Computerised Breast Measurement System

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INTRODUCTION

Mammary gland physiology has been extensively investigated in both dairy and laboratory species. However, in women little is known about the control of breast function, due to the lack of suitable measurement techniques. Conventional test-weighing techniques measure the amount of milk transferred to the infant. However, since babies that are breastfed on demand drink to appetite and usually do not empty the mother's breasts at each breastfeed, test weighing does not necessarily measure the synthetic activity of the breast (Daly and Hartmann, 1995). We reasoned that the increase in breast volume from the end of one breastfeed to the beginning of the next, divided by the time between breastfeeds, provides a measure of the mother's short-term rate of milk synthesis. Following the exploration of a number of photo-topographic systems, we developed a non-invasive Computerized Breast Measurement (CBM) system capable of quantifying changes in breast volume from one breastfeed to the next. This paper describes the conception of the volume measurement system and its evolution. We highlight the principle findings from studies using the CBM system, and explain how they relate to the understanding of breast physiology

CONCEPTION OF THE IDEA

Western Australia has a large mining industry, and for many years mining surveyors, here and elsewhere, have quantified large stockpiles of ore by stereoscopic aerial photography. Stockpiles of ore and ore-containing mountains (Fig. 1), viewed from an altitude of about 1000 m, have similar characteristics to a breast viewed from a distance of about one metre. This lead to the concept of measuring the volume of the breast stereoscopically. Working in collaboration with a local mining company (Associated Surveys International Pty, Ltd), the volume of volunteers' breasts were measured. Unfortunately the breast was smoother and had a more uniform colour than ore bodies, presenting problems for the stereoscopic measurement technique. Nevertheless, it was possible to calculate breast volume (albeit in metric tonnes!).

Figure One. Stockpiles of salt (left) and a mineral containing mountain (right), that provided the inspiration to measure breast volume stereoscopically.

MOIRE TOPOGRAPHY

Following the success of the stereoscopic measurement of breast volume, Arthur et al. (1986) investigated breast volume, this time using Moire fringe patterns to create topographic maps of the breast (Figure 2). While Moire topography allowed accurate measurement of breast volume, slow data processing made this method impractical for the measurement of large sample numbers. Also, the method required the formation of uninterrupted fringe patterns on the breast and, hence, was limited to the study of smaller breasts (Fig. 2), since large breasts exhibit sharp depth discontinuities at the base and sides and these discontinuities cause the fringe patterns to break up. Therefore, a topographic system that could rapidly determine breast volume, on a wide range of breast sizes, was required. These conditions have been satisfied by the development of the CBM system (Figure 3).

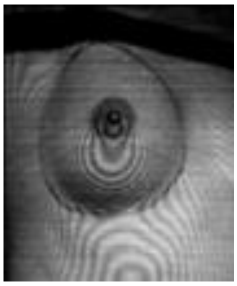

Figure 2. Moire fringe patterns projected onto a breast. These patterns were formed by projecting light through a screen of closely spaced moving wires.

COMPUTERISED BREAST MEASUREMENT SYSTEM

The CBM system consists of a repositioning frame which provides physical constraints to enable the mother to return to approximately the same position each time a measurement is made (Figure 3). Precise repositioning for subsequent measurements is achieved by using a video mixer so that the mother can view a video monitor and match her live image to an overlaid image stored from her initial measurement. In order to measure the changes in breast volume a circle, encompassing all of the breast tissue, is drawn around the breast with non-toxic, black acrylic paint. The CBM system is both a hardware and software development of the ShapeC Measurement System (Alexander & Ng, 1987), which utilises the apparent distortion of horizontal coded light stripes to make volume measurements. A sequence of structured light patterns is projected on to the woman's breast (Fig. 4) so that interrupted stripes can be tracked by the computer program. The images are captured over a period of 0.3 second by a CCD camera linked to a frame grabber. We now have two projector-camera pairs coupled to the system so that the breast can be sequentially viewed from above and below (Fig. 3).

Figure Three. The CBM system

This improves the precision of measurements for women with larger breasts. When the breast is viewed by the CCD camera from a position offset (by 15o in our system) from the plane of the light stripes (Figure 4), the parallel pattern of stripes is distorted by the curvature of the breast and a topographic map is created (Figure 5). From the apparent distortion of the light stripes, the x, y, and z co-ordinates of individual points which track the light stripes are calculated by active triangulation. The aggregate of these points describes the three dimensional surface of the breast. Relative breast volume is then simply calculated by integration of the region under the surface curve, and within the black painted circle that surrounds the breast (Figure 6; Huynh et al., 1990). Thus, the CBM system does not determine absolute breast volume, but rather measures a relative volume, that is, the volume of tissue enclosed within the black painted circle. It is assumed that when synthetic tissue is making and secreting milk, the volume of non-breast tissue remains the same.

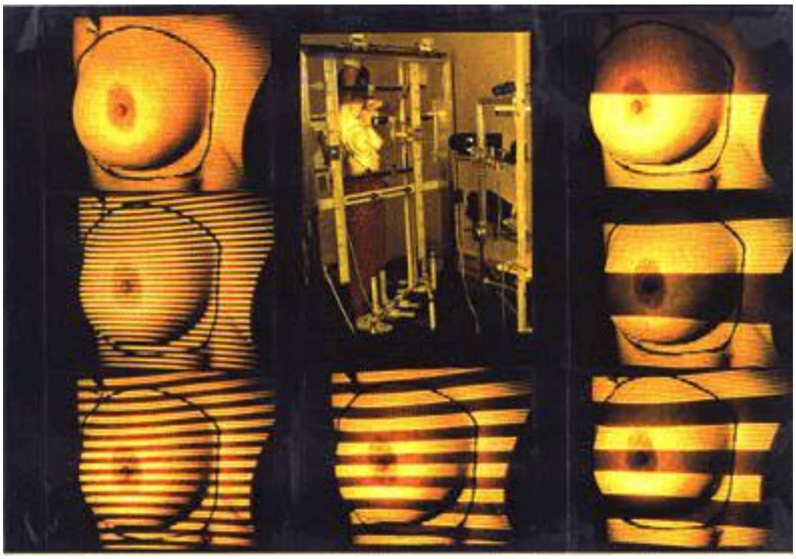

Figure Four. The CBM system (inset panel), surrounded by images of a breast with each of the coded light striping patterns projected onto it. The final image that is captured and used for the topographic reconstruction contains no stripes.

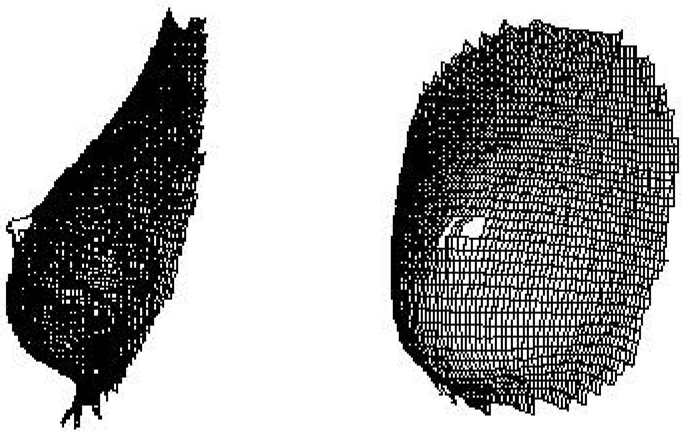

Figure Five. Three-dimensional topographic maps of a breast viewed from two angles. These surface maps were constructed as described by Cox et al. (1994).

VALIDATION OF MEASUREMENTS

The CBM system has been designed to maximise accuracy and sensitivity for the measurement of changes in breast volume. The validity of using the CBM system for these measurements was confirmed by relating the change in breast volume from before to after a breastfeed (measured by the CBM system) to the mass of milk removed from the breast over the same interval (measured by test weighing). These two parameters were strongly related ($r^2=0.93$), for volumes ranging up to ~200 mL (Daly et al., 1992). Consequently, it was concluded that any increase in breast volume after a breastfeed must be related to the volume of milk that is synthesised, and therefore the increase in breast volume divided by the time between measurements gives a measure of the short-term (between feeds) rate of milk synthesis (Figure 7).

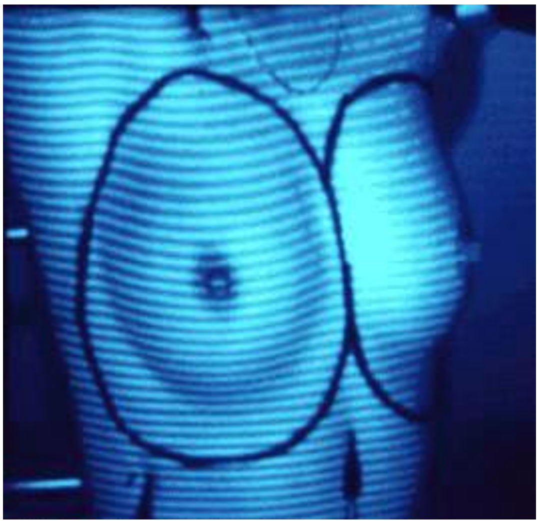

Figure Six. View of the breast from an angle offset from the plane of light. Note the apparent distortion of the stripes as they fall on the breast. Also note the hand-applied black acrylic paint circle that delimits the tissue for volume determination.

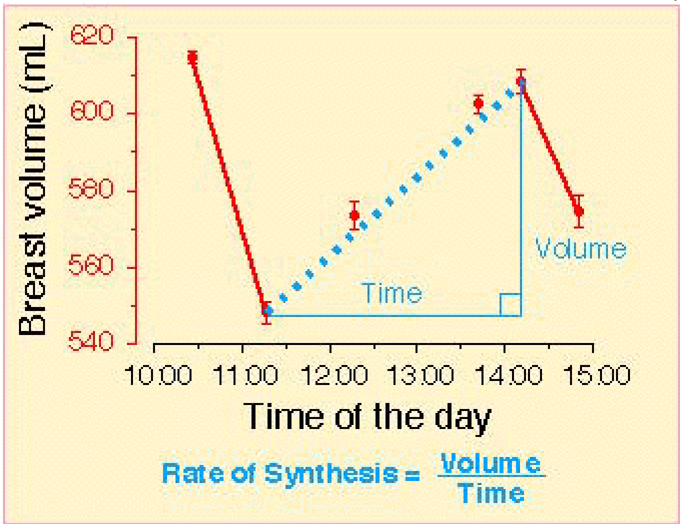

Figure Seven. Calculation of the rate of milk synthesis. The solid red lines represent the change in breast volume with breastfeeding, and the dashed blue line represents the change in breast volume with the synthesis of milk. The rate of milk synthesis was calculated as the change in breast volume over time.

SHORT-TERM RATE OF MILK SYNTHESIS

Using the CBM system we have focused on identifying the factors regulating the short-term (i.e. between breastfeeds) rate of milk synthesis.

Popular theory suggests that milk synthesis is controlled through prolactin. The rationale for this was that the prolactin levels in the maternal plasma increase in response to suckling (Noel et al., 1974). Thus, it was envisaged that the elevated prolactin levels would stimulate the synthesis of enough milk to replace the removed milk. Although this theory has not been tested, it has become entrenched in the text-books (e.g. Dulbecco, 1987).

We used the CBM system to measure the in vivo rate of milk synthesis and to investigate its relationship with prolactin. We measured the concentration of prolactin in the plasma before and 45 minutes after the commencement of breastfeeds over the first six months of lactation. Both the basal and the peak concentrations of prolactin in the plasma declined over this period. In contrast, neither 24 h milk production nor the average short-term rates of milk synthesis changed significantly over this period. Thus, the concentration of prolactin in the plasma was not related to the rate of milk synthesis (Cox et al., 1996). In addition, it was concluded that the control of milk synthesis was located within each breast, since the rate of milk synthesis in one breast was not related to the rate of milk synthesis in the other breast (Fig. 8; Cox et al., 1996).

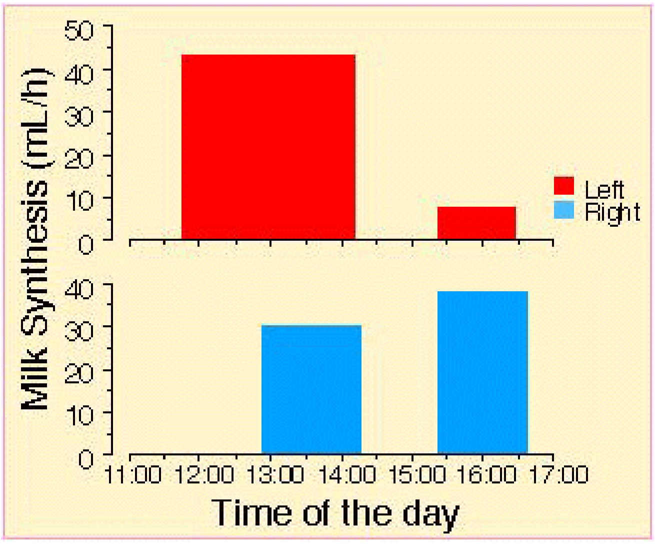

Figure Eight. The variation in the rate of milk synthesis, both within and between the breasts, of an individual mother over a single day.

Daly et al. (1993b) used the CBM system to measure the changes in breast volume of seven breastfeeding mothers over each breastfeed during a 24 h period. From these measurements they could determine the maximum and minimum volume of the breast over the 24 h period, the storage capacity of each breast (maximum-minimum breast volume), the degree of emptying of the breast, before and after each breastfeed, and the short-term rates of milk synthesis. They found that the storage capacity of the breasts ranged from 80 to 600 mL. The breast was not necessarily completely emptied at each breastfeed (Mother A; Fig. 8), indicating that the infants regulated their milk intake presumably according to their appetite. Daly et al. (1993b) suggested that the storage capacity of the breast influenced the frequency of breastfeeding. Compared to mother A, mother B had a much smaller storage capacity and her infant nursed more frequently. By more frequent breastfeeding this infant was able to obtain at least as much milk as the infant of mother A (956 vs 896 mL/24 h, respectively).

The rate of milk synthesis varied from breastfeed to breastfeed (Figs. 8 and 9). Taking the example of mother A, the rate of milk synthesis was lowest when the breasts were full and highest when they were near empty. In the case of mother B there was no major variation in the rate of milk synthesis throughout the day. Overall, Daly et al. (1993b) found that the rate of milk synthesis was related to the degree of emptying of the breast and concluded that the control of the rate of milk synthesis was localised within the breast. Furthermore, this control responded to changes in the degree of breast fullness (Daly et al., 1993b; Cox et al., 1996). The short-term rates of synthesis for mother B's right breast are consistent with this conclusion as it was emptied to a constant degree (Figure 9)

Since prolactin is a potent stimulator of the synthesis of milk components (Cowie et al., 1980), and the control of milk synthesis is localised within the breast (Daly et al., 1993b; Cox et al., 1996), we hypothesized that the control of milk synthesis may be related to a restriction on the binding and subsequent entry of prolactin into the mammary gland. Noilin (1979) found that the entry of prolactin into lactating rat lactocytes was restricted by the morphology of the lactating cell, that is, prolactin entered the cells only when they were tall and columnar and had minimal milk in the alveolus. We found that the amount of prolactin in the milk from a full gland was high at first and then declined as milk was removed from the breast. This is consistent with Noilin (1979) assuming that there is minimal mixing of milk within the breast, and that the fore-milk is synthesized during the periods when the lactocytes are in the columnar formation and the alveolus is close to empty (Cox et al., 1996).

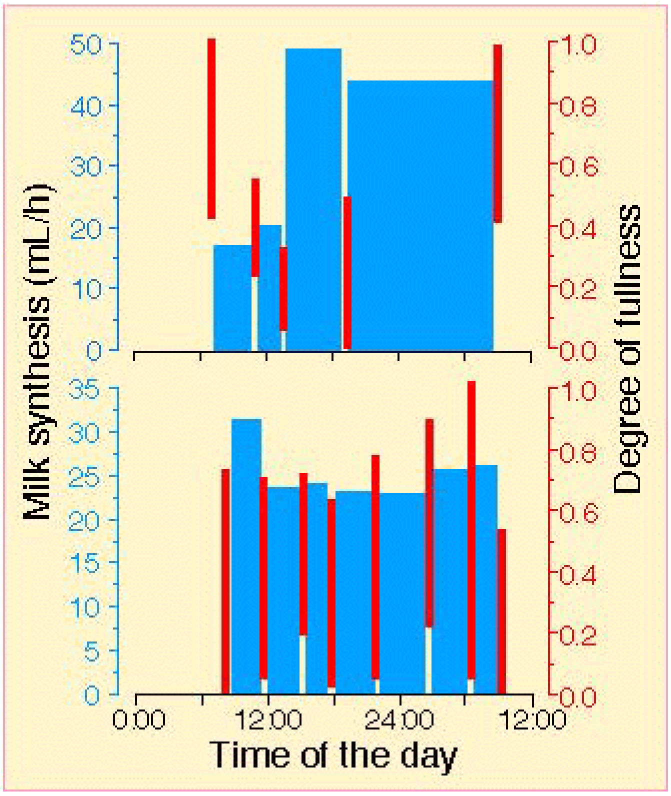

Figure Nine. The degree of fullness (1-degree of emptying (Cox et al., 1996)) of the left breast from before to the end of a breastfeed and the rate of milk synthesis in that breast for two of the women described by Daly et al. (1993b). Note that there is an inverse relationship between these two factors in the case of mother A, while for mother B both the rate of milk synthesis and the minimum degree of fullness after each breastfeed are relatively

MILK FAT

For many years it has been known that the fat content of milk that is expressed from the breast following a breastfeed (hind-milk) is higher than in the milk before a breastfeed (fore-milk). This has lead to the suggestion that, in cases of lactation insufficiency, women should feed their infants more "hind-milk", assuming that this milk has a higher energy content. Daly et al. (1993a) measured the fat content of the milk, before and after every breastfeed for 24 h and found that rather than being related to whether it was fore- or hind-milk, the fat content was related to the degree of fullness of the breast. Therefore, as the breast is progressively emptied, the fat content in the milk increases.

PRINCIPAL FINDINGS

1. The concentration of prolactin in the maternal plasma does not control milk synthesis.
2. Infants can regulate their own milk intake.
3. The rate of milk synthesis is regulated within each breast.
4. The rate of milk synthesis is related to the degree of emptying of the breast.
5. The capacity of each breast to store milk varies greatly between women.
6. Storage capacity of the breasts can influence the flexibility a mothers has in relation to the frequency of breastfeeding her infant.
7. The control of milk synthesis may restrict the binding and entry of prolactin into the cell.
8. The fat content of the milk progressively increased as the breast was emptied, thus the fat content of milk was related to the fullness of the breast.

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