Summary of Key Findings

Background: This study was conceived and initiated against a background of change among the scientific and practitioner community over how a baby breast-feeds. While it has been the conventional view (presiding for 350 years, or so) that babies use a predominantly peristaltic tongue motion to express milk from the breast, this view has been challenged by fresh ultrasound work from the research group in Perth, Western Australia (funded by Medela). Their work has suggested babies predominantly use suction to remove milk from the breast, generated by localised drawing down of the tongue surface. This assertion replicates the original observation of Eishima (1991), but has been extrapolated beyond her original interpretation.

This modified view of breastfeeding, approximates more closely to the conventional view of bottle-feeding as portrayed in many lay textbooks. The introduction of bottles is commonly view as militating against the successful establishment of breastfeeding, and the intrinsic physiological differences in the mechanisms of milk removal from each, have been viewed as the likely basis of this. The current set of ultrasound studies of babies both breast- and bottle-feeding was initiated, therefore, to assess these potential intrinsic differences in feeding style (it followed shortly after a separately-funded study of breastfeeding alone).

S1 Key findings from the present were as follows:

S1.1 A total of 36 studies were conducted with babies who were predominantly breast-fed, but whose mothers had introduced bottles. Ultrasound scans of feeding were usually undertaken at a single feeding session, while breastfeeding, and while bottle-feeding from two alternative research designs of bottle teat (from a choice of three[1]).

S1.2 The research yielded a total of 99 feeding episodes, with 8hr 6min of ultrasound study recorded onto DVD for later analysis. The median recording time per feeding episode was 4min, with a range from 52sec to 20min 51sec.

S1.3 Findings from this study provided support for both the *conventional* view and the *novel* view. ALL babies studied show peristaltic tongue movements (p.t.m's.) throughout the period they were actively sucking, irrespective of whether they were feeding on the breast or the bottle.

S1.4 The present study also supported the findings of Eishima (1991) and Geddes et al (2008) to the extent that ALL babies also showed 'extractive tongue depressions' (e.t.d's.) for a *proportion* of the time they suck, and this also was observed on both the breast and the bottle.

S1.5 The proportion of the feed for which e.t.d's. were shown varied between babies, from as little as 5-15% of the time in some babies to 85-90% of the time in others.

[1] All research teats were manufactured by The Pigeon Corporation, Japan; comprising one narrow-necked design (branded as Lansinoh), and two wide-necked designs (branded as Pigeon). This is mentioned because the design brand was visible to the mother.

S1.6 It was also quite explicitly the case that e.t.d's. could not exist in isolation, but were only ever superimposed upon the intrinsic pattern of peristaltic tongue movements (p.t.m's).

S1.7 Not only were they overlain on p.t.m's., they also occurred at *a specific, predictable point* in the suck cycle, usually (but not invariably) just beyond the nipple/teat tip.

S1.8 There was minor variation in the *point* of application of the e.t.d. which varied in some babies. But we saw no variation in the *point* of application within the same baby as a function of whether they were breast- or bottle-feeding; which may therefore be regarded as an example of 'carry-over' from breast to bottle.

S1.9 There was surprising conformity between the style of sucking seen on the bottle and that seen on the breast; the pattern of feeding on the breast being the best indication of how the baby was likely to feed on the bottle. We did not expect this, so this lack of difference between breast- and bottle-feeding was contrary to our expectation. <u>In light of the commercial rationale for this study, this may be viewed as a positive finding</u>.

S1.10 The probable explanation for this would seem to be that babies appear to possess individual-specific styles of sucking. It is plausible for the babies in this study that these have developed in the context of breastfeeding as an adaptation to their mother's individual anatomy/physiology. There was comparability (or 'carry-over') between the style of sucking observed on the breast and on the bottle.

S1.11 While we are unable to say explicitly which mode of feeding influences their sucking style the most, we would suspect it is breastfeeding, as the styles of sucking shown by the babies in this ultrasound series while breastfeeding, were the same as those observed in a separate series of studies conducted on exclusively breast-fed babies (Woolridge et al, unpublished).

S1.12 The individual-specific characteristics observed tend to relate to the balance or ratio of p.t.m's. to e.t.d's. (i.e. ratio of *propulsion* to *extraction*) employed by babies. So, some babies showed a heavy bias towards predominantly peristaltic tongue movements for most of the feed, while others showed a predominant 50:50 balance of p.t.m. to e.t.d. throughout feeding.

S1.13 Babies, however, remained extremely flexible and were able to vary this ratio of sucking style in a fluid, dynamic manner throughout the feed.

S1.14 They also varied them in relatively small, but fairly specific ways between the breast and the bottle, tending to vary within small limits around the basic pattern.

S1.15 In this sense babies did not show a dramatic or markedly overt change in sucking style between breast and bottle, which was also contrary to our expectation at the inception of the study.

S1.16 Babies showed a moderately greater tendency to show extractive tongue movements on the bottle, with these differences mainly being in the proportion of time, and/or the intensity with which babies showed them. But these differences were much less than anticipated, and less than the variation seen within a breastfeed by the same baby at the same age.

S1.17 We were surprised by the habitual persistence of conspicuous peristaltic tongue movements when feeding on the bottle. The fact that the majority of babies did not always occlude the neck of the teat, would seem to render this mode of suckling less effective, on theoretical grounds at least. *The issue of whether babies can 'express' milk in the absence of teat occlusion is debated in the body of the report*.

S1.18 By the same token, the extractive tongue movements shown by babies on bottle teats were usually slow and measured, and showed less of a tendency to be vigorous and dramatic, as they sometimes appeared on the breast: this was a qualitative difference which was not predicted at the outset.

S1.19 This suggests that babies employ just enough suction to remove milk efficiently from the bottle teat, to secure milk at a sufficient rate, as a function of the teat hole or aperture size. However, we did NOT commonly see babies making exaggerated e.t.d's. when they were presented with bottle teats with a very small hole size. This was contrary to our expectation.

S1.20 Accordingly, we have the strong conviction that babies are extremely complex and sophisticated in the way they apply different strategies for sucking, as a function of whether they are feeding from the breast or the bottle.

S1.21 We do not view the persistence of p.t.m's. on the bottle as accidental, but as being more likely to represent the most cost-effective way of sucking, even if the baby is placing a greater reliance on e.t.d's to extract milk.

S1.22 We cannot account for this observation, although we shall speculate later that this may be because the baby only needs to secure milk from a bottle at an optimal rate; there is no benefit in expending much higher levels of energy to secure milk at a faster rate (especially as the bottle is rarely withdrawn before the baby has taken sufficient milk).

S1.23 This situation may differ on the breast, where the baby may have more ability to regulate milk flow from the breast, enhancing or accelerating milk flow by generating e.t.d's; but potentially less opportunity to ensure complete milk removal from the breast, which will be influenced by the pattern and efficiency of the mother's let-down reflex, and the time permitted by the mother for milk removal (on the bottle this can be done visually on the basis of the amount of milk remaining).

S1.24 <u>Comparison between bottle teats</u>: we did not observe any marked or consistent differences in the depth to which bottle teats were introduced into babies' mouths (in terms of the distant from the teat tip to the junction of the hard and soft palate). Whatever differences there were did not seem to impact on the baby's sucking style; in other words, we observed no differences between teats related to this dimension.

S1.25 The greatest differences observed were in the degree to which the teat body (neck and/or bulb) were compressed routinely during active sucking. All three varieties of research teats (Pigeon) were compressed to a greater degree by the tongue, than any of the other commercial brands, which the mothers had brought with them, as the brand normally used.

S1.26 No baby refused the research teats when first offered (this was their first exposure to them); all fed from them normally, without any indication that they were being perceived, or reacted to, as a novel stimulus.

S1.27 Among the three varieties of research teats, the two with three internal annular rings (one narrow-necked, one wide-necked) tended to show between 50-90% compression, while the wide-necked textured teat showed 60-100% compression; the wide-necked textured teat was the one on which one was most likely to see 100% compression (there were some exceptions to this rule – see S1.30 below) – this is in accord with the technical data supplied by Mr Koji Matsutori on wall thickness and compliance.

S1.28 Despite the baby's ability to compress more effectively one style of research teat, it could not be stated that the baby was routinely tending to capture milk within the teat bulb, enabling this to then be expressed into the mouth. In practice, babies appeared to use a blended ratio of p.t.m. to e.t.d., so that there was clear evidence of peristaltic action, although it was not possible to define the degree to which this achieved milk transfer.

S1.29 Similarly, e.t.d's. were evident in many babies and it was possible to link milk extraction to these tongue movements. But, when they were less conspicuous, it may be presumed that milk transfer was achieved by low levels of suction pressure in the oral cavity, perhaps caused by persistence of the peristaltic wave, which is likely to have both convex-wave positive pressure components and concave-wave negative pressure components (see Section 6.6 for explanation).

S1.30 At a relatively late stage in analysis, one baby was identified who was able to achieve 100% compression of the narrow-necked teat, possibly because it projected quite well into the mouth (it was not able to achieve this on the wide-necked teat, because it did not project so far into the mouth). This baby was observed to be able to express milk from the teat bulb (absence of e.t.d's.), and there was a direct relationship between the volume of milk in the teat prior to expression, and the volume appearing in the milk space, beyond the nipple tip, after expression and prior to swallowing. To date, only one sequence has yielded this degree of explicit evidence, so we cannot generalise it more widely to the feeding of other babies in this study.

Section One

1 Introduction

1.1 Background:

1.1.1 Philosophical perspective: This research study has important scientific objectives: the evaluation of the broad similarities and differences between the style of sucking shown during breastfeeding, compared with that seen during bottle-feeding (among breast-fed babies) when these observations are strictly contemporary. It also has commercial objectives, which seek the answers to questions which have relevance in everyday practice, as well as clinical practice.

1.1.2. The protocol for the Lansinoh-funded study was devised, based upon the premise that the baby has two distinct styles of sucking, one characteristic of, or adapted to, breastfeeding; the second characteristic of, or adapted to, bottle-feeding. This supposition was based largely on descriptions of such differences in feeding style presented in lay textbooks on lactation (e.g. Riordan, 1983; Woessner et al, 1987; Lawrence, 1989); but also upon the description of Eishima (1991), who made her observations during bottle-feeding (by breast-fed babies) who were being bottle-fed.

1.1.3 The majority view, based on independent observations made by several authors, is that babies employ an intrinsic pattern of rhythmical, peristaltic waves of positive pressure against the underside of the 'teat-like' shape, formed from the breast and nipple, and held within the baby's mouth by a baseline level of suction pressure. These undulating waves of compression, applied to the underside of the breast, tend to express or squeeze milk from the ducts lying within the breast.

1.1.4 Geddes et al (2008) proposed an entirely different mechanism, based on the baby generating high levels of intra-oral negative pressure, by drawing down the central section of the tongue, proximal to the nipple tip; this observation was confirmed by direct recording of intra-oral suction pressure within the baby's mouth. The negative pressure generated by this suction was linked, by these authors, to peak milk flow from the nipple surface; a conclusion based on the subjective appraisal of milk flow/velocity from ultrasound recordings.

1.1.5 These two mechanisms appear set against each other, in many people's minds, as almost mutually exclusive means for removing milk from the breast. There seems little acceptance of the notion that the two forces might be acting in a synergistic relationship, acting together for the removal of milk with optimal efficiency. This viewpoint is likely to have been compounded in part by conference presentations made by Donna Geddes, in which she denied the existence of peristaltic tongue movements (asserts that they do not see them), and by the development of a novel design of feeding bottle ('Calma') by Medela which rewards the baby with milk only when suction is generated above a certain threshold. The logical train of thought leading to this development can only be that suction is the predominant, if not sole, mechanism of milk removal, so that a bottle, designed in this way, is emulating the natural method of feeding on the breast. This would appear to be a logical extension *ad absurdum*.

1.1.6 Independent of the current study therefore, we have sought either to confirm or refute the findings of Geddes et al., which appear to have had some prior basis in the observations of Eishima (1991), using a different methodology. Eishima employed a different approach to visualising events in the baby's, by filming through the back of a transparent bottle teat. She observed, separately: (i) waves of peristaltic pressure being propagated from the tip of the tongue posteriorly (commonest in the absence of milk flow, i.e. during non-nutritive sucking); (ii) forced depression of a localised section of the baby's tongue, centrally located and just beyond the nipple tip (these movements were commonest on bottle teats with a slow milk flow rate); (iii) a relative absence of both peristaltic tongue movements and forced suction movements, on bottle teats with large holes, which required the baby to make relatively little effort to remove milk. The intrinsic value of her observations was that they made no attempt to refute previous work, or assert that one force was more important or predominated over the other. Nonetheless, they left the impression that forced suction movements, produced by localised exaggerated depression of the tongue surface were related specifically to slower rates of flow on a bottle, while peristaltic tongue movements perhaps reflected the more naturalistic pattern.

1.1.7 The polarisation of scientific views, created by the work of Geddes et al (2008), raises the need either to embrace their observations, or explain why the contrary view, based on several ultrasound studies, was misinformed. Or it required us to determine whether there were methodological differences between the Geddes study, and those conducted previously, which might explain the discordant findings. Two such possibilities existed: they might be the result of: (i) an altered scanning methodology (use of a different probe and/or different strategy for scanning); or (ii) be attributable to an age difference in the babies studied – it might be the case for example that only young babies suck in a predominantly peristaltic manner; which is replaced by a different style of sucking as the baby gets older, as he/she acquires more experience of sucking on other objects. For example, with increasing age, babies may gain more exposure to artificial teats (bottle and pacifiers), as a result of which an altered mode of feeding develops, reflecting this exposure to alternative stimuli.

1.1.8 Accordingly, the present study was preceded by a large series of fresh ultrasound studies of normal breastfeeding, which sort to examine age-related changes in feeding. This was also an essential precursor to the present study, as it established a baseline for feeding style at particular ages (this could not be controlled in the present study, as the mother decided if, and when, to introduce bottles to her baby). Knowledge of the age-related changes in feeding would allow us to evaluate whether the breastfeeding observed in the present study was normal for babies of that age, or had been distorted by the use of bottles.

1.1.9 In response to the first of these issues, there are certain specific differences in scanning methodology, which may impact on the way the baby feeds, but we do not regard these as having generated artificial patterns of feeding; so we regard their observations as credible.

1.1.10 The short response to the second of these issues is: there are no age-related changes in the way the baby feeds. Babies appear to possess individual-characteristic patterns of feeding (in terms of the balance between alternative sucking strategies), and these are consistent over time. One implication of the baby's tendency to show individual-specific patterns of feeding is that the sucking style may prove to be common across feeding on both the bottle and the breast.

2 Aims and objectives

2.1 Scientific objectives:

2.1.1 A substantial number of studies have been made of breastfeeding using direct observation, cine-radiography, ultrasound and other methods. The majority of them have asserted that babies use a peristaltic feeding action to remove milk from the breast. The baby's tongue is believed to apply an undulating pressure wave to the underside of the 'teat' (formed from both breast and nipple), which the baby retains between its jaws and filling its oral cavity. Of the seven ultrasound studies so far reported, the majority (6/7) describe the predominant role of these peristaltic tongue movements. We have recently repeated a large series of ultrasound studies of breastfeeding (unpublished) which have confirmed this general picture. One study, however, the most recent (Geddes et al, 2008) departs significantly from previous studies by asserting that babies employ 'forced' downward depressions of the central portion of the tongue, which generates increased suction pressure, which in turn draws milk from the ducts, so equalising the internal pressure within the oral cavity to external atmospheric pressure.

2.1.2 The way the case has been presented, may give the impression that these are mutually exclusive forms of sucking, although they are not forces which would work in opposition. In contrast, they would be far more likely to work synergistically to achieve the most effective removal of milk. Nonetheless, there has been some contention (usually by verbal reference made at conferences, rather than in the press) as to which action is most important for milk removal.

2.1.3 A flavour of these views is contained in an interview with Donna Geddes (first author of Geddes et al, 2008) conducted by a journalist with the New Scientist; in that interview she is purported to have stated:

> "*What we see is that when the tongue is lowered and the vacuum is applied, that's when the milk is coming out of the breast, and that doesn't involve any compression of the nipple; it's not a milking action at all*." Donna Geddes, interviewed in New Scientist.

This is a more contentious presentation of the issues, typifying more the dialogue used in conference presentations.

2.1.4 Another issue in this debate is the source of funding for these studies and whether it has created commercial pressure to create a contentious, alternative view. Donna Geddes has been in direct receipt of a bursary from Medela to undertake her PhD, and the studies themselves are funded directly by Medela. Medela is, first and foremost, a manufacturer of electrical and hand breast pumps, which extract milk from the breast solely by the generation of negative pressure.

2.1.5 The two main clinical problems identified by Geddes et al (during conference presentations) are babies who feed ineffectively, and are shown to be generating too little pressure, and babies who provoke sore, cracked nipples by generating too much pressure. The solution recommended for the former problem is to use a breast pump, not, as is held to be sound, evidence-based best practice by international agencies (WHO & UNICEF), the promotion of optimal positioning and attachment. This finding therefore would be of commercial benefit to Medela in terms of increased sales of breast pumps.

2.1.6 Where the baby generates too much suction, the recommended solution is to use a nipple shield. This practice is also mandated against by the "Ten steps to successful breastfeeding" (WHO/UNICEF) as being potentially harmful to the establishment of breastfeeding, and no substitute for best practice in terms of attending to, and improving, positioning and attachment (Medela also manufactures nipple shields, so their sales would also benefit from adhering to the management principles they espouse).

2.1.7 Accordingly, we have serious concerns that the observations and assertions of the Perth group, which is heavily funded by Medela, have commercial implications which will benefit Medela directly, and be to the disbenefit of the majority of breastfeeding mothers and their babies. From a scientific perspective, therefore, we regarded it as vital to either confirm or refute the findings of Geddes et al (2008).

2.1.8 So it was that, set against this background, we chose to initiate a fresh series of ultrasound studies, using modern ultrasound imaging equipment, and employing a qualified ultrasonographer to undertake the studies, to evaluate the observations and claims made by Geddes et al (2008).

2.1.9 In accord with the views of Geddes et al (2008), however, there was a previous research study which did not employ ultrasound, but which instead, used direct observations obtained by filming through the back of a clear Perspex bottle teat, directly into the baby's mouth during feeding (Eishima 1992). One does not gain the full benefit of Eishima's studies from her published report, but she also produced a videotape of her studies which provides the clearest direct evidence that babies do use their tongue in the way described by Geddes et al, some 16 years later. Her study also clearly identifies peristaltic tongue movements as a complementary element of the feeding process.

2.1.10 There is a further scientific justification for conducting these studies, which was not adopted at the outset, but which became an important issue following on from the study breastfeeding, which immediately preceded this one (Woolridge et al, unpublished). Those studies suggested that the *rate of milk flow* from the breast, which is highly variable, was a key determinant of the style or pattern of sucking shown by the baby. Using bottles to deliver milk to the baby offers the opportunity to control this aspect of feeding (i.e. milk flow rate) and hence study directly, the impact of this on the baby's pattern or style of feeding, in a way which is not possible during breast-feeds. So, use of an artificial stimulus (bottle teat) allows us to keep certain qualities/features of the feeding stimulus constant across studies (such as teat size, material resilience/compliance), while varying others in a specific way (e.g. teat aperture and flow rate) in a way which is not possible on the breast. A specific design element of this study, built in from the outset, was the scope not only to compare feeding on the breast and on the bottle, but also to compare and contrast two designs of artificial teat, differing in specific ways, in consecutive studies.

2.1.11 The key clinical concern raised by studying bottle-feeding in the breast-fed baby, relates mainly to the early neonatal period, during the establishment of breastfeeding, when babies have been described as showing "nipple confusion". While this might more viably be referred to as "acquired teat preference" (Woolridge, 1995), it is nevertheless a real concern to the extent that it has become entrenched as Step 9 in the WHO/UNICEF guidelines. Cup-feeding has become recognised as the better way to supplement the breast-fed baby, as it avoids the oral stimulation and gratification provided by a stiff, self-prominent bottle teat.

2.1.12 We do not know the risk of introducing bottles later in lactation, despite this being a common wish of mothers. It is a legitimate scientific objective therefore (as well as a commercial one), to seek to identify the qualities of a bottle teat which make it least discordant in design from the breast, thereby seeking to minimise any differences in the oral stimulatory qualities of an artificial teat compared to the mother's nipple.

2.2 Commercial objectives:

2.2.1 The concern over the issue of 'nipple confusion' is not simply a clinical one, but one of which mothers themselves are familiar with, as are the health professionals advising them. 'Nipple confusion' describes a baby's reluctance to persist in the establishment of breastfeeding, when artificial teats/bottles have been introduced in the early post-natal period (Neifert et al, 1995). Beyond the early stages of lactation, there is also evidence, mostly indirect, that the introduction and use of bottle teats may militate against the successful maintenance of breastfeeding (Vallenas & Savage, WHO/UNICEF 1998) and may reduce its duration (Victora et al, 1993; Barros et al, 1995; Ingram et al 2004).

2.2.2 A commercial rationalisation for this study, therefore, was to seek to identify a design/style of teat which would encourage a more naturalistic style of feeding, as would be seen on the breast, in order to minimise the differences between the two. This might enable the breastfeeding mother to introduce bottles to her baby without it disrupting her wish to maintain her own breastfeeding.

2.2.3 There are a variety of reasons why breastfeeding mothers introduce bottles or plan to mixed feed their baby: it may be in anticipation of them returning to work, or because they wish to engage in a particular social activity, at which time they plan to leave their baby in the hands of a carer. But, whatever the circumstances, they naturally wish to avoid the possibility that their choice to introduce bottles might either make it more difficult for them to continue breastfeeding, or may even cause them to terminate breastfeeding prematurely. The aspiration, therefore, was to identify a design of bottle teat, and/or the features of that teat, which might obviate ‘nipple confusion’ by encouraging a more peristaltic-like feeding action, as is commonly seen on the breast (Smith et al, 1985; Weber et al, 1986; Woolridge, 1986; Bosma et al, 1990; Bu’lock et al, 1990)

2.2.4 It was our expectation at the conception of the study that we would observe two profoundly different styles of sucking as a function of whether the baby was feeding on the breast or on a bottle. This view was derived mainly from accounts in textbooks of lactation management, and partially through direct observation of older breastfeeding and bottle-feeding babies, when visually at least, they seem to feed in distinct ways on the breast compared to a bottle. Having said this, a previously published study of bottle-feeding by premature babies described the relative similarities in feeding, rather than the differences (Bu’lock et al, 1990).

2.2.5 So, against this background, this study was devised to compare breastfeeding and bottle-feeding in the same babies. It would be regarded as unethical, however, to introduce bottles to a breast-fed baby, purely for the purposes of research on the basis that it might cause *nipple confusion*. We chose instead, therefore, to recruit breastfeeding women who had already made the informed choice to introduce bottles to their own baby, either of their own expressed breast milk, or of artificial formula if this was their choice. This meant, therefore, that we had no opportunity to specify the age of the baby for our studies; we simply sought to recruit mothers as close as possible to the time at which they introduced bottles.

2.2.6 While the babies recruited may have experienced from one or two, to a few or several previous feeds by bottle, this would have been with a bottle and teat of the mother’s free choice. Similarly, they may also have had variable exposure to a dummy/pacifier. Babies were given no prior exposure, however, to the design of bottle teats used in these studies and so it was always the baby’s very first exposure to the research teats when they were scanned using ultrasound.

2.2.7 So, the principal ambitions, both scientific and commercial, were to undertake a relatively naturalistic study (without artificial interventions or controls) of both breastfeeding and bottle-feeding in the same baby. Accordingly, the decision was made on practical, methodological and ethical grounds to make contemporary ultrasound recordings of breastfeeding and bottle-feeding in the same baby, preferably at the same age. This opportunity presents itself when a mother, who has previously established breastfeeding successfully, chooses to introduce bottles, either of her own expressed breast milk or of formula; this may either be for social reasons, or as an initiation of the process of weaning her baby from the breast (outlined in our original Study Proposal and Protocol).

3 Methodology

3.0 Study Design

3.1 Introduction

3.1.1 Ethics permission was secured from Leeds East NHS Research Ethics Committee (09/H1313/59) for the initiation of this study in Dec 2009, after which the study protocol was initiated as planned. The initial protocol development phase scanning sessions took place during December, based on a revised plan. Formal study scans starting in January 2010.

3.1.2 At the initiation of this study, a separate study was in progress examining the basics of how a baby breast-feeds; this study looked at breastfeeding at 5 distinct ages (from 1-2 weeks to 12-16 weeks) to determine whether there were age-related changes in sucking style. This previous study was crucial to the current study both for defining normal breastfeeding behaviour, and for determining whether the baby's age would affect the feeding style of babies in the present study. Accordingly, the basic findings from the separately-funded study will be addressed briefly in order to provide the context for interpretation of the present study's results (see Section 3.6 below).

3.1.3 In order to recruit mothers for the present study, the pragmatic decision was made, in the first instance, to use mothers and babies who had been recruited into the breastfeeding study, if and when they introduced bottles alongside breastfeeding. As far as the present study was concerned, we could see no practical reason why it should matter whether the mother was offering bottles of her own Expressed Breast Milk (EBM) or was supplementing with formula. While not excluding any mother on these grounds, we made note of the type of milk the baby was being given and how frequently.

3.1.4 Further pragmatic decisions were made during the conduct of the study. For example, mothers were reluctant to make a repeat visit to the hospital on consecutive days – instead they voiced a preference to both breast-feed and bottle-feed their baby at the same visit to the Paediatric Ultrasound Suite; this was regarded, therefore, as a legitimate change to the protocol.

3.2 Methods

3.2.1 Recruitment: Potential participants were recruited by two main routes – first, from the post-natal ward of the Clarendon Wing, Leeds General Infirmary. Initially, women recruited by this route into a study of breastfeeding, were sought to be co-opted into the present study, at the point at which they introduced bottles; later mothers were recruited directly and only into the current study. This proved to be a less reliable route – mothers recruited into the breastfeeding study failed to notify us when they introduced bottles, or only introduced bottles at a stage when we believed that their baby was probably too old to participate. At the close of the study (8/10/10), there remained three mothers, recruited through this route, who had not yet introduced bottles – at that point, their babies were 16-17 weeks in age, having been recruited in early June 2010.

3.2.2 The second route was through Baby Cafés operated in the Leeds area and from Child Health Clinics at Health Centres. By this route a satisfactory number of women proved willing to be co-opted into the study at the point at which they introduced bottles (there remained four babies, at the close of the study, aged between 12-34 weeks who had not established bottles).

3.2.3 Sixteen weeks of age had been set as the upper limit for the study of breastfeeding, but in the current study babies were scanned successfully as old as 26 weeks.

3.2.4 Participants: Thirty-six mother-baby pairs participated at the close of the study, the median age of the baby being 13.0 wk (range 3.1 to 25.7 wk). The reasons mothers reported for introducing bottles were varied; some had introduced occasional bottles of their own expressed breast milk, in order to be able to leave their baby with another carer for a short period; others had introduced more regular bottles of artificial formula, either because of personal concerns over their baby's weight gain, or specifically as part of the process of weaning their baby from the breast (in anticipation of returning to work, for example). Prior to this decision all mothers had established full breastfeeding, and were feeding in a relatively trouble-free manner. For several mothers, who had started to give bottles in order to wean their baby, this became a relatively sharp transition, with the result that by the time the mother and her baby came in for a scan, they were either unable to, or declined to offer their baby the breast (6 cases). This was contrary to the aims of the protocol, but a comparison of at least two, and often three bottle teat types, was achieved.

3.2.5 Research materials: For the purposes of this study, we compared three research designs of bottle teat. All were manufactured by the Pigeon Corporation (Japan), and are constructed of silicone-rubber with an average thickness of 1.5 mm. One was a small-necked teat, branded as 'Lansinoh', which has a smooth surface and three annular rings internally, spaced 8mm, 13mm & 20mm from the nipple tip. The other two bottle teats were wide-necked (both branded as 'Pigeon'), one being of similar design to the Lansinoh teat (smooth surface, with internal annular rings), while the second had no internal rings, but had 3 linear ridges to prevent the teat from remaining collapsed, as well as at textured surface externally.

3.3 Research procedure

3.3.1 Scanned feeds: In theory, it would have been preferable to randomise the order of feeds, but most mothers expressed a clear view as to what the order of feeding should be to ensure that their baby took some milk from both sources. Accordingly, we let mothers determine the chosen order for offering either breast or bottle, although we randomised the order of presentation of the bottle teats when these were given. The majority of mothers offered the breast first (69%), with the smaller proportion (31%) starting with bottle – this was usually a function of where in the process of introducing bottles they were.

3.3.2 Ultrasound scans: All ultrasound scans were made with Philips HD11XE Ultrasound Scanner, using a C8-5 small hand-held probe (8 to 5 MHz frequency range). All sessions were recorded directly onto DVD using a Philips HDR3700 Recorder for later viewing and analysis. The dimensions of the probe are: 90mm (L) x 30mm (W) x 30mm (D).

3.3.3 All babies were scanned from the sub-mental aspect in the midline, to give a medial sagittal view. The sector scan image was inverted, so that it was naturally oriented, and the orthodox view, accepted as standard for these studies, was for the breast and/or bottle to appear to be introduced from the left hand side.

3.3.4 It was decided, on the basis of experience in previous such studies, that a minimum of three minutes of active feeding would be needed on each sucking ‘stimulus’[2] to evaluate the mode or style of feeding typical to that object (breast or bottle). Because feeding on the breast is far more variable (see section 3.3), a longer sequence of breastfeeding was scanned, to include at least one release of milk (‘let-down’ or milk ejection reflex). This was also because we had ethical concerns over asking mothers to terminate breastfeeds prematurely, so instead, we left it to the mother to decide when she would finish the breast feed, in anticipation of allowing her baby some opportunity to take the bottle. We aimed to record a minimum of 3 minutes of feeding on each bottle teat.

3.3.5 In practice, the median recording time for breastfeeds was 6min 8sec (range 52sec to 11min 24sec), while that for bottle-feeding episodes was 3min 27 sec (range 52sec to 26min 12sec).

3.4 Study procedure & priorities:

3.4.1 For each study, the first priority became to secure an ultrasound scan of part of a normal breast-feed, in order characterise typical feeding at the breast (although on 31% of occasions this followed a bottle-feed which was at the mother’s instigation). We sought to scan a reasonable proportion of a breastfeed in order to include a minimum of three minutes of uninterrupted nutritive feeding on the breast (i.e. after milk release had occurred).

[2] Sucking ‘stimulus’ is used here to refer to the object in the baby’s mouth from which he/she is feeding from – i.e. either the breast or a bottle.

3.4.2 The second priority was to compare feeding on two designs of bottle teat, these being alternative research designs supplied by the Pigeon Corporation – the options being (i) narrow-necked, ribbed internally (3 annular rings), smooth finish; (ii) wide-necked, ribbed internally (3 annular rings), smooth finish; & (iii) wide-necked, no internal annular rings, textured finish.

3.4.3 All three bottle teats were of an anti-colic design in that they had a vented hole manufactured into them. At a few of the early scanned feeds, functioning of this anti-colic vent may have been impaired by over-tightening of the teat collar, which was avoided during later feeds.

3.4.4 Teats were available with different hole/aperture size from extra small (SS), small (S), medium (M), large (L), and with a Y-shaped hole (Y); this last design of aperture does not allow the free flow of milk under gravity, but requires the baby to exert a degree of suction pressure to open the 'flaps' of the valve.

3.4.5 We sought to match the research teats to the hole size of the teat the mother brought in with her. This was not always possible, however, and data on the respective flow rates both of the Pigeon teats, and of the other two commercial brands (Tommee-Tippee and Avent) most frequently used by mothers in this study, were not available till later in the study.

3.4.6 There was not complete parity in the hole sizes/styles across the three designs of research teat and, while the designated hole aperture was reliable on teat styles (i) & (ii), style (iii) were pre-production prototypes, on which we found the flow rates to be less predictable than designated on the teat. In part, this was because the 'M', 'L' and 'Y' models in style (iii) all had Y-shaped apertures, making it difficult to select the appropriate comparison for the teat which the mother normally used. As a consequence, during the latter half of the study, all teats were pre-tested by us to determine their flow rate, prior to being used for study, then re-tested after sterilisation and use.

3.4.7 We elected not to use the 'correct' hole size for the *age* of the baby (as designated by the manufacturer), but instead sought to match the teat aperture on the bottle teat which the mother was using herself, when not breastfeeding – this may not have been appropriate to the baby's age; for example a 23-week old-baby was still being offered a grade 1 hole (newborn, 0+ months), but it reflected the teat hole size the mother was using with her baby at that age (issues arising from this are discussed latter – see Section 6.5.2)

3.4.8 A problem with this approach, however, is that the teat hole on the bottle which the mother brought in with her, may have been damaged, tampered with or doctored, so may not have been the size designated on the teat[3].

[3] One mother had purchased her teats on eBay, and they had already been cut or enlarged artificially.

3.4.9 Once other objectives had been met, the final (lowest) priority was to record a sequence of feeding on the bottle teat which the mother brought in, and which the baby was 'used to'. In two feeds, a final short recording was made of non-nutritive sucking, in one case of a baby on a pacifier, and in the second case, of the baby sucking his own finger.

3.4.10 The proportion of studies for which the above comparisons were made is shown in Table 2. Not all of the comparisons below follow the optimal plan; this was for several reasons including: lack of availability of a sterile research teat in the size required; failing to secure an adequate ultrasound scan during one or other feeding episode (the cause of variation in scanning efficiency are dealt with later); or because the baby satiated, became disinterested, or became distracted by events around them, before the requisite number of feeding episodes had been scanned.

3.4.11 Following a meeting with the funders (18th June 2010), the protocol was revised, so that teats manufactured by a competitor were no longer the focus of comparison. This was largely because we felt we could not compare research teats against competitive brands in a structured way (we had no influence over the mother's choice of teat); also because it might have drawn a hostile reaction from the competitor, who might have perceived that they had been targeted. The decision was made instead to focus on a comparison of the three types of Pigeon-manufactured teats; the comparison, for any one baby, being between two of the three designs of research teat. When the opportunity arose, we continued to record feeding on the baby's usual teat, in order to provide a frame of reference with respect to what each baby was familiar with.

3.5 Study benefits and limitations

3.5.1 The principal benefit from scanning babies while bottle-feeding is that it is generally easier to secure a midline scan; this is always difficult to achieve during breastfeeding because of the way the baby is positioned, but is more readily achievable when bottle-feeding. This is offset by the intrinsic problem created by the fact that bottle teats do not project very far into the baby's mouth (irrespective, largely, of the design and/or manufacturer). The feature which limits viewing of the anterior sector of the baby's mouth is the lower jaw (mandible) which, as it comprises bone, does not transmit ultrasound. This means it cannot be scanned through, so casts a vertical shadow blocking the view of the neck of the teat. It is not possible to obtain any better view by slanting the probe to point more anteriorly, as this rotation would bring the probe body/handle up against the baby's chest.

3.5.2 We opted to let the mother feed her baby herself, in the manner/style which she was most used to. While we did ask some mothers to adjust their baby's position so that the scanhead could be located more easily, we did not ask mothers to change the way they offered the bottle, e.g. asking them to insert the bottle further into their baby's mouth.

3.5.3 As a measure of how far the research teats projected into the baby's mouths, it was possible to visualise the internal annular rings (on two of the teat designs). But it was usually only possible to view either one or two of the rings closest to the teat tip (located 9mm & 15mm from the tip); the furthest ring (23mm from the tip) was always obscured by the jaw. This indicates that, on average, no more than 20mm of the research teats could be visualised on ultrasound (beyond the baby's lower jaw), with the bottle teat tip falling some 10-15mm short of the junction of the hard and soft palate.

3.6 Known differences between breastfeeding and bottle-feeding likely to influence feeding

3.6.1 Certain key differences can be stated *a priori* between breast- and bottle-feeding, which might be predicted to influence the style of sucking in quite predictable ways. So, for example, the rates of milk flow on the breast are highly variable, varying from an absence of milk flow prior to the 'let-down', which is typified by non-nutritive sucking (NNS); to very fast flow rates immediately after the let-down (nutritive sucking (NS), high flow); settling into much more variable rates of milk flow, as the available milk tends to subside (NS, moderate flow); finally dwindling towards the later stages of the feed when very little milk flows (NS, low flow). Sucking in the early and late stages tends to be predominantly peristaltic, with extractive tongue movements being more obvious during the middle phases (NS moderate flow), when milk flow settles to a more regular pace.

3.6.2 On the bottle, in contrast, the flow rate is set very much at the outset, with milk being available from the moment the baby takes the bottle, and is relatively fixed throughout the feed, as function of the size of the teat hole/aperture. The style of sucking is likely to reflect, therefore, a relatively invariant mode, adapted to the rate of flow from the bottle. Given this, it is perhaps surprising that the styles of sucking on both breast and bottle were so similar.

3.6.3 One possible explanation for this is that if, overall, the style of sucking across the entire breast feed is essentially peristaltic, then it is also likely to be so on the bottle. Conversely, if the style on the breast comprises predominantly extractive tongue movements, then the same style of sucking will be more likely to be observed on the bottle. The existence of individual-specific sucking styles suggests they are set very early, perhaps at the first feeds after delivery, or they may even be set in the womb, as a function of whether or not the baby has access to a sucking stimulus (thumb, fingers, hand).

3.6.4 A further way in which breastfeeds and bottle-feeds differ is in terms of the relative stiffness/rigidity of the bottle teat compared to the breast. Bottles teats tend to be relatively rigid to the extent that they are *self-supporting*. They show negligible inflexibility in their long axis, so cannot be extended in length to any degree. They are much more compressible in the lateral axis; the degree of compliance being determined by largely the thickness of the silicone-rubber from which they are manufactured.

3.6.5 In contrast, the breast is neither rigid nor self-supporting, but must be drawn out by suction generated in the baby's oral cavity. The nipple extends by 200-300% of its natural length, when at rest, while its compressibility is limited solely by the finite thickness of the tissue held between the jaws. In order for the baby to draw out and retain the teat-like shape formed from nipple and breast, he/she must generate high levels of suction towards the rear of the oral cavity. So, at the start of the suck cycle, the baby generates a marked level of suction pressure, to create and hold the 'teat' within the mouth.

3.6.6 This is not essential on a bottle teat, even though babies do still grasp and retain the teat using suction (n.b. even pacifiers are retained by suction). This initial, and subsequent baseline, level of intra-oral suction must therefore be an intrinsic, inborn reflex element of feeding on the breast, which is similarly triggered by feeding on a bottle and sucking on a pacifier.

3.6.7 On the breast, as milk flows out from the breast, it critically reduces the intra-oral suction pressure, which might result in the baby losing its grasp of the breast; accordingly it must re-apply the suction in a cyclical manner, to maintain its grasp of breast tissue. Once again, while this would also apply to bottle-feeding, it should not cause the baby to lose his/her grasp of the bottle teat, if the suction were not re-applied.

3.6.8 Finally, as milk is removed from the breast it 'collapses' under atmospheric pressure. If the bottle is not fitted with an anti-colic vent, or it is inoperative, then negative suction pressure will build up in the bottle as milk is removed. The baby will then have to generate increased suction to remove milk from the breast, which might be expected to elicit a greater proportion of extractive tongue movements. During two or three feeds on a bottle, the bottle teat was seen to invert during sucking (invaginate into itself), so that the bottle had to be removed from the baby's mouth to allow it to evert again.

3.6.9 So, irrespective of its involvement in milk removal, the baby must generate, and re-generate, intra-oral suction in a cyclical manner. It should not surprising therefore, purely on ergonomic grounds, for the baby to harness this force to augment the peristaltic tongue movements in the removal of milk.

3.7 Data analysis – coding of feeding episodes

3.7.1 Feeding on the breast is known to be highly variable, but as feeding on the bottle is invariably nutritive, we chose to exclude from the analysis, periods of sucking on the breast which were non-nutritive. These have been shown both in this study, and a previous one, to comprise exclusively peristaltic tongue movements; this is logical, if there is no milk available, there is no need to generate 'extractive tongue depressions (e.t.d's.) to enhance milk removal. This also eradicated the potential problem that if there were relatively little milk transfer during a breastfeed, it would tend to be characterised as 'mainly peristaltic tongue movements (p.t.m's.). If the bottle-feed, in contrast, were typified by greater milk flow, the appearance of e.t.d's. would be related to milk availability, rather than to differences in the sucking stimulus.

3.7.2 To a large extent, therefore, the comparison between sucking on the breast and on the bottle was limited (for the breast) to periods when milk was flowing. If, during this time, the baby showed any tendency to superimpose extractive tongue depressions on peristaltic tongue movements, this tended to involve a roughly 50:50 ratio of the two, with minor variation of ±10% in either direction.

3.7.3 We had anticipated at the outset that, at the very least, it might be possible to characterise feeds simply as comprising: ‘predominantly peristaltic tongue movements’ (predom. p.t.m’s.); ‘predominantly extractive tongue movements’ (predom. e.t.d’s.) (as claimed by Geddes et al, 2008); or a particular ‘balance’ or ratio of the two. In practice, this simple approach was not feasible, as the sucking patterns shown by babies tended to be much more flexible and dynamic than anticipated, making this approach to classification rather too simplistic in practice.

3.7.4 As a consequence, the present report is limited to a qualitative description of the study findings. In the long-term, however, for the purposes of publication, we shall continue to strive to achieve a numerical coding of sucking pattern and style during test feeds. To date, a six-point scale appears to have some utility – on this basis, the ratio of peristaltic tongue movements to extractive tongue movements are loosely coded for qualitative purposes as: pure p.t.m. (i.e. 100%:0%); 90:10; 75:25; 60:40; 50:50 & 40:60 (least common). Although relatively crude, this is the maximum number of levels we can discriminate on a subjective basis. The level 40%:60% p.t.m. to e.t.d. signifies that while both actions are present, the extractive tongue depressions are as marked as they can ever be observed.

3.7.5 Even this approach, however, does not readily accommodate periods when the baby inserts an extractive tongue movement on every alternate sucks.

4 Results

4.1 Study Process Results:

4.1.1 Thirty six studies were completed, with recordings of the ultrasound sessions made onto DVD for later review and analysis. A total of 99 separate feeding sequences have been recorded (i.e. 2.75 per mother-baby pair).

4.1.2 The total duration of ultrasound records of feeding which have been recorded is 8hr 6min, with a median duration of 4min per ultrasound sequence (min. 52sec, max. 20min 51sec).

4.1.3 The details of the protocol were not fully satisfied in the case of each participant, but collectively, adequate data have been collected to evaluate the primary outcomes of the study.

4.1.4 Study comparisons: Table 1 shows the breakdown of breast and bottle comparisons made during this study.

Table 1: Showing number of recorded ultrasound sequences by type.

<table>
<tr><th rowspan="2">Breast</th><th colspan="3">Lansinoh/
Pigeon</th><th rowspan="2">Tommee-
Tippee
‘Closest to Nature'</th><th colspan="2" rowspan="2">Other</th></tr>
<tr><td>Narrow-neck, ribbed</td><td>Wide-neck, ribbed</td><td>Wide-neck, textured</td></tr>
<tr><td>31</td><td>9</td><td>12</td><td>16</td><td>15</td><td>5</td><td>Avent</td></tr>
<tr><td rowspan="3"></td><td colspan="2">21</td><td></td><td rowspan="2"></td><td>1</td><td>Dr Brown's</td></tr>
<tr><td colspan="3">37</td><td>1</td><td>Born Free</td></tr>
<tr><td colspan="4">52+8</td><td>1</td><td>Boots</td></tr>
</table>

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4.1.5 The commonest brand of bottle teat mothers brought in with them, when attending for scanning sessions, was Tommee Tippee ‘Closest to Nature’ Size 1-2 ; a smaller proportion were using Avent, or another brand. Most mothers (15) were using the first size teat hole, for newborn babies, up to 3 months; only six had made the transition to a large holed-teat size, even though the majority of babies were older than 12 weeks at the time of study.

4.1.6 In the previous study no babies were scanned beyond 16 weeks of age. In the current series, babies as old as 26 weeks were scanned – this, therefore, extends the data collected in the previous study.

4.1.7 The breakdown of individual feed comparisons by participating mothers and babies is shown in Table 2.

Table 2. Number and sequence of recorded ultrasound sessions by type.

	1	2	3	(4)
LUL-0101	trial	trial	trial	
LUL-0202	Breast*	TTCtN	LNRS	
LUL-2003	Breast*	Avent	LNRM	
LUL-2504	Breast*	TTCtN	-	
LUL-2705	Breast*	BrnFree	LNRS	
LUL-4606	Breast*	TTCtN	LWRS	
LUL-5907	Breast*	Boots	LNRM	
LUL-6608	LWRS	Breast	LNRS	
LUL-6909	Breast	Avent	LWRM	
LUL-7010	Breast	TTCtN	LWTS	LWRY
LUL-7111	Breast	Avent	LWRM	
LUL-7212	TTCtN	LWRS	LWTM	
LUL-7313	TTCtn	Breast	LNRS	
LUL-7414	Breast	DrBr'n	LWRS	
LUL-9015	LWRS	TTCtN	LWTS	
LUL-9416	Not possible to record			
LUL-8717	Breast	LWRS	TTCtN	
LUL-6818	Breast	LWRS	TTCtN	
LUL-7219	Breast	LWTS	TTCtN	
LUL-8520	Missing, not recorded/erased?			
LUL-0021	Breast	LWTS	LWRM	
LUL-9122	LWTS	Avent	Breast	
LUL-9923	Breast	LWRM	LWRM	TTCtN
LUL-0224	TTCtN	LWRS	Breast	
LUL-0425	Breast	LNRM	LWRM	TTCtN
LUL-9626	Breast	LWRM	-	
LUL-9727	LWTS	LWRS	Breast	
LUL-6928	Breast	LWRS	LWTS	TTCtN
LUL-0829	LWTS	LNRM	Breast	
LUL-6330	LWTS	LNRM	Breast	
LUL-0231	Breast	LWTM-Y	LWTS	
LUL-8732	Breast	LWTY	LWTS	finger
LUL-9133	Breast	LWTM	LWTY	Avent
LUL-9034	LWTM-Y	LWTL-Y	TTCtN	
LUL-7235	Breast	LWTL	-	
LUL-7336	Breast	dummy	-	

LNRS = Lansinoh Narrow-neck Ribbed Small;
LWRM = Lansinoh Wide-neck Ribbed Medium
LWTY = Lansinoh Wide-neck Textured Y-shape
TTCtN = Tommee-Tippee Closest-to-Nature

**in the first 6 studies, u/s recordings of breastfeeding were made at an earlier age, so were not contemporary.*

4.2 Study Outcome Results:

4.2.1 During the planning stages of the study it was anticipated (and discussed in explicit terms) that there would be two distinct styles of feeding, depending upon whether it was the breast or the bottle which was being fed from; this expectation was not supported. It was anticipated that breastfeeding would typified by predominantly peristaltic tongue movements, which propel milk in a posterior direction within the baby's mouth – these are referred to as *peristaltic* or *propulsive tongue movements* (p.t.m's.).

4.2.2 *Peristaltic tongue movements* (p.t.m's.) were evident in ***all*** breastfeeds, but they were equally evident in ***all*** bottle-feeds.

4.2.3 Bottle-feeding, in contrast, was expected to be typified more by localised depression of the tongue surface, mid-point through the suck cycle (as described by Eishima 1991, and Geddes et al, 2008) – the effect of these movements is to extract milk from the nipple through suction – accordingly, they may be termed *extractive tongue depressions* (e.t.d's.).

4.2.4 *Extractive tongue depressions* (e.t.d's). were evident in the ***majority*** of bottle-feeds, but they were equally evident in the ***majority*** of breastfeeds. Accordingly, there was no major division of sucking styles seen on the breast or the bottle in the present study.

4.2.5 We expected there to be a division of feeding styles such that p.t.m's. would predominate during breastfeeds, while e.t.d's. would predominate during bottle-feeds. No such simple dichotomy was seen, the two styles of sucking identified were not explicitly associated with feeding on any particular stimulus, i.e. breast or bottle. ***This finding was contrary to our expectation.***

4.2.6 In contrast, the closest approximation to the feeding observed on the bottle, was the style of feeding observed on the breast, and vice versa. So, the style of feeding on the first sucking stimulus provided the best indication of what it would be like on the second stimulus. There were exceptions to this rule, but they were in the minority. ***This finding was contrary to our expectation.***

4.3 Findings from breastfeeding:

4.3.1 The observations of breastfeeding made in this study, confirmed those of our previous study. In simple terms they were as follows:

4.3.2 All active sucking on the breast involves a primary pattern of *peristaltic tongue movements* – there were no departures from this general picture, irrespective of the age of the baby (i.e. there were no age-related shifts or change in sucking style).

4.3.3 The localised *extractive tongue depressions*, described by both Eishima (1991) and Geddes et al (2008), were also commonly observed in these babies during breastfeeding. The proportion of the feed for which they were observed was highly variable being as little as 5-15% in one baby, to as much as 80-90% in another.

4.3.4 Much of the baby's sucking on the breast involved a blended 50:50 ratio of p.t.m's. to e.t.d's. On many occasions when babies were feeding, the e.t.d. element was not reliably present on every suck, but appeared on every alternate suck, i.e. in an ordered manner rather than in a completely chaotic and random manner. So, at times such as this, the 50:50 ratio might refer instead to this alternating pattern, with e.t.d's. appearing on alternate sucks (also referred to as '1-in-2').

4.3.5 The e.t.d's. were only ever observed in the middle of the suck cycle, as the wave of peristaltic compression passed the body of the teat, and were most conspicuous in the region of the tongue just beyond the tip of the nipple. There was some individual variation in this, and in a minority of babies, while breastfeeding, the point of application was more anterior in the mouth. The point of application of the e.t.d. was always preceded by a wave of compression by the tongue against the underside of the nipple/teat, and followed by a wave of compression which displaces the soft palate, and propels the bolus of milk into the oro-pharynx for swallowing. Babies would not ingest milk without the bolus being displaced to the rear of the mouth, into the oro-pharynx, by the peristaltic action of the rear of the baby's tongue.

4.3.6 All styles of feeding are seen as early as one week of age, so the newborn baby appears to be equipped, from birth, with the full range of alternative sucking styles which were observed throughout breastfeeds from as early as the first week after birth. The same variation in feeding style was seen at all ages up to 26 weeks of age, so was evident at all ages of babies studied.

4.3.7 Visually, it would appear that most *compressive* tongue movements are preceded by an *extractive* tongue depression. To explain this appearance, the movements of the tongue can be characterised by reference to the physiology of propagation of peristaltic waves generally within the human body (see later – Section 6.6).

4.4 Findings from bottle-feeding

4.4.1 The styles of sucking on *all* three research teats were surprisingly similar to feeding on the breast, based on contemporary ultrasound recordings.

4.4.2 If anything, we were surprised that babies in the present study appeared equally likely to show peristaltic tongue movements on the bottle, as we would expect them to do at the same age on the breast. ***This finding was contrary to our expectation.***

4.4.3 Babies were equally likely to show e.t.d's. on the bottle and because most feeding on a bottle is nutritive (c.f. the breast), they tended to be present for a greater proportion of the feed. However, the e.t.d's. generated during bottle feeds appeared to be of *lower intensity* than those seen on the breast; this is a subjective view which is difficult to qualify.

4.4.4 A proportion of babies, showed a greater tendency to show ‘extractive tongue depressions’, but these were not specific to bottle-feeding, and were equally likely to be shown on the breast.

4.4.5 The overriding impression was that babies showed *individually-characteristic* styles of feeding that were not wholly explicable in terms of either the teat characteristics, or the rate of milk flow.

4.4.6 ‘Flutter-sucking’ (referred to as *Quiver frequency* by Balint, 1948), which is commonly seen on the breast, was much less evident on the bottle – this may be of relevance in helping to resolve the competing propositions for why ‘flutter-sucking’ exists.

4.4.7 Upon review of the recorded sequences, one particular sequence, unexpectedly, seems to have provided definitive proof of the fact that there can be a direct quantitative relationship between the volume of milk captured in the teat bulb and that which is delivered into the mouth by expression, and *not* by extraction. This does not mean, however, that this observation can be generalised to all feeds by all babies, but it does provide definitive proof that milk *can* be expelled from the teat *by expression alone.*

4.4.8 Study LUL-6608 was of a mother whose baby was 10.9 weeks old. At the study session she fed first by bottle, using the Lansinoh wide-necked, textured teat, with a small hole, for a period of just two minutes. On this teat, the baby fed fairly rapidly, showing peristaltic tongue movements, but also with marked extractive tongue movements, and evidence of milk flow. The baby showed 80-90% compression of the teat bulb. In the later parts of this short feed the image of the tongue has high contrast, which made the peristaltic nature of the tongue movements particularly striking.

4.4.9 This was followed by a sequence of breastfeeding lasting 11 min 24 sec. Feeding on the breast was typified in this baby by very marked, conspicuous peristaltic tongue movements. It is difficult to state with certainty, but it appeared that, when feeding on the breast, this baby applied the localised drawing down of the tongue (i.e. an e.t.d.) more anteriorly to the underside of the teat, and not beyond the nipple tip. This movement was associated with overt filling of the duct(s) adjacent to the point of application of the e.t.d. The location of this movement exaggerated the quality of the peristaltic movements (we have seen this more anterior displacement of localised tongue depression before, in perhaps 3-4 other babies).

4.4.10 The third sequence was of the baby feeding on a narrow-necked, ribbed, teat, with a small aperture. Initially only the teat bulb was visible, and the baby showed 70-90% compression of the teat bulb. A short while after, however, the neck of the teat became visible, demonstrating that the baby was completely occluding the neck of the teat (i.e. 100% compression).

4.4.11 There seemed little evidence of extractive tongue movements on this teat type (c.f. the wide-necked teat) and the baby appeared to be removing milk from the teat by expression alone. It also became clear that the amount of milk entering the baby's mouth, as indicated by the volume of the 'milk space' at the teat tip, was directly proportional to the volume of the milk in the teat bulb shortly prior to this. There was, in fact, a clear one-to-one relationship between the milk in the teat, prior to it being expressed, and the volume entering the mouth, prior to it being swallowed.

4.4.12 This, to our knowledge, is the first definitive proof of the fact that the baby can express milk, by peristaltic tongue movements alone, and that there is a 1:1 relationship between the volume expressed and the volume taken. It is remarkable that this proof comes from a bottle-feed for which one might expect there to be more likelihood of the baby using use extractive tongue movements to remove milk. However, the visual evidence that this baby was able to achieve 100% compression of the teat neck is crucial to this observation.

4.4.13 This does not mean that every baby feeds in this way, but it does indicate that some breast-fed babies can feed with the same pure peristaltic action on a bottle teat that is seen much more commonly on the breast.

4.4.14 This finding, from this particular sequence came relatively late in the day, with regard to the overall analysis of the data collected, and indicates that all the recorded material should now be re-evaluated from this perspective, to determine whether there is any further evidence of this nature in other sequences.

4.5 Commercial implication:

4.5.1 The observations made in sections 4.4.8 to 4.4.14, in combination with other observations, would suggest that the most effective teat design might involve producing a teat of the same overall dimensions as the narrow-necked teat (the narrowness of the teat, allows the baby to take a greater length of teat into its mouth), but with the thickness of material used in the design of the wide-necked teat. Alternatively, the design of the wide-necked, textured teat might be modified, so that the teat section (neck and bulb) is longer, allowing the baby to take a greater length of this into his/her mouth. The length of teat would seem, on theoretical grounds at least, to determine the efficiency and/or quality of the baby's suckling action.

5 Discussion

5.1 Comparison of breast- and bottle feeding from present study:

5.1.1 Sucking styles – Peristalsis versus localised Extractive tongue depression: In the present study both *peristaltic tongue movements* (p.t.m's.) and *extractive tongue movements* or *depressions* (e.t.d's.) were observed during **both** breastfeeding **and** bottle feeding.

5.1.2 *Peristaltic tongue movements* were conspicuous throughout all phases of active sucking, by **all** babies, at **all** ages, irrespective of whether they were feeding from the breast or the bottle – there were no departures from this rule,

5.1.3 Superimposed upon this core pattern of rhythmical waves of compression generated by the tongue against the underside of the sucking stimulus, be that the breast or the bottle, babies also showed *extractive tongue movements*, which involve localised depression of the central region of the tongue, usually just beyond but proximal to the tip of the nipple or bottle teat ('piston-like' action of the tongue surface localised to the region of the teat/nipple tip).

5.1.4 It would seem that, as a general rule, neither method of sucking is more or less common during either breastfeeding or bottle-feeding, although there are some important caveats to this statement.

5.1.5 This study identified the fact that one of the main determinants of the type of sucking seen is the rate of milk flow from either the breast or the bottle, but, based on the following statements it will become clear that we also believe babies have individual-specific styles of feeding.

5.1.6 On the breast, the rate of milk flow varies in a continuously graded manner from an absence of flow, to profuse milk flow, during milk ejection. On a bottle, the rate is set predominantly by the teat hole size (aperture) which is fixed from the outset; this therefore is likely to exert a dominant influence on the style of sucking.

5.1.7 The characteristic feature of the way in which the baby feeds, which is preserved during both breast- and bottle-feeding by the same baby, is the precise mix or ratio of the two methods, when both are present. So, for example, if the *extractive tongue depressions* are relatively shallow and a minor component, the ratio of p.t.m's. to e.t.d's. may be 90:10. As e.t.d's. become more conspicuous, ratios of 75:25, 60:40 & 50:50 may be discerned; they may even appear to be the more dominant element, with a ratio of 40:60 (ratios larger than this, e.g. 25:75, were not observed, however).

5.1.8 One baby might show a 90:10 ratio throughout most of the feed on both the breast and the bottle, while another may be more likely to show a 50:50 ratio throughout most of its feeding, irrespective of whether it is from the breast or the bottle. This was contrary to our expectation and suggests that while the flow rate may influence the style of sucking, there are over-riding, individual-specific characteristics which mean that individual babies can be associated with specific sucking styles.

5.1.9 We cannot say to what extent this was a function of the fact that we were studying breastfeeding babies who were also being mixed fed, so had not developed an independent style of feeding; as they might have done, had they been bottle-fed from the start.

5.1.10 An important caveat to the statements above is that *extractive tongue movements* are more likely to be seen on the bottle, but largely as a function of the fact that moderate flow rates persist for a much greater proportion of the feed than on the breast. If one could select 'like-for-like' periods of milk flow on the breast and the bottle, it is likely that there would be no difference in the relative frequency of p.t.m's. to e.t.d's.

5.2 The relationship between teat hole size and sucking pattern

5.2.1 There would appear to be predictable changes in sucking style with variation in the teat hole size, and some generalisations are proposed below. The main difficulty, however, with developing a unifying theme, is that any basic underlying pattern is confounded by two factors:

- babies showed individual-specific styles of sucking (as described above), and
- different babies seem able to secure milk at different rates from the same teat, suggesting individual differences in the strength of their suck.

Both these sources of variation can modify the general rules/principles set out below; this means that the scheme proposed should not be regarded as either absolute, or even strictly reliable with each and every baby.

5.2.2 <u>Fast to moderate flow rates</u>: At high flow rates on the breast babies tended to show predominant or exclusive 'peristaltic tongue movements'. This was rarely the case when feeding on bottles, suggesting that, even when teats with a large hole were capable of delivering milk at a fast rate, this did not approach the sometimes explosive milk release found during when the 'let-down' reflex is at its peak.

5.2.3 So, on teats with a large hole size (can also be true of medium-holed teats), which deliver milk at a moderate to fast rate, the baby commonly used a combination of *peristaltic tongue movements* (p.t.m's.) and localised extractive tongue depression (e.t.d's.). The e.t.d's. appeared long, slow and 'measured', presumably to draw out milk at an optimal rate.

5.2.4 The rate of milk extraction was usually sufficient for the baby to accumulate enough milk for it to be swallowed with each suck. As a result, babies showed a 1:1 ratio of sucks to swallows with large holed teats. The typical suck duration with moderate rates of flow was close to the maximum (1 second), with the result that the suck frequency was at, or close to, its slowest rate of 1 suck/sec.

5.2.5 Slow flow rates: On teats with only a small hole size, the amount of milk the baby drew out with each suck was insufficient for a swallow. The baby did not adapt by increasing the suck duration, but instead took a sequence of shorter sucks, which could give the appearance of fast, short, even 'frenetic' sucking. This altered strategy with low flow, therefore, seems to be to generate a brief string of sucks (from 2-3, or several), until sufficient milk has accumulated for to initiate a swallow.

5.2.6. Alternatively, the baby might insert one longer extractive tongue movement, in a burst of say 3-6 sucks which were predominantly peristaltic. This also means that the suck:swallow ratio varied from as little as 3:1, up to 6:1 sucks per swallow.

5.2.7 Medium flow rates: With medium rates of flow, an intermediate pattern emerges. Sufficient milk to trigger a swallow was secured over the course of two sucks, which resulted in the very common pattern of an extractive tongue movement occurring on every alternate suck (1-in-2).

5.2.8 The more marked extractive tongue action usually followed the swallow; it then appeared as if the second suck in the sequence merely 'topped-up' the accumulated milk, triggering the swallow.

5.2.9 This *alternating pattern* was so common that it may signify that other functional priorities are being met at the same time. For example, it may be a particular *energy-efficient* way of linking sucking elements together, and for coordinating swallowing with breathing. An analogous example might be with doing the 'breast-stroke' when swimming, when it is more economical to take a breath on every alternate stroke, rather than with every stroke.

5.2.10 The *alternating pattern* is not specific to bottle-feeding, but was also commonly seen on the breast; it simply occurred for shorter periods on the breast (presumably because flow rate changes in a more dynamic manner on the breast). It can be classed as an adaptive feature of feeding, rather than an individual-specific characteristic, on the basis that its appearance varies during a feed, across stimulus types (breast, & teats of different hole sizes), as well as between babies.

5.2.11 The scheme outlined above assumes that the baby is both effective at gauging the flow rate accurately (i.e. they are an effective '*transducer'* of flow rate), and are able to respond to it by modulating their sucking pattern. This is not unreasonable, but it requires us to acknowledge that babies possess a high level of sophistication in the coordination of their sucking behaviour (people are commonly reluctant to accept such assertions).

5.2.12 The flow rate of milk from the breast constitutes the 'rate of milk reward' for the baby, so we are simply claiming that the baby has an adaptive sucking repertoire which enables it to modulate this *rate of reward*. We regard it as highly credible that the baby can modulate its sucking style to *optimise* milk flow (rather than necessarily to *maximise* it).

5.2.13 This proposition also suggests that there are other constraints affecting sucking style. The possibility might exist, for example, that an overly vigorous sucking action might either traumatise the mother's breast/nipple from which the baby is feeding, or even to damage the internal tissues of the baby's mouth (self-inflicted damage). If the baby were to generate persistent high levels of suction, it might traumatise the mouth; in this context, it may be noted that baby's with several oral thrush are extremely fretful when feeding, as if the feeding causes them acute discomfort.

5.2.14 Conversely, while mothers do suffer from sore, cracked nipples, this may not be the natural order; it would be maladaptive for the baby to inflict such profound damage to the breasts/nipples, which could jeopardise the continued supply of its sole source of nutrients.

5.2.15 So, although this may sound highly speculative, in evolutionary terms it would be functionally maladaptive for the baby to compromise its sole source of nutrition. There are likely to be, therefore, intrinsic naturally protective mechanisms which operate to minimise the chances of trauma or damage[4].

5.2.16 An alternative suggestion would be that certain forms of sucking are *'energy-efficient'* at particular flow rates but not at others. Vigorous extractive tongue movements may only be energy efficient to produce when there is an adequate reward rate in terms of milk flow – it may be 'energy-*in*efficient' to sustain high-intensity extractive tongue movements at low flow rates. Peristaltic tongue movements would seem to be the most energy efficient, on the basis that they are present throughout all forms of feeding, and are the sole sucking pattern in the absence of milk flow.

5.2.17 While suggestions are speculative, they are aimed at constructing a rational explanation of why baby's sucking patterns vary in the way they do with changes in teat characteristics.

5.3 Evidence base on relationship between flow-rate and sucking style.

5.3.1 <u>Teat hole/aperture size (presumed flow-rate):</u> Previous work has indicated that the fluid delivery rate on either the breast (Drewett & Woolridge, 1979) or the bottle (Crook 1976, Burke, 1977) influences the rate of sucking; the sucking rate slowing as more fluid is delivered. This may be partially accounted for by the fact that when swallowing occurs the inter-suck interval is increased to accommodate the duration of the swallow (Burke, 1977).

5.3.2 This study suggests a new proposition that changes in suck duration also occur as a function of whether or not a localised *extractive tongue depression* is inserted, **and** the relative duration of that action - whether or not this is slow and exaggerated (e.g. 'measured'

[4] The fact that 'sore nipples' is such a common cause of the premature cessation of breastfeeding would imply that cultural/societal practices are capable of subverting the natural evolutionary pattern.

in appearance) or fast/brief (e.g. 'frenetic' in appearance). This is a novel observation, and potentially has more explanatory ability than the assertion of Burke (1977). The limitation of the previous claim was that the insertion of a swallow would tend to have an 'all-or-none' effect on suck duration, which might be expected to produce a bimodal distribution of suck duration. However, no simple dichotomy in suck length is found, with the suck duration being continuously variable between 1 suck/sec (nutritive sucking) and 2 sucks/sec (non-nutritive sucking) (see Section 6.2.1 *et sequ*. below).

5.3.3 Eishima (1991) showed by direct observation that with slow flow rates, commensurate with a small teat aperture, the baby showed a greater tendency to make localised tongue depressions, suggesting the baby was making increased efforts with its tongue to extract milk. With fast flow rates from teats with a large hole, there was much less evidence of the baby using its tongue to extract milk, the principal task then being to process the fast flow.

5.3.4 We believe that the very high flow rate used by Eishima (1991) in her study, which was associated with a relative absence of *both* peristaltic tongue movements *and* extractive tongue depressions, were physiologically atypical. As a result, it is unlikely that the flow rate was matched by our research teats, even those with the largest holes; this may explain why we did not observe this most extreme form of sucking, described by her, in our own current studies.

5.4 Further observations:

5.4.1 <u>Nipple compression/teat neck occlusion:</u> Babies showed substantial variation in the degree to which they compressed the neck and/or bulb of the teat during scanned feeds. Some teats, brought in by mothers, resisted to a large extent the baby's efforts to compress them (e.g. Avent, Dr Brown's); in some the neck could be compressed but not the teat bulb. Compressions of 10-75% were recorded in the commercial teats used by mothers. The research teats supplied by Pigeon were generally much more compressible – typical values for the wide-necked, 'ringed' teat being 50-90%, while for the wide-necked, textured teat, they were in the region 60-100%. At least four babies were able to achieve 100% compression of the textured teat, when they had not been able to do so with the ringed teat.

5.4.2 Silicone rubber bottle teats, however, remain far more elastic than the breast (in a plane at right angles to their long axis), so tend to resume their natural shape quicker; the thicker the silicone-rubber the more elastic they were. It may be that the baby's ability to compress the teat fully, and to maintain it in this compressed state, may have little functional significance for the efficiency of bottle-feeding in these babies. However, the elastic properties of some teats appeared to 'push' the oral tissues apart again, before effective teat bulb expression could have taken place. Despite this, we took the baby's efforts and ability to compress the artificial teat as a marker for their efforts to emulate sucking on the breast.

5.4.3 <u>Nipple distortion</u>: During feeding on certain types of bottle teats, we were able to observe some 'shearing' distortion of the teat body during feeding. We were only able to observe this phenomenon in teats with the internal annular rings, but may assume that it applies to all teats (and to the breast). When babies sucked and partially occluded the teat body, it could be observed that the annular ridge on the top of the teat (in the baby's mouth) did not always match up to the annular ridge at the bottom of the teat (adjacent to the tongue). If the two ridges were displaced, the lower one would be more anterior in the baby's mouth. This signifies that the baby applies a degree of shearing force to the teat within the mouth in the ventro-dorsal plane which distorts it (it might be possible to estimate the forces required to achieve such distortion). This probably has little functional relevance to the efficiency of feeding on a bottle teat, but may help to explain an additional force applied to the breast, capable of inflicting trauma.

5.4.4 Teat projection into baby's mouth: The essential difference between the narrow-necked and the wide-necked teat is that they may allow the baby to take different lengths of teat into their mouth. However, the majority of babies were bottle-fed by their mothers when performing the ultrasound scan (occasionally the baby's father or the attending midwife). We did not intervene to influence how far the bottle teat was introduced into the baby's mouth, so this was determined by the mother's typical feeding practice.

5.4.5 While there were some observed differences in the extent to which the two teat types projected into the mouth, these were not reliable across mother-baby pairs. So, while we were more likely to visualise the two terminal annular rings inside the narrow-necked teat, as compared with one on the wide-necked teat, the next baby studied might confound this 'rule'. In this respect, there were many times when we were only able to observe one annular ring on the narrow-necked, and several occasions when we could observe two on the wide-necked teat. We attribute this variation to differences in practice between the various 'carers' when feeding their baby.

5.4.6 In a similar manner, despite differences in the width of the neck of the teat, over which area the baby was able to deliver peristaltic pressure with the tongue, we discerned no clear or fixed differences in sucking as a function of the width of teat neck.

5.4.7 Teat location in baby's mouth: An unusual finding, but one which should be self-evident, is that the bottle-fed baby has much greater flexibility over where he or she holds the bottle teat body in their mouth. This became apparent when the bottle teat suddenly disappeared from the midline view on ultrasound, usually when the baby glanced to one side or another. This was particularly notable in older babies, who were more easily distracted and chose to look around while feeding. Accordingly, the bottle-fed baby was able to slip or re-locate the bottle teat to the side of their mouth, and yet continue to feed. This adds another source of variation in the flexibility shown by older babies when bottle-feeding.

5.4.8 Unlike a bottle teat, the breast is naturally protractile (elastic in its long axis), so the breast-fed baby must expend a degree of effort to hold and retain a teat-like shape from the breast within the mouth, and to hold it centrally within the mouth. If the baby relaxes his grasp on the breast, it recoils elastically from his mouth – a bottle teat does not do this.

Accordingly, for a breast-fed baby to retain the nipple/breast in its mouth and continue breastfeeding, it must continue to hold onto the teat-like shape formed from the breast, using suction, and to keep this tissue centrally located within the furrow/channel created by the baby's tongue (i.e. the act of suckling from the breast is more constraining). Because the mother's breast/nipple is more pliable, it is likely to be further distorted by any sideways movement of the baby's head.

5.4.9 The bottle-fed baby, in contrast, moves his head from side-to-side and can switch the teat from the centre of the mouth, to the side, while still appearing able to feed from it. This seemed to have relatively few practical implications for feeding, although it was a practical hindrance to successful scanning on some occasions.

5.4.10 <u>Teat retraction:</u> Although all teats evaluated were of the anti-colic design, this did not always function as anticipated (rare in the research teats, less so in other commercial brands). Occasionally, the baby would build up suction in the bottle, with the removal of milk, which would cause the teat to suddenly withdraw and retract from the baby's mouth, as it collapsed back into the bottle. The mother/carer would then have to remove the bottle from the baby's mouth to allow the suction in the bottle to equalise with atmospheric pressure.

Section Two (More speculative views)

6 Differences between breast- and bottle-feeding:

6.1 Teat compliance and its impact on feeding.

6.1.1 A key difference between the breast and the bottle is the relative compliance and flexibility of the two stimuli (i.e. the object within the baby's mouth which triggers sucking). The breast, we assume is almost completely compressible, with the only resistance arising from the connective tissue matrix which, as the jaws come together, will reach a point when further closure is resisted. The breast has no natural elasticity in the plane orthogonal to the long axis, which means it has no ability to resist this compressive force.

6.1.2 The same should also be true of the bottle teat, in that the teat neck and/or bulb will only completely resist further compression when the anterior and posterior walls of the teat come together (100% compression). However, because the teat is elastic, closure of the teat may be resisted by this natural elasticity, so that as the jaws come together, the elasticity of the teat starts to resist this movement. This is suggested by the subjective impression that even when the baby does achieve quite strong closure of the teat body, the jaws seem to spring back, faster than they would if the baby were feeding on the breast.

6.1.3 Teat compliance and teat flexibility are related qualities, so the wide-necked textured teat is more flexible and compliant. It should also be less intrinsically flexible, in terms of the tendency to push the baby's jaws apart again. But, at the point where the jaws are applied (close to the teat neck), it is much wider, and also constructed of thicker silicone-rubber. This will make it less compliant and less compressible, and more likely to resist jaw movements.

6.1.4 We plan, in the future, to develop methods for measuring the compresses forces generated by the baby's jaws, which could then be applied, primarily, in the context of bottle-feeding, across a range of teat designs, including pacifiers. Such an approach is essential if we are to evaluate the relationship between teat elasticity and the degree of teat compression achieved by the baby. This would enable us to determine not only whether the teat neck is fully or partially occluded, and the forces involved, but also for how long the baby is able to maintain this closure, before elastic forces reverse this (in contrast to the breast); such factors are extremely difficult to determine with any confidence from ultrasound.

6.2 Determining the optimal teat hole size and shape.

6.2.1 Dealing first with holes of finite size, hole size is a rate-limiting factors, so will be the main determinant of the rate of milk flow from the teat; this was demonstrated some while back and the various published studies, conducted mainly by psychologists, were reviewed by Crook (1979). An unfortunate aspect of these early studies, however, was that quantitative measures of 'sucking frequency' and 'suck duration' were based on the total period of time for which babies fed. It was only some while later that researchers came to understand the need to discriminate the 'gaps' between sucks within a burst of sucking (intra-burst, inter-suck interval) from the gaps between bursts of sucking (inter-burst intervals) (Drewett & Woolridge, 1979). As a result, sucking frequencies, as defined in most early studies, counted the net number of sucks per unit time, irrespective of whether the baby was actively sucking or not. Nowadays, we limit our calculations of sucking rate to the rate of sucking within a burst of sucks.

6.2.2 Small holes result in low flow rates, which are associated with a faster pace of sucking within a bout/burst of sucks. Accordingly, as the hole aperture increases in size, so too does the flow rate, and the pace of sucking slows. Sucking rates appear continuously variable from the fastest rate of 2 sucks/sec during Non-Nutritive Sucking (NNS), observed on a blind teat, pacifier, or finger, to the rate typical of Nutritive Sucking (NS), when milk is being delivered at its peak rate, which is 1 suck/sec, or even slightly lower (Drewett & Woolridge, 1979). Accordingly, most variation in sucking rate falls within the range 60-120 sucks per minute (during bursts of active sucking).

6.2.3 Variation in the sucking rate was observed in the current study as a function of hole size (as stated above), with larger holes being associated with slower sucking rates and *vice versa*. There were also more subtle differences, for which we do not yet possess the appropriate analytical techniques to evaluate. On large holed teats, babies seemed to use more 'measured' or 'studied' tongue movements, drawing out the phase of the suck cycle, by employing longer *extractive tongue depressions* to remove milk. On smaller holed teats, the style of sucking seemed more 'frenetic' or 'frantic'.

6.2.4 Some of this may be related to differences in teat compliance (addressed above), with any tendency for the teat to 'spring' back to resume its natural shape, perhaps contributing to the subjective appearance that the baby sometimes 'struggles' to achieve smooth, coordinated teat closure.

6.2.5 These observations have potential explanatory ability, which had not previously been anticipated. First, the observations of Eishima (1991) and Geddes et al. (2008) have not previously been considered alongside descriptions of peristaltic tongue movements in the context of bottle-feeding. Not only has the present study confirmed that both styles of sucking be observed within breast-feeds, it has also shown that they can both be observed in contemporary studies of bottle-feeding in the same baby.

6.2.6 The insertion of localised extractive tongue depressions, superimposed on peristaltic tongue movements, appeared to slow down or delay the progress of the suck cycle, increasing its duration. The impact of e.t.d's. should therefore be detectable by detailed studies of the temporal patterning of sucks. While, subjectively, this appears to be the case, i.e. that their insertion prolongs the suck duration, this would need to be determined objectively.

6.2.7 Y-shaped holes: With teats that have a fixed size aperture it is possible to derive a 'natural drip rate' (n.d.r.) for the teat (the rate at which water drips from a teat, loaded with water, solely under the influence of gravity, and without any resistance from a bottle). Teats with Y-shaped apertures, however, do not have a n.d.r. as a degree of force is necessary to open the Y-shaped hole.

6.2.8 In the discussion below we address the issue of the persistence of peristaltic sucking movements on the bottle, when they may be very much less effective for removing milk. One potential benefit arising from this, however, is that even if they are relatively ineffective at achieving teat neck occlusion and teat bulb compression, they will still cause distortion of the teat tip, possibly encouraging opening of the Y-shaped aperture.

6.2.9 As noted above, in scans of babies feeding on the two teat types with internal annular rings, the two sides of the ring did not always match up as they came together (the majority of feeds with this teat type). This suggests that the tongue movements create a degree of *shear* in the teat body, pushing the lower side out of the baby's mouth slightly. While this did not seem to have any obvious impact or significance on the feeding process or its efficiency, it does highlight some of the intrinsic forces at work in the baby's mouth during feeding.

6.2.10 During bench testing of teats with Y-shaped holes, a degree of distortion is applied to the teat body, to open the Y-shaped hole (K Matsutori, *pers. comm.*) of the teat, in order to measure the relative flow rate. It would seem that natural distortion of the teat with the baby's mouth, and the persistence of peristaltic tongue movements, could both enhance opening of the Y-shaped teat aperture. No specific differences were observed, however, between sucking on teats with a fixed diameter aperture, compared to the Y-shaped hole, which requires some effort to open.

6.3 Why do babies employ peristaltic tongue movements on the bottle?

6.3.1 Peristaltic tongue movements are only presumed to be an efficient means for removing milk, if there is complete occlusion of the teat body. Not only should there be complete occlusion of the teat neck, but this also needs to be maintained throughout the phase when the teat bulb is being compressed. If there is incomplete teat occlusion, compression of the teat bulb is most likely to cause milk to flow back into the bottle (least resistance), rather than onwards into the mouth, where intra-oral volume is likely to be limited in contrast. While we saw babies who were able to achieve 90-100% compression of the teat body, many only sustained this for a very short period of time, the teat bulb appearing to recoil elastically in the baby's mouth.

6.3.2 It may seem somewhat surprising therefore that ALL babies maintained peristaltic tongue movements on bottle teats, despite the assumption that this is a relatively ineffectual means for removing milk. There are several possible explanations for this:

6.3.3 First, *peristaltic tongue movements* appear to constitute the core, intrinsic feeding modality of infants. *Extractive tongue depressions* can only be superimposed upon this core pattern, implying that e.t.d's. cannot exist in isolation. Peristaltic feeding movements of the tongue must therefore be maintained, in order for e.t.d's. to occur.

6.3.4 One might expect, however, that the peristaltic component might be 'downgraded' in intensity if a greater reliance for milk extraction was placed on increased suction created by downward tongue movements; this appeared to be suggested by the studies of Eishima (1991), but was not demonstrably the case in this series of ultrasound studies.

6.3.5 Alternatively, p.t.m's. may not be as ineffectual as first appears, so that the baby sustains them, to ensure the continued supply of milk. It is worth reiterating that the dual forces of *positive tongue pressure* and *negative extractive movements* of the tongue are complementary, and likely to act in a synergistic manner, i.e. they are not in competition with each other. Accordingly, the most efficient removal of milk can probably be achieved by the two forces being in equipoise.

6.3.6 This does not take into account the possibility that one force might be energetically more costly than the other. It may be the case that *peristaltic tongue movements* (the baseline pattern of sucking) are energetically less demanding, involving relatively little effort. *Extractive tongue movements*, in contrast, may be energetically more costly, so are seen for a much shorter proportion of the time on the breast. While they are seen for much of the time the baby feeds on the bottle, babies appeared to apply them with very much less vigour on a bottle teat, as if they were 'conserving their energy' (see 6.4 below).

6.3.7 It has to be acknowledged that babies are highly variable in the degree to which they show these two sucking modalities during a feed. They are also flexible and dynamic in the way they shift or adjust the balance, or ratio between them, over the course of the feed. One can only presume that these shifts or changes are *adaptive*, being *responsive* to instantaneous changes in milk flow, and/or to the perceived availability of milk.

6.4 Extractive tongue movements – why do they appear less vigorous on the bottle?

6.4.1 The extractive tongue movements shown by babies during bottle-feeding seemed less intense, less vigorous, than comparable movements seen on the breast. On the breast, e.t.d's. were accompanied by two behavioural markers: (i) extension of the breast/nipple further in to the baby's mouth (this is contrary to the retrograde movement of the nipple tip out of the baby's mouth, when only peristaltic tongue movements impact on the nipple); & (ii) a downward and forward shearing movement of the soft palate.

6.4.2 During breastfeeding, the soft tissues lying at each end of the oral cavity drawn inwards by the suction pressure generated, and their respective movements are comparable; in other words, the nipple tip is drawn into mouth to the same degree that the soft palate is drawn forward. In many instances during breastfeeding, the degree of movement is quite large and marked; in one extreme sequence the nipple tip and soft palate repeatedly made contact over several cycles of sucking. The degree to which the soft palate is distorted can be taken as a proxy for the level of suction being generated. At low suction, the soft palate was simply displaced downwards; at more extreme suctions, it also sheared forwards.

6.4.3 While downward, forward shearing of the soft palate, indicating high levels of suction, was common on the breast, it was very much less common on the bottle; when it did occur it seemed to be for much shorter periods (we saw marked evidence of shearing of the palate in only one out of 67 separate bottle-feeding episodes). We are left speculating as to why this might be.

6.4.4 Two possible explanations might be proposed: first, in the case of breastfeeding, the relative extensibility of the soft tissues (nipple, soft palate) are comparable; in the case of bottle feeding, the bottle teat is both more resilient and resistant to stretch than the soft tissues of the mouth. Accordingly, if the baby were to generate the same levels of suction during bottle-feeding, that they do during breastfeeding, there would be much less movement of the bottle teat tip into the mouth, with proportionately greater forward distortion of the soft palate. Consequently, during bottle-feeding, it would be the soft palate, to a large extent, which would be distorted by the level of negative intra-oral pressure generated. This might prove uncomfortable for the baby, or pose the risk of trauma to the soft palate, which the baby might avoid by generating lower intensity sucking pressure within the mouth.

6.4.5 Second, there is no obvious reason why the baby should need to *maximise* milk transfer; so, all other things being equal, it may be adequate for the baby to *optimise* milk transfer. This essentially means making feeding as energy efficient as possible, i.e. securing the greatest volume of milk , in the shortest time possible, but with the least expenditure of effort. So, for example, if the baby were faced with a bottle teat with a very small hole, it could employ high levels of suction to maximise the amount of effort devoted to removing milk. This, however, might be energetically costly and inefficient; as a consequence, it might be better to generate lower levels of suction, and simply feed for longer in order to secure the same volume – this would involve optimising milk transfer.

6.4.6 It may well be the case that the baby is a highly effective ‘transducer’ of milk flow from the breast/teat and is able to modulate the amount of effort required, according to the reward rate for receiving milk. So, as milk flow dwindles, there might be a period when it becomes more beneficial to increase suction to remove more milk. But there might also come a point when the expenditure of effort was disproportionate to the rewards received, at which stage it might be injudicious for the baby to persist with the same intensity. ‘Stepping-down’ the intensity of sucking might be an appropriate strategy at this time, thereby accepting a lower rate of reward, but without expending unnecessary effort.

6.4.7 This view of the ‘energy-efficiency’ of sucking, or of ‘energy conservation’ during feeding, was only developed in the context of bottle-feeding. During breastfeeding, milk availability to the baby cannot be determined, so the highly flexible, dynamic changes in sucking pattern can only be presumed to be related to variability in milk flow from the breast. So, it cannot be known why the baby, at one stage, seems to be feeding in a purely peristaltic manner when only small amounts of milk are available, then sometime shortly after, can be seen to be making more vigorous efforts by using extractive tongue movements, when milk flow is subsiding (in the wake of a ‘let-down’ reflex).

6.4.8 The same baby may be observed to feed on a small-holed teat in a slightly more ‘frenetic’ manner (faster paced), with shallow e.t.d’s. On a teat with a large hole, however, the baby can be observed to feed with a slower, more measured pace, with deeper drawing movements typifying the e.t.d’s. One might have expected the reverse if the rate of milk reward were the sole factor driving the process; only if one takes an ‘energy conservation’ view of feeding, do these observations make more logical sense.

6.4.9 Pure peristaltic sucking might be viewed, in these terms, as the most energy-efficient method of sucking; it is the exclusive method during non-nutritive sucking when there are no increased gains to be made by sucking more vigorously. Similarly, during high flow rates, for example when the mother has just had a ‘let-down’, there is unlikely to be any need to exert increased energy to take milk at a faster rate. Once the flow rate starts to subside, however, and there is still plenty of milk to be consumed, there may be some overall gain from the baby attempting to secure milk at the fastest rate.

6.4.10 One possible explanation for why one sees this association on the breast may be related to the duration of the ‘let-down’ reflex. Once the myo-epithelial (muscle) cells surrounding the alveoli (the sacs where the milk is made) are no longer maintained in a state of tonic contraction (by supra-threshold levels of oxytocin), they will relax and milk will no longer be pushed towards the nipple surface. In fact, it may even be the case that milk becomes very much less accessible to the baby, at this point. The baby, therefore, may only have a finite window of opportunity to remove milk from the breast, without triggering another let-down; so, during this period, it may be in the baby’s interests to maximise milk removal. This may explain why more vigorous e.t.d’s. are more likely to be observed during the middle phases of breast-feeds.

6.5 What is the optimal teat design to offer during breastfeeding?

6.5.1 It is perhaps worthwhile to consider what may be the optimal teat design to be used when the baby is still breastfeeding, not simply in terms a design or style which most resembles the breast, but also in terms of not exaggerating the differences (for example, in flow rate) between the breast and the bottle.

6.5.2 So, from one perspective, one would not want to make the milk so easily available from a bottle, relative to the breast, that its faster delivery rate made it more appealing than the breast. It is perhaps of interest that most mothers attending scanning sessions brought with them the bottle and teat originally purchased to supplement their baby, which were invariably Size 0 or Size I, i.e. for the youngest age, 0-3 mo. This was not a conscious decision on their part, as most stated that they had simply bought the 'first stage' teat for getting started; none commented that they had changed this as their baby got older. Many of the babies studied were older than 3 months, but were still using teats for babies aged 3 months and under. This might be viewed as a 'sensible' choice, as it would tend to limit the easy availability of milk from the bottle, and hence not create too discordant a rate of flow compared to the breast.

6.5.3 From a different perspective, one would not want to make the milk so difficult to remove from the bottle, that the baby could only secure adequate milk by making more exaggerated extractive tongue movements (e.t.d's.), thereby encouraging the baby to suck in a way which is more discrepant relative to the breast.

6.5.4 Further issues relate to both the length of the teat, and the width of the teat neck. It is likely to be the case that the longer the teat, the greater the amount of oral gratification the baby receives from the teat, which is not ideal. Similarly, a narrow-necked teat would require the baby only to make a moderate gape (jaw/mouth opening), when a wide-necked teat would perhaps encourage a wider gape, as would be required on the breast.

6.5.5 A compromise design would therefore be appropriate, which is not exaggerated in length, but is long enough to strip milk from in a peristaltic manner. Similarly, the fabric of the teat should not be too stiff and inelastic, and should be supple and flexible enough to be compressed effectively. It is clear that these considerations have been taken into account in the design of the research teats, but there may be further scope for adjustment in the light of the findings from these ultrasound studies.

6.6 The physiology of peristaltic waves in the human body

6.6.1 <u>Peristaltic wave physiology:</u> This area of work will be discussed as it has specific implications for bottle-feeding.

6.6.2 Peristaltic waves, as they appear physiologically in the human body, are of two simple wave types: *convex* and *concave*. In *convex* waves, the walls of the vessel bulge outwards, and this widening of the duct wall is propagated in a linear direction. Alternatively, the wave may be *concave*, so that there is an inward indenting of the walls of the tube, which are again propagated in a linear dimension (see Figure 1 below - from Dobrolyubov & Douchy, 2002).

6.6.3 If there is no complete occlusion of the tube, and both types of wave travel in the same direction, they move a fluid in opposite directions. So, a *convex* wave will move fluid in the same direction as the wave, while a *concave* waveform moves fluid in the opposite direction to the wave. This could mean that with complete occlusion of the ducts, as is seen on the breast, milk would move in the same direction as the wave; on a bottle teat, however, if there were no occlusion of the neck, milk might move in the contrary direction, although the volume displaced may be minimal.

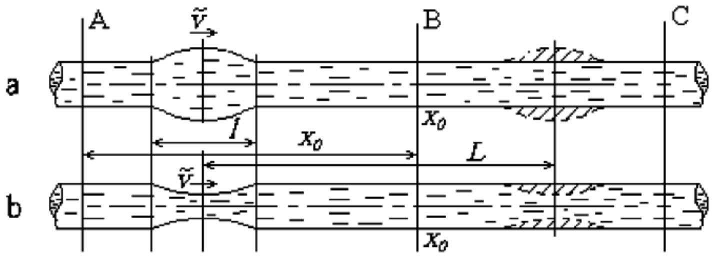

FIG. 1. Peristaltic tubes: (a) convex travelling peristaltic wave and (b) concave travelling peristaltic wave.

Taken from Dobrolyubov & Douchy. "Peristaltic transport as the travelling deformation waves". J. theor. Biol. 2002; ***219:*** *55-61.*

6.6.4 Many peristaltic waveforms in the human body are complex, however, that is they involve both a *concave* and a *convex* component. One type is usually larger than the other, and this determines the overall direction of fluid movement.

6.6.5 During predominantly peristaltic tongue movements the *concave* component of the waveform is substantially larger than the *convex* component, which may even appear to be absent. In contrast, when extractive tongue depressions predominate it is clear that the *convex* component of the waveform is larger than the *concave* waveform. These considerations, which are well established for peristaltic motion within ducts/tubes in the human body, have not previously been applied to infant feeding to our knowledge.

6.6.6 They are unlikely to apply when complete occlusion of a duct occurs (e.g. during breastfeeding), but become relevant, affecting the efficiency of fluid transport, when the duct is not fully occluded (e.g. during bottle-feeding).

7.0 Future Analysis

7.1 All recorded ultrasound sequences have been reviewed, evaluated and a primary analysis of their content, in both real-time and slow-motion, has been undertaken. This has, however, tended to focus on the unique attributes of each recording, more so than on a comparative evaluation of the sucking style in consecutive feeding episodes. Our preliminary analysis does not lead us to believe that there will be substantive revelations arising from a quantitative analysis of ultrasound scans; so we believe it is the case that our qualitative analysis of feeding episodes and recorded sequences has provided both a necessary and a sufficient appraisal of the research data collected (ultrasound recordings). It is likely to remain the case, however, that new methods of analysis, which may emerge in the near future, may throw some additional light on the material already collected (although the funding issues associated with secondary analysis of ultrasound recordings would need to be addressed).

8.0 Summary

8.1 This study produced unexpected results, largely in terms of the *absence* of any expected differences, which had been construed during the preparation of the research proposal (*as opposed to a preponderance of unexpected findings*).

8.2 In the majority of babies, there was a striking similarity between the style of feeding seen on the breast, and that on the bottle. Babies employed both *peristaltic tongue movements* and *extractive tongue depressions* during breast- and bottle-feeding. Peristaltic tongue movements were commonly seen during breastfeeding, but they were often also the dominant style of feeding on a bottle, which was contrary to our expectation.

8.3 There were observable differences in feeding style between the breast and the bottle, for example, babies rarely compressed and occluded the teat and/or bulb of an artificial teat (as we expect them to do on the breast), and in the majority of cases the teat wall appeared to recoil elastically, rather than be held in a collapsed state by the baby.

8.4 The style of bottle teat with internal annular rings appeared to offer no specific advantages in this respect, and the wide-necked textured teats appeared to be the most compressible of the teat designs tested in this study. There was no clear advantage of the narrow-necked teat over the wide-necked teat, so the wide-necked textured teat was therefore seen to perform best, largely because of its greater compressibility.

8.5 However, the wider neck may limit the extent to which these teats can be drawn into the mouth, suggesting that some small, compensatory increase in teat length might be considered.

8.6 The teat aperture sizes on the ribbed teat designs were reliable, although we encountered some greater than expected variation in the hole size on the textured teats. The larger sizes of teat (M, L & Y) all had Y-shaped apertures which made them difficult to match to the bottle teats which the mother commonly used with her baby.

8.7 Babies did not feed from bottle teats in *exactly* the same way they fed from the breast, but the similarities were more striking than the differences. Within the same baby, the flow rate, as dictated by the teat aperture, was the main determinant of whether or not the baby showed *extractive tongue depressions*, but individual-specific differences between babies meant that some did not show them when one might have expected them to do so. Conversely, a minority of babes showed *extractive tongue depressions* over a greater proportion of both breast- and bottle-feeds than was the norm; these individual-specific differences could not be accounted for by teat characteristics.

8.8 Overall, we were gratified by the absence of systematic differences in feeding style when the same babies were feeding on either the breast or the bottle. Babies possess a highly flexible and dynamic array of sucking strategies, which adapt them to feeding on the breast; it is perhaps this variation which enables them to adjust so well to feeding on artificial teats.

8.9 We do not know whether the lack of a difference between breast- and bottle-feeding was related to the fact that we chose to study babies who had been breastfed from birth, and for whom bottles were only introduced after the establishment of breastfeeding. All babies had managed to adapt successfully to mixed feeding, such that the introduction of bottles had not compromised their willingness to continue breastfeeding. So, it is plausible that their feeding style on a bottle was 'ingrained' by their typical feeding style on the breast; yet, babies should be sufficiently adaptable that they should be able to change their sucking style to whatever stimulus they are presented with. Furthermore, in our assessment, the prevalence of babies showing a dominant peristaltic tongue movement rhythm on the bottle was the same, if not greater, than we would expect of breastfeeding babies at the same age.

8.10 In conclusion, the babies studied in this series showed a much greater predisposition to show the same style of feeding on a bottle, that we saw (and would have expected to see them show) on the breast. We cannot say to what extent this was a function of teat design, or the fact that we were studying 'mixed feeding' in an essentially breast-fed groups of infants. Whatever the explanation, mothers should be reassured by the results of this study, which suggests that the introduction of bottles (with newer, more sympathetically and sensitively designed silicone-rubber teats) should not be assumed, automatically, to thwart their current success with breastfeeding. A different approach, using more consumer-based research, would be needed to determine the prevalence of babies for whom the introduction of bottles did in fact militate against the continued success of breastfeeding; although on the basis of the current evidence, we would not expect this to be a common event.

8.11 Across the series of 36 babies, there was not a single baby who was put off, or overtly affected, by the first offering of the research teats. Babies accommodated and adapted to the novel teat stimulus, without seeming to be 'thrown off their stride' in any way.

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