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Real-time 3D ultrasound imaging of infant tongue movements during breast-feeding☆

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ABSTRACT

Background: Whether infants use suction or peristaltic tongue movements or a combination to extract milk during breast-feeding is controversial. The aims of this pilot study were 1] to evaluate the feasibility of using 3D ultrasound scanning to visualise infant tongue movements; and 2] to ascertain whether peristaltic tongue movements could be demonstrated during breast-feeding.

Methods: 15 healthy term infants, aged 2 weeks to 4 months were scanned during breast-feeding, using a real-time 3D ultrasound system, with a 7 MHz transducer placed sub-mentally.

Results: 1] The method proved feasible, with 72% of bi-plane datasets and 56% of real-time 3D datasets providing adequate coverage [>75%] of the infant tongue. 2] Peristaltic tongue movement was observed in 13 of 15 infants [83%] from real-time or reformatted truly mid-sagittal views under 3D guidance.

Conclusions: This is the first study to demonstrate the feasibility of using 3D ultrasound to visualise infant tongue movements during breast-feeding. Peristaltic infant tongue movement was present in the majority of infants when the image plane was truly mid-sagittal but was not apparent if the image was slightly off the mid-sagittal plane. This should be considered in studies investigating the relative importance of vacuum and peristalsis for milk transfer.

1. Introduction

It is generally considered that the mechanics of infant feeding, including tongue movement and intra-oral pressure, differ during breast and bottle-feeding. This may in turn affect the rate of milk flow and milk intake, with potential consequences for infant behaviour – for example, colic – and also for growth. Given the recognised associations between rapid growth during early infancy and increased later risk of obesity and cardiovascular disease [1], this is an important issue. Studying the physiology of breast-feeding is also relevant to progress in the management of breast-feeding problems and also in order to improve the design of breast pumps.

Two theories have been advanced to explain how the infant removes milk from the breast. The first proposes that the infant uses compression of the areola and surrounding tissue, combined with a stripping peristaltic action of the tongue [2]. The second model proposes that the infant relies almost entirely on vacuum to remove milk with an up-and-down or piston-like tongue action [3,4]. Older studies using either fluoroscopy or ultrasound machines with large transducers have failed to clarify the situation, with support for both types of tongue movement [5–7]. One study [8], using fibre-optic imaging within a teat in 5-day old infants, suggested that both peristalsis and vacuum could be observed in the same infant, with peristalsis predominating when milk flow was slow but diminishing with faster flow. More recently, Geddes et al. [9] have exploited the improved resolution of modern ultrasound machines to perform real-time 2D imaging of the infant's mouth during breast-feeding, combined with measurements of intra-oral pressure during the suck cycle. Using conventional 2D ultrasound, they showed that milk flowed into the oral cavity as the tongue moved down, the nipple expanded and vacuum increased; contradicting the compression theory that peristaltic compression or upward movement of the tongue along the length of the nipple is associated with milk flow. They also showed using this technique that infants were able to obtain milk from an experimental teat designed to release milk only when a vacuum is applied [10], suggesting that vacuum plays an important role in the removal of milk during breast-feeding.

The orofacial structures contributing to suction and removal of milk are an ever-changing volumetric complex, and one limitation of a cross-sectional imaging technique such as 2D ultrasound is that it is unable to examine the dynamic morphology in its spatial totality. This could result in some important structural and/or functional information about the process of milk removal being missed using 2D methodology. Using reconstructed 3D ultrasound imaging techniques, Deng et al. showed that, by using a “water bath” to facilitate a scan with minimal compression, together with probe movement tracking and oral movement timing, the acting lip musculature can be visualised, for the first time, in 4D i.e., in

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dynamic 3D [11]. In further studies involving healthy volunteers and patients with cleft-lip and facial palsy, the team has used real-time 3D ultrasound techniques [12] to quantify the orbicularis oris at repose and in a full pout and the dynamic thickness of three pairs of expression muscles through planes standardised by 4D imaging [13]. During those studies, the tongue was often "accidentally" captured within the volume of interest, demonstrating the feasibility of quantitative analysis of its movement in 3D, albeit in adults with larger facial structures.

The aims of this pilot study were, firstly, to evaluate the feasibility and success of real-time 3D ultrasound to examine infant tongue movements, non-invasively, during breast-feeding; and secondly, to ascertain whether peristaltic tongue movements could be demonstrated during breast-feeding. The study was not designed to investigate the role of vacuum in milk removal, but rather to determine whether peristalsis could be consistently observed using 3D ultrasound.

2. Methods

2.1. Subject recruitment

15 mother–infant pairs were recruited for this pilot study. All infants were healthy, born at term [>37 weeks gestation] and with birth weight >2.5 kg. Participants were recruited from health centres [baby clinics], post-natal mother and infant groups, websites [university, mother and baby organisations], by word-of-mouth and using flyers and information sheets in community areas. Infants were between 2 weeks and 4 months of age when studied. The study was planned in two phases. Initially, 5 infants were recruited and studied to test feasibility and refine the technique. Once this had proved to be successful, a further 10 infants were then recruited and studied. The study was approved by the National Research Ethics Committee London [Reference no. 09/HO713/4] and mothers gave written, informed consent. The techniques used were considered non-invasive and would not interfere with feeding or result in discomfort. Mothers were advised that if an infant became unduly distressed during the scan, it would be discontinued. 3D ultrasound is safe and has been used to image the foetus and infant, and the ultrasound scans were performed by a single investigator [JD] with more than 17 years of experience in using the technique.

2.2. Study procedures

Each mother and infant attended the study centre at the Great Ormond Street Hospital or UCL Institute of Child Health. The infant was studied during a single breast-feed, with the timings of the feeds dictated by the infant's normal routine. Each mother filled in a general questionnaire providing information on background variables related to infant feeding, including frequency of breast feeds and any feeding problems.

2.3. Data acquisition and analysis

2.3.1. Ultrasound data acquisition

A real-time 3D ultrasound system [iE33, Philips Healthcare, Bothell, WA, USA] was used for data acquisition with a 7 MHz probe [X7-2 transducer] [Fig. 1a]. The probe was placed sub-mentally during each feed. After using the system's conventional real-time 2D imaging to locate the tongue approximately through the mid-sagittal plane [i.e., the human body's median plane], X-Plane imaging was activated to acquire two cross-sectional anatomic datasets with two perpendicular real-time 2D imaging planes [Fig. 1b]. Subsequently, Live-3D imaging was activated to collect volumetric anatomic data [Fig. 1c]. Ultrasound transducers [probes] were set to run at 5 to 7 MHz to achieve a good spatial resolution at a real-time [cinematic] rate. The volume imaging rate allowed the probe to be moved slowly without causing significant motion artefacts. Hence, increased information on the functional anatomy could be acquired in a shorter time, in comparison with conventional 2D imaging approaches.

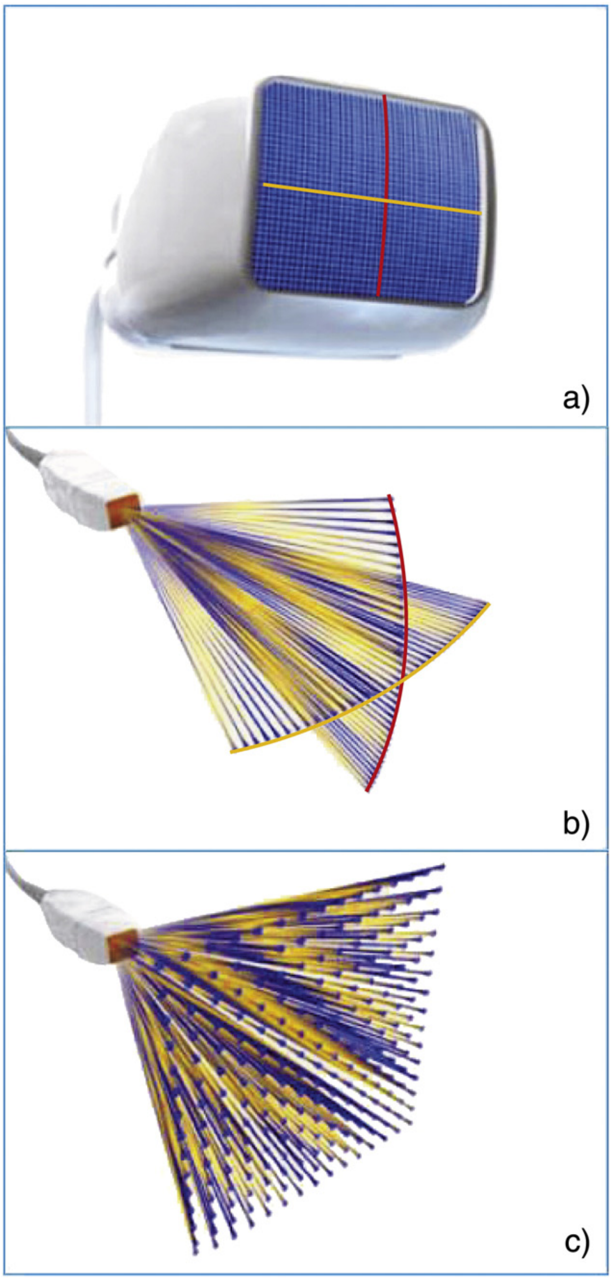

Fig. 1. [a] The 3D ultrasound transducer [probe] with 2400 matrix-array elements [minute blue squares]. X-Plane imaging is achieved by "simultaneously" sending out, from the crossed [X] red and yellow lines, two mutually perpendicular ultrasound beams [see [b]]. [b] The resultant X-Plane scanning with two perpendicular, real-time imaging planes. [c] Live-3D imaging volume is achieved by all the elements "simultaneously" transmitting ultrasound beams, forming a real-time imaging volume.
Figure slightly modified from an illustration at http://www.healthcare.philips.com/us_en/products/ultrasound/technologies/xmatrix.wpd.

2.3.2. Data analysis

[i] *Gross qualitative imaging analysis* of the oral functional anatomy during breast-feeding was performed online.

[ii] *Detailed qualitative analysis* was performed offline on a more versatile 4D workstation [4D Cardio View, TomTec Imaging System, Munich, Germany]. This was due to the complexity in dealing with

Table 1
Analysis on successful acquisition rate[a] and additional information rate[a].

	Useful datasets/total acquired datasets [rate]	
	X-Plane	Live-3D
Successful acquisition	108/150 [72%]	67/120 [56%]
Additional information provided by X-Plane or Live-3D approach	84/150 [56%]	48/120 [40%]

[a] See definitions in the Outcomes section, under the Methods section.

inhomogeneous ultrasound data, complicated by expected artefacts caused by excessive air-bubbles and bony structures in the mouth [through which ultrasound cannot penetrate].

2.4. New scanning technology

The following specific aspects of the new scan technology were examined:

2.4.1. Volunteer pairs' acceptance of the techniques

A *questionnaire* was completed by the mother, recording her perception of the infant's behaviour during the feed, any perceived problems, and opinions about the acceptability of the techniques and the extent to which they may have altered the infant's feeding behaviour.

2.4.2. Spatial resolution and anatomical coverage

This was judged by the recognition of known anatomic and feeding features such as the tongue, the soft- and hard-palates, the nipple and milk flow.

2.4.3. Temporal resolution and tongue motion patterns

This was judged as achievement of sufficient frame rate [with X-Plane] or volume rate [with Live-3D] when covering an adequate volume of interest [see "Successful Acquisition" defined below] and whether examination of tongue motion patterns gave additional information not obtainable from a conventional, real-time 2D ultrasound approach [see "Additional Information" defined below].

2.5. Outcomes

2.5.1. Technique feasibility

The initial phase outcome was whether or not the tongue and surrounding orofacial structures could be visualised in a single dataset by either the X-Plane or the Live-3D approach during breast-feeding. Because acoustic artefacts caused by air bubbles and bony structures affect ultrasound imaging of the front part of the tongue [for both 2D and 3D ultrasound], if more than 75% of the functioning tongue could be imaged on sagittal views with either approach, this would be described as a 'successful acquisition' [Table 1], and the methodology regarded as feasible.

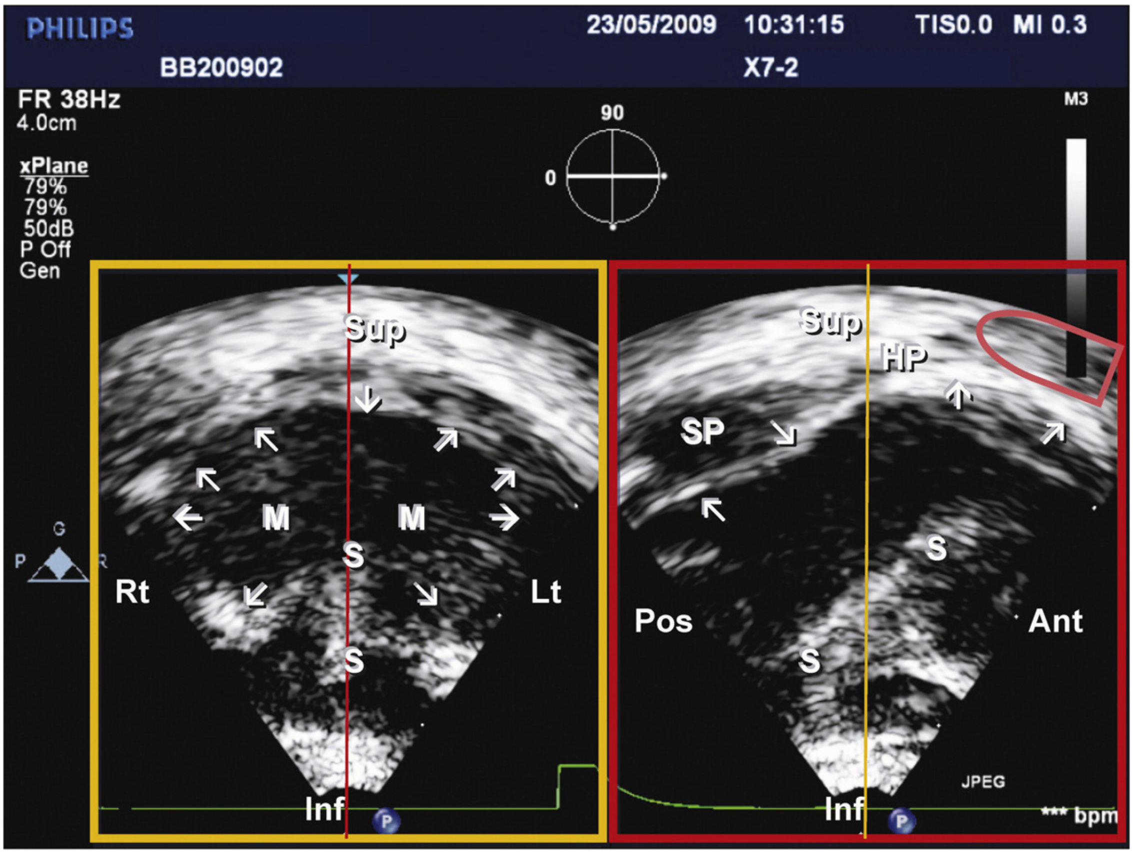

Fig. 2. X-Plane imaging with a true mid-sagittal view. The two framed images are perpendicularly across each other along the red-yellow line. The sub-mental position of the probe is indicated by small blue circles with a letter P in each image. The yellow-framed coronal view shows the connective tissue [bright] separation [S] between the two lateral muscular [dark] areas [M] of the tongue. In the human body, the separation should normally be on the mid-sagittal plane. With the red line cutting through or very close to the separation, a true mid-sagittal view is obtained in the red frame, showing a wavy [peristaltic] upper surface [arrows] of the tongue together with the nipple [open pink arrow] during breast-feeding. The peristalsis from the reader's right to left is dynamically displayed in the linked Video clip 1. [Ant: anterior; HP: hard palate; Inf: inferior; Lt: left; Pos: posterior; Rt: right; SP: soft palate; Sup: superior. The same abbreviations are used for the following Figures and video clips].

2.5.2. Comparison with conventional ultrasound study findings on infant tongue movement

X-Plane and Live-3D ultrasound findings were to be compared with findings from conventional [cross-sectional] views obtained in this study and in published studies with respect to movement of the tongue during breast-feeding to withdraw milk from the breast. If motion patterns different from those in conventional views were noted in either an X-Plane or Live-3D dataset, the dataset would be considered as providing 'additional information' [Table 1].

3. Results

3.1. Volunteer pair's acceptance of the techniques

No infant showed any sign of discomfort or distress during scanning as they breast-fed. Mothers made no negative comments when asked and were happy with the procedures and that their infants were not unduly disturbed during breast-feeding.

3.2. Ultrasound imaging

3.2.1. Spatial resolution and anatomical coverage

Successful acquisition: 5 to 15 datasets were recorded in each infant with the X-Plane approach, and 6 to 10 datasets with the Live-3D approach [Table 1]. Of the 15 babies studied, a total of 150 X-Plane datasets and 120 Live-3D datasets were acquired [Table 1]. 72% of the X-Plane datasets and 56% of the Live-3D datasets provided sufficient [over 75% of the functioning tongue] coverage.

As shown in Figs. 2 and 3, the X-Plane approach provided sufficient spatial resolution to delineate typical anatomical features that would be seen in conventional cross-sectional views. The X-Plane sagittal views were comparable to those obtained by conventional cross-sectional views, i.e., except for part of the tongue tip and part of the nipple, the remaining areas of interest could be captured by both approaches. However, with an additional plane to provide coronal views not obtainable by the conventional 2D approach, the X-Plane approach assisted identification of the truly mid-sagittal plane [compare Figs. 2 and 3, and Video clips 2 and 3].

Live-3D imaging is illustrated in Figs. 4 and 5. Again, except for part of the tongue tip and part of the nipple, the volume of interest could be embraced by the approach. With the ability to reformat 2D views in any user-desired orientation through the volumetric datasets, the Live-3D approach proved to be superior to the X-Plane approach in assisting identification of the truly mid-sagittal plane [see 3 below].

3.2.2. Temporal resolution and tongue motion patterns

For X-Plane imaging, the temporal resolution [frame rate] for sufficient anatomical coverage with sufficient spatial resolution was 36 [range 30–45] bi-frames/s. Considering a regular tongue motion cycle duration of approximately 1/2 to 1 s observed in this study, this gave approximately 19 to 38 phases per tongue motion cycle, more than sufficient for the assessing the phasic changes. For Live-3D imaging, the temporal resolution [volume rate] for sufficient anatomical coverage with reasonably sufficient spatial resolution was 12 [range 9–16] volumes/s. This visualised approximately 6 to 12 phases per tongue motion cycle, providing reasonably sufficient to sufficient resolution for assessing the phasic changes.

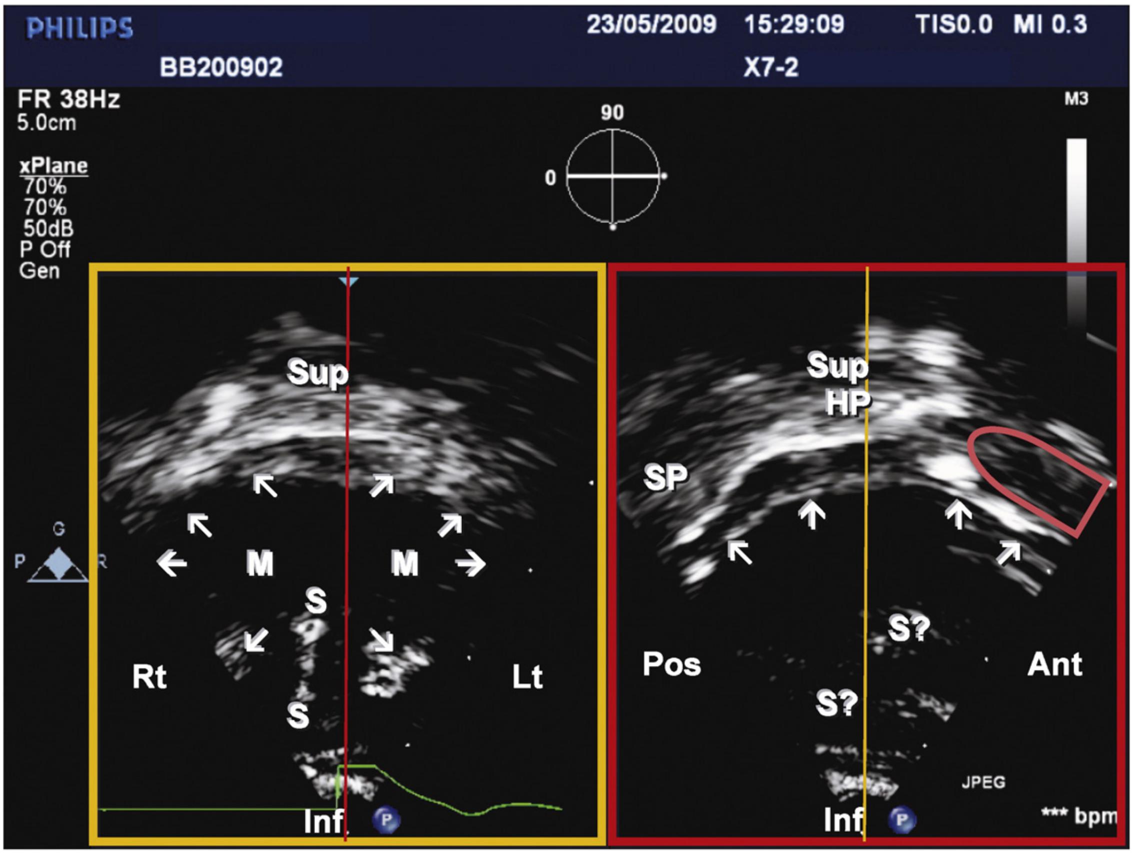

Fig. 3. X-Plane imaging with an untrue mid-sagittal view. The yellow-framed coronal view also shows the connective tissue [bright] separation [S] between the two lateral muscular [dark] areas [M] of the tongue. However, the red cutting line is well off the mid-sagittally located separation. Therefore, the red-framed "sagittal" view is not truly mid-sagittal. Note that such a view often shows an unconvincing peristaltic, or even up-and-down, motion pattern of the upper surface [arrows] of the tongue during breast-feeding [see the corresponding Video clip 2]. An off-mid-sagittal view can usually be confirmed if the connective tissue [bright] separation is inconsistently visible [S?] during tongue motion cycles in the view.

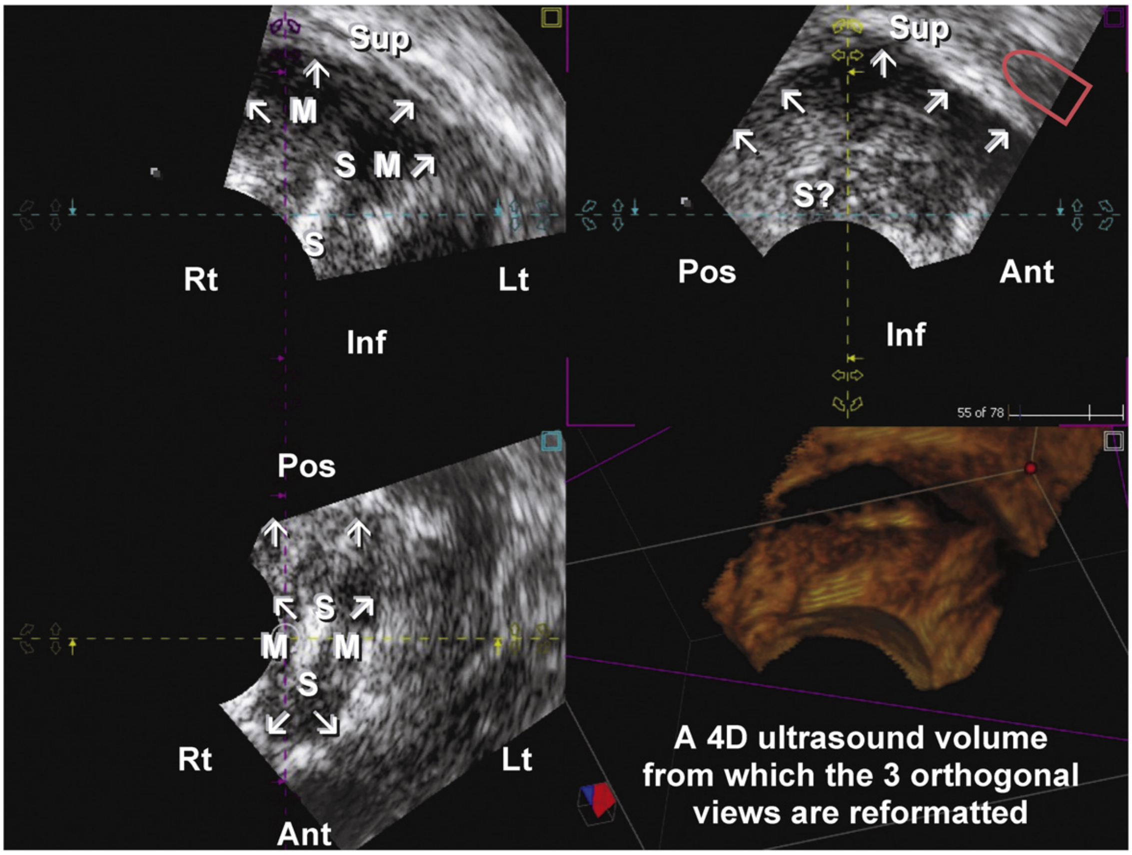

Fig. 4. Live-3D imaging. On reformatted coronal [upper left] and transverse [lower left] views, the tongue's mid-sagittal, bright, connective tissue separation [S] between the two lateral dark muscular areas [M] is off the reformatting plane [i.e., not overlapping the dotted purple line]. The purple-framed sagittal view [upper right, which is therefore not a true "mid-sagittal" view] does not show a convincing wavy [peristaltic] upper surface [arrows] of the tongue [open arrow]. Instead, it appears to move more like in an up and down pattern, as demonstrated in the linked Video clip 3, with the separation not consistently displayed [S?].

3.3. Improved recognition of motion patterns

In some of the datasets with the adequate spatial and temporal resolutions and anatomical coverage described above, variable motion patterns, e.g., both up-and-down and peristaltic motions of the tongue upper surfaces, could be observed in some of the infants even during a short period of one feed when, on external orofacial observation, they did not show obvious changes in how they were feeding. A close examination revealed that these variations were related to the orientation of the imaging plane in the dataset.

On X-Plane imaging, the coronal views could delineate the thin, hyperechogenic [bright] area of the connective tissue that separates two relatively bulky, hypoechogenic [dark] areas of tongue muscles on either side [Figs. 2 and 3, yellow panels]. When sagittal views were obtained by cutting through or cutting very close to the hyperechogenic area, they were most likely through the mid-sagittal plane of the tongue, and, in this plane, a peristaltic pattern could be consistently observed [Fig. 2, red panel and Video clip 1]. When the sagittal views were moved off the hyperechogenic area, i.e., off the mid-sagittal plane, the pattern became less peristaltic or even up-and-down, depending on how far the imaging plane was off the mid-sagittal plane [Fig. 3, red panel and Video clip 2]. During off-line assessment of the total of 150 X-Plane datasets acquired, 84 [56%] provided 'additional information' for verifying whether the imaging plane was on [48 datasets] or off [36 datasets] the anatomical mid-sagittal plane [Table 1]. A peristaltic pattern was observed in all 48 on-plane datasets but only in 10 of the 36 off-plane datasets.

On Live-3D imaging, reformatted 2D views could also delineate the hyperechogenic mid-sagittal plane, ensuring actual attainment of sagittal views [Figs. 4 and 5, and Video clips 3 and 4]. During off-line assessment of the total of 120 Live-3D datasets acquired, 48 [40%] provided 'additional information' via 2D reformatting of views from the truly mid-sagittal plane [Table 1]. A peristaltic pattern was observed in all 48 datasets [since Live-3D data is true volumetric data, a true mid-sagittal plane is always available from 2D reformatting] [Fig. 5 and Video clip 4]. The above statistics were based upon findings from all the acquired datasets.

3.4. Proportion of infants/feeds in which peristalsis could be confirmed

5 to 15 X-Plane datasets and 6 to 10 Live-3D datasets were obtained from each infant during the course, a single breast-feed [Table 1]. A peristaltic pattern was observed in 13 [87%] infants from true mid-sagittal views. In the remaining 2 infants, the presence or absence of peristalsis could not be assessed due to insufficient imaging information.

4. Discussion

The first aim of this study was to evaluate the feasibility and success of the 3D ultrasound technique for visualising infant tongue movements during breast-feeding in a pilot sample of 15 infants. The study confirmed the feasibility and the potential of this technique, and its acceptability to mothers and infants. Within some limitation of temporal and spatial resolutions, known anatomic structures were recognised on scanning and a sufficient frame rate was achieved with X-Plane and, additionally, a sufficient volume rate with Live-3D, when covering adequate volumes of interest. This allowed us to successfully analyse tongue movements in 13 of 15 infants.

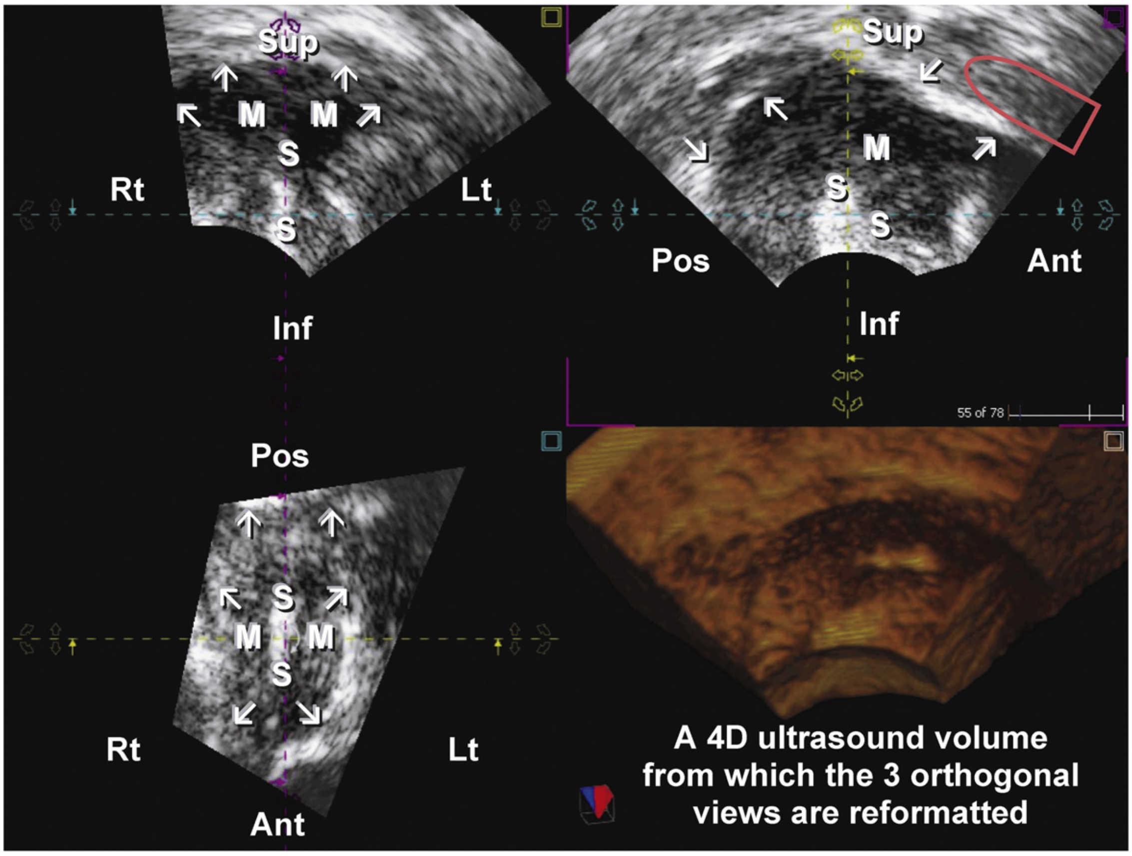

Fig. 5. Live-3D imaging. The same 4D dataset as in Fig. 4. Guided by the reformatted coronal [upper left] and transverse [lower left] views, the dataset is so orientated that the tongue's mid-sagittal, bright, connective tissue separation [S] between the two lateral dark muscular areas [M] is now on the reformatting plane [as indicated along the dotted purple line]. As a result, the purple-framed true mid-sagittal view [upper right] now shows a wavy [peristaltic] upper surface [arrows] of the tongue [open arrow]. The peristalsis from the reader's right to left is vividly demonstrated in the linked Video clip 4, with the separation consistently displayed [S].

The second aim of the study was to evaluate whether peristaltic tongue movements were present during breast-feeding. Both up-and-down and peristaltic patterns of movement were noted in each of the 13 infants. Using the X-Plane approach, an up-and-down motion was noted in the coronal plane as well as in sagittal planes which were not exactly on the mid-sagittal plane. When the sagittal plane was confirmed as being midline by a corresponding coronal plane view, a peristaltic motion was noted in almost all clear quality datasets. Similarly, using Live-3D to reformat 2D views through the true mid-sagittal plane, peristaltic motion was also noted in all quality datasets. When the scan was obtained off the midline plane, the pattern observed was less peristaltic. Geddes et al. [9] state that the transducer in their studies using 2D ultrasound was positioned along the mid-sagittal line of the infant's body, with the position altered as the infant moved to maintain this view. However, whether a motion pattern is truly observed from mid-sagittal views is not simple to assess in conventional cross-sectional views. We found that when performing scans without the guidance of the tongue's medial septum on X-Plane or Live-3D imaging, it is difficult to determine whether the imaging plane is actually through the mid-sagittal plane. Our data suggest that positioning on the mid-sagittal plane [not just along the mid-sagittal line] is of the utmost importance, as when slightly off this plane, we observed less peristaltic patterns. To our knowledge, limited published data exist showing differences in tongue movement patterns with varying positioning of the probe in relation to the midline [14,15]. Further, larger studies would be of merit to confirm whether our findings apply to all healthy, breast-fed infants, and whether this changes in infants with age and in the presence of breast-feeding problems.

Our study was designed to investigate infant tongue movements rather than the mechanism of milk removal from the breast, which would require the simultaneous measurement of intra-oral pressure. The mechanism by which milk is removed from the breast during breast-feeding has been controversial for some years. Using sub-mental scans of the infant oral cavity performed simultaneously with measurement of intra-oral vacuums, Geddes et al. [9] demonstrated that the flow of milk from the nipple into the infant's oral cavity coincided with both the lowering of the infant's tongue and peak vacuum. They concluded a major role of vacuum in milk removal from the breast; reinforced by the findings of a more recent study demonstrating that infants can successfully remove milk from a teat designed to release milk only when vacuum is applied [10]. The importance of vacuum is supported further by earlier studies [3,4] and by a recent study using an electric breast pump, where it was demonstrated that maximum milk yield was produced by use of the mother's maximum comfortable vacuum [16]. Nevertheless, other studies have reported peristaltic or wave-like tongue movements [5–7], and a study using fibre-optic imaging within a teat in 5-day old infants, suggested that both peristalsis and vacuum could be observed in the same infant, with peristalsis predominating when milk flow was slow but diminishing with faster flow [8]. A recent study using video-fluoroscopy to measure tongue movements during bottle-feeding in preterm infants reported that suckling is characterised by an anterior–posterior lingual wave that may serve the function of moving liquid to the back of the mouth [17]. Most recently, Geddes et al. [8] have suggested that the type of tongue movement observed may vary depending on the rate of milk flow and that flow rates during milk ejection are sufficient to promote a more piston-like tongue action. Whilst we did not measure milk flow in our study, our observations, mothers' comments and data obtained from test-weighing in some subjects suggested that our scans showing peristalsis were performed during 'normal' breast-feeds in terms of milk transfer, which would tend to refute the suggestion that peristaltic tongue movements are only seen in situations of low milk flow.

Our study has a number of limitations. Firstly, we were unable to obtain quality X-Plane datasets in two infants and Live-3D datasets in four infants. This was mainly [in three infants] due to the inconvenience of operating the non-purpose built transducer which was designed for transthoracic cardiac imaging with the footprint at the end of the longer axis of the probe [Fig. 1b], rather than at the end of the short axis as in a transvaginal probe, widely used [without 3D function] in such studies. The 3D probe has to be operated in the sub-mental space restricted by the infant's chin and neck and the mother's breast, with a delicate manoeuvre that must not disturb the infant or the breast-feeding process. Secondly, there was difficulty in scanning older infants who, albeit providing a larger sub-mental space, are more alert and resistant to the intrusion of the probe. In comparison with the X-Plane approach, the Live-3D approach provides a more reliable method for attaining the truly mid-sagittal plane, as it is able to obtain any user-desired 2D view through 2D reformatting. However, important trade-offs are reduced spatial and temporal resolutions compared to the X-Plane approach. Therefore, fewer useful datasets were obtained in Live-3D acquisition [56%] as compared to X-Plane acquisition [72%]. However, we speculate that, with the technical improvements expected in spatial and temporal resolutions, together with miniaturisation of 3D transducers, within the next 5 to 10 years, the above problems are likely to be overcome. With a purpose-built transducer, we believe that 3D approaches could become the standard means of imaging infant tongue dynamic morphology in the future.

In conclusion, this pilot study is the first to demonstrate the feasibility of using 3D ultrasound to assess infant tongue movements during breast-feeding, and highlights the importance of obtaining measurements in the mid-sagittal plane to evaluate the presence or absence of peristaltic infant tongue movement. The relative contribution of peristalsis and intra-oral vacuum in the removal of milk from the breast needs further investigation with this in mind.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earlhumdev.2013.04.009.

Conflict of interest statement

Dr Fewtrell and Dr Burton have received research funding from Philips AVENT, the sponsors of this study. Dr Fewtrell has also received research funding and performed advisory or consultancy work for manufacturers of infant feeding products not related to this study.

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