14 or d 7 to 21 of lactation (Wall & McFadden, 2007b). We observed an acute milk yield response in both treatments; and a significant carry-over effect in the d 7 to 21 group. There was a numerical carry-over for the d 1 to 14 group; however it was not significant. Our results indicate that within the first 21 DIM, an interval of frequent milking as short as 2 wk can elicit a persistent increase in milk production. As mentioned previously, similar observations have been made on the response of cows and heifers to suckling during early lactation (Fulkerson et al., 1978; Peel et al., 1979). Further narrowing of this “window” within the first 21 of lactation, as well as characterization of the cellular response could provide insight into the mechanisms underlying the receptiveness of the mammary gland to stimulus during this time.

4. Endocrine response to frequent milking or suckling

It has long been thought that the hormones released at milking may be involved in regulating the galactopoietic effects of frequent milking on milk production. Indeed, multiple hormones are released during milking including glucocorticoids, oxytocin, and prolactin (Tucker et al., 1975; Carruthers & Hafs, 1980; Akers & Lefcourt, 1982). Oxytocin is responsible for milk ejection. Cows suckling calves are thought to have more efficient milk ejection due to increased secretion of oxytocin elicited by the presence of the calf. In fact, on dairies using cross breeds and cows not bred for high milk production, the calf is often used as a facilitator of milk letdown during milkings (Little et al., 1991; Krohn, 2001; Bruckmaier & Wellnitz, 2008). In addition, treatment with exogenous oxytocin was associated with increased milk production of both dairy cows (Nostrand et al., 1991; Ballou et al., 1993; Lollivier & Marnet, 2005) and sheep (Zamiri et al., 2001). Therefore, it is possible that oxytocin is involved in regulating the increase in milk production elicited by frequent milking or suckling, perhaps by allowing for more complete milk removal and a decrease in negative feedback on the gland.

Along with enhanced milk production, Bar-Peled et al. (1995) observed increased concentrations of growth hormone, insulin-like growth factor-1, oxytocin and prolactin in circulation of cows that were frequently milked or suckled. In addition, the magnitude of milking-induced PRL release declines concomitantly with the decrease in milk production as lactation progresses (Koprowski & Tucker, 1973). Consequently, PRL has been hypothesized as a candidate regulator of the effects of frequent milking on milk production (Dahl et al., 2004a). In an attempt to determine whether milking-induced PRL release indeed mediates the effects of frequent milking on milk production, we assigned cows to 2X, 4X, or 2X + twice daily injections of PRL (Crawford et al., 2004; Wall et al., 2006). Four times daily milking or PRL injections increased milk production relative to 2X (Crawford et al., 2004);

however our results indicated that PRL injection or frequent milking exerted distinct effects on mammary cell growth and gene expression, thus probably increased milk production via separate mechanisms (Wall et al., 2006). The response to unilateral frequent milking during early lactation supports this concept; frequent milking may stimulate milk production via local factors, whereas PRL injections may increase milk yield through a more systemic pathway.

5. Cellular response to frequent milking

Several authors have speculated that frequent milking increases milk yield via an increase in mammary cell number and (or) activity (Bar-Peled et al., 1995; Stelwagen & Knight, 1997; Sanders et al., 2000; Hale et al., 2003), both of which are critical to improved lactation performance (Capuco et al., 2003). Hillerton et al. (1990) observed an increase in activity of mammary enzymes, protein and lactose synthesis (in heifers only), DNA synthesis, and alveolar area in response to increased milking frequency, and concluded that cellular differentiation and proliferation were optimized with frequent milking. Hale et al. (2003) reported an increase in mammary cell proliferation at 7 DIM in cows that were milked 4X for the first 3 wk of lactation compared to cows milked 2X; however, differences in proliferation were only observed in one of the two frequently milked cow groups. In contrast to those experiments, Norgaard et al. (2005) reported that despite an increase in milk yield (+18%), there was no effect of frequent milking on cell death, proliferation, or enzyme activities in the mammary gland. In agreement with that report, we have observed across multiple experiments that relative to 2X, 4X did not affect mammary cell proliferation or apoptosis (Wall et al., 2006; Wall & McFadden, 2010; Wall et al., 2011b), indicating that changes in milking frequency influence milk yield through an alternative mechanism.

Using a unilateral frequent milking model and a functional genomics approach, we determined that the increase in milk yield associated with frequent milking is regulated by changes in gene expression elicited by removal of milk from the gland (Wall et al., 2011a). We then used a sequential biopsy approach and obtained mammary tissue at various times during and after exposure to unilateral frequent milking and determined that the temporal expression of 64 genes was co-regulated by unilateral frequent milking (Wall et al., 2011b). Importantly, the pattern of differential expression of the 64 genes was negatively correlated with differential milk yield (Figure 4); therefore, we hypothesize that we have identified a pathway for the autocrine regulation of milk production. Furthermore, this transcriptional signature appears to be malleable and adaptable to the needs of the offspring (mimicked by changes in milking frequency), since expression of some of the genes was still different between udder halves nearly three weeks after cessation of treatment (Figure 4). Future experiments will clarify the role of these genes in the mammary gland and their involvement in the autocrine regulation of milk production.

What is unique to early lactation, when the stimulus of frequent milking for a short duration can elicit a persistent increase in milk production? This question remains

unanswered, but work by Stelwagen and Knight (1997) has provided some clues. Using a half-udder model, they compared 1X to 2X of cows in early or late lactation and reported a more dramatic increase in milk secretion efficiency in response to 2X during early lactation compared to late lactation (Stelwagen & Knight, 1997). In agreement, Walsh (1974) observed different effects of suckling during early vs. late lactation on mammary health. During early lactation, suckling of a calf was associated with a 27% decrease in clinical mastitis, whereas suckling during late lactation had no effect (Walsh, 1974). Taken together, the observations of Walsh (1974) and Stelwagen and Knight (1997) indicate that there are distinct differences in the cell population during early vs. late lactation. It is possible that during early lactation, there are more secretory cells present in the mammary gland, and these cells may have more potential to respond to stimulus than cells present in late lactation. Frequent milking may prevent otherwise unused cells from undergoing apoptosis, or may provide the stimulus to push the cells to reach higher levels of differentiation and secretory capacity. These scenarios could result in an increase in the number of cells in the gland throughout lactation, an increase in the activity of cells throughout the lactation, or both. Shorten et al. (2002) proposed a hypothetical model by which frequent milking for the entire lactation increases the number of active alveoli by reducing the rates of quiescence and senescence in the mammary gland. If such an event occurs with frequent milking during early lactation, this could permanently increase the number of actively secreting alveoli and enhance milk production potential for the remainder of lactation. Many of the biopsy studies that have been previously conducted could have captured changes in mammary cell activity, but would not have captured changes in total cell number or in rates of quiescence and senescence within the gland.

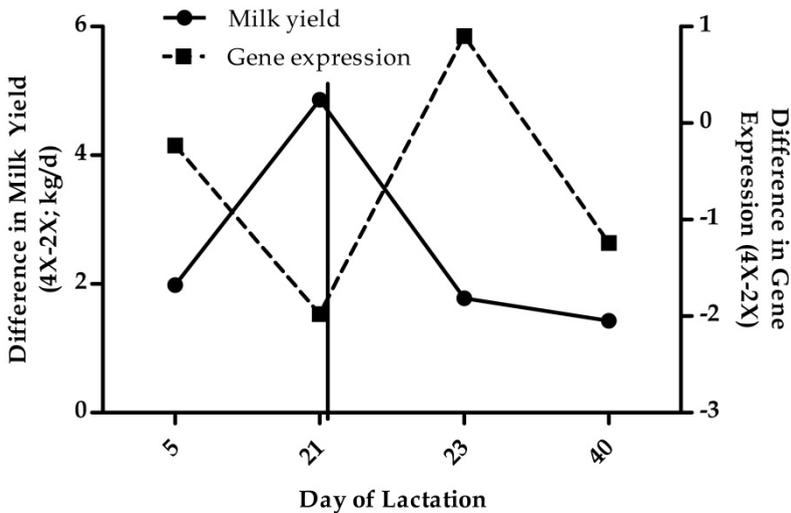


Figure 4. Unilateral four-times daily milking for days 1 to 21 of lactation is associated with coordinated changes in mammary expression of 64 genes, and this is negatively correlated with differential milk yield. Solid vertical line represents cessation of unilateral frequent milking.

6. Conclusions

Research in the area of frequent milking of dairy cows has established a robust milk yield response to increased milking frequency or suckling, and has identified a window of time during early lactation wherein the mammary gland is especially responsive to the stimulus of frequent milk removal. In addition, there is now evidence that this response is regulated within the mammary gland. Consequently, the concept of 'use it or lose it' is becoming more clearly established, that is, the stimulus of frequent milking or suckling during early lactation permanently increases the milk production capacity of the mammary gland. Exciting research opportunities now present themselves, and ongoing experiments seek to identify the local factor(s) that are involved in the regulation of milk production efficiency of dairy cows. The opportunity now exists for dairy scientists to identify the mechanisms involved in local regulation of milk production potential, and for dairy producers to further refine milking management practices to maximize milk production efficiency of their operations.

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