Three-Dimensional Ultrasound Imaging of Mammary Ducts in Lactating Women
A Feasibility Study

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Objective. The main function of the breast is to produce milk for offspring. As such, the ductal system, which carries milk from the milk-secreting glands (alveoli) to the nipple, is central to the natural function of the breast. The ductal system is also the region in which many malignancies originate and spread. In this study, we aimed to assess the feasibility of manual mapping of ductal systems from 3-dimensional (3D) ultrasound data and to evaluate the structures found with respect to conventional understanding of breast anatomy and physiology.

Methods. Three-dimensional ultrasound data of the breast were acquired using a mechanical system, which captures data in a conical shape covering most of the breast without excessive compression. Manual mapping of the ductal system was performed using custom software for data from 4 lactating volunteers.

Results. Observational results are presented for ultrasound data from the 4 lactating volunteers. For all volunteers, only a small number of ductal structures were engorged with milk, suggesting that the lactiferous activity of the breast may be localized. These enlarged ducts were predominantly found in the inferior lateral quadrant of each breast. The observation was also made that the enlarged, milk-storing parts of the duct were spread throughout the ductal system and not directly below the nipple as conventional anatomy suggests.

Conclusions. Ultrasound visualization of the 3D structure of milk-laden ducts in an uncompressed breast has been shown. Using manual tracing, it was possible to track milk-laden ducts of diameters less than 1 mm. Key words: ampulla; breast; lactation; mammary duct; 3-dimensional ultrasound.
Ultrasound examination of the breast ducts is also useful in the assessment and study of lactation and associated problems. An understanding of the breast anatomy is important within the field of human lactation. The ability to assess the anatomy, both of the breast and of the ductal systems, using quantitative 3D ultrasound may enable further research into lactation and breast-feeding.

**Previous Studies of the Ductal/Lobular System**

A number of previous studies have considered the 3D ductal structure of the breast, although this has been achieved largely by use of dissection and histologic sections rather than by use of ultrasound imaging. Cooper injected each ductal/lobular system with colored wax, via the nipple, before dissection. This allowed the ducts to be clearly distinguished during dissection and the different lobes to be identified using different colors. Figure 1 shows a drawing from such a dissection. Cooper noted that there were typically only 7 to 10 openings on the nipple, which allowed injection of wax for ductal dissection, whereas he observed up to 22 straight tubes within the nipple, suggesting that not all ductal systems opened onto the nipple. Each of the wax-injected openings led to separate ductal/lobular systems, showing these systems to be isolated from each other.

More recently, Going and Moffat created a 3D anatomy of the ductal system by manually tracing ducts from histologic sections (2 mm thick) onto acetate sheets. These manual tracings were then analyzed and reconstructed using computer software. They found large differences in the tissue volume drained by different ductal systems within the breast, with the largest lobe draining 23% of the breast volume and the 8 smallest ductal systems together only draining 1.6% of the breast volume. Serial sections (100 µm thick) through a nipple from another breast revealed that only 7 of 34 ducts entering the nipple had an opening on the surface of the nipple, whereas the remaining 27 terminated either at the base of the nipple or about 1 mm below the nipple surface. Ohtake et al performed a similar computer-assisted 3D reconstruction of the ductal system from 2-mm sections through a breast. The purpose of their study was to identify anastomoses connecting different ductal/lobular systems. Of the 16 ductal/lobular systems within a single breast, 2 anastomoses were found that connected otherwise separate ductal/lobular systems.

Three-dimensional ultrasound mapping and study of ductal systems has been limited. Ramsay et al used 2-dimensional (2D) ultrasound to scan the breasts of lactating women and recorded scans on video for later analysis. The ultrasound images were annotated to give an indication of the approximate position within the breast, although no quantitative measurements of the location were made. Each main duct was traced from the nipple back into the parenchyma to the limits of detection by ultrasound, and various linear measurements were made of each main duct (depth of the main duct, distance to the first branch from the nipple, and diameter and depth from the skin of branches). However, 3D reconstruction or modeling of the ductal systems was not performed, nor were branches from the main duct examined in detail. Moskalik et al used a stepper motor to drive a linear array probe across the medial side of the breast, away from the nipple, allowing the generation of a 3D ultrasound data volume for part of the breast. This was performed for a single lactating breast of a volunteer. Manual tracing of ducts enabled 3 ductal systems to be identified and mapped within this volume. Therefore, a 3D model of the ductal system could be produced for a small section of the total breast volume.
Overview of This Study
In this study, we sought to extend the work of Moskalik et al, who suggested the development of methods to scan the whole breast volume, and to perform automatic mapping of all of the ductal/lobular systems. We show that 3D scanning of most of the breast tissue is possible using a scanning system previously reported, and manual tracking and display of the ductal systems are feasible, at least in the lactating breast. In this study, only manual analysis of the ultrasound data was performed, with the aim of assessing the feasibility of tracking ducts within such data. Initial work toward the automatic detection of ductal structures is reported elsewhere. Results are presented from a study of 4 lactating volunteers. Finally, anatomic and functional observations from the study are discussed with reference to previous literature.

Materials and Methods

Three-Dimensional Ultrasound Imaging
Only a brief overview of the 3D ultrasound acquisition system used for this research is given in this section. The system has been described in detail elsewhere and was designed to allow acquisition of a data set including most of the breast tissue, with only the axilla excluded. The breast is scanned in a radial fashion using automated mechanical movement of a linear array transducer from a commercial ultrasound scanner, together with video capture and digitization of the ultrasound images. The breast tissue is immobilized to acquire a consistent set of images. The immobilization device is a 45° cone, which supports the dependent breast as the patient lies prone. The effect of breathing is minimized because the breast is dependent and constrained by the cone while the sternum is supported by the scanning table, and the low level of compression applied by the scanner is advantageous in allowing the visualization of ducts, which collapse at higher compressions.

The linear array probe is held against a narrow thin polymer film window so that the scan plane lies along a radial plane. This plane was identified as valuable for imaging geometric features in breast disease and allows the ductal structures to be imaged approximately longitudinally. The transducer is held at a fixed height, and the entire mechanism including the cone and transducer is rotated about the breast through at least 360°. Overlapping rotations are completed with the transducer held at 2 or 3 heights, with respect to the cone, if the length of the transducer is insufficient to image the complete breast in a single rotation. Light mineral oil (Johnson’s Baby Oil; Johnson & Johnson, New Brunswick, NJ) serves as both a lubricant and a coupling agent between the breast tissue and the cone. Ultrasound images are recorded throughout each rotation from the output video signal using a PCCOMP frame grabber (Coreco Imaging; St Laurent, Quebec, Canada). A Technos ultrasound scanner (Esaote SpA, Genoa, Italy) was used with a linear array probe (LA532, 13–4 MHz) at nominal frequencies of 12.5 and 9 MHz, depending on the volunteer. Imaging parameters were visually optimized by a sonographer on a case-by-case basis from the 2D images while still allowing a frame rate in the range of 15 to 25 Hz. The system hardware is shown in Figure 2. It should be noted that the height and size of the cone can be adjusted to accommodate a range of patients. The cone is shown in a lowered position for illustrative purposes only.

The data are reconstructed into an isotropic Cartesian voxel array using geometric information about the location of each image plane derived from the height of the transducer against the cone and the rotation speed. Nonrigid image registration is used to correct for measurement inaccuracies, speed of sound variations, and tissue movement. For this study, a voxel side dimension of about 0.15 mm was used (exact details in the next section).

Volunteers
In vivo acquisitions were performed with 4 volunteers using the 3D system described. The acquisition protocol was approved by the institution’s Ethics Committee, and all volunteers gave informed consent to the acquisition. The volunteers were lactating mothers who had successfully established a breast-feeding routine with a single infant. Both breasts of each volunteer were scanned before a breast-feeding session. Relevant details of the volunteers and the scans are given in Table 1.
**Analysis of the Ductal/Lobular System**

Manual tracing of ductal structures was performed using custom software. This software enables researchers to view the data set in the radial and coronal planes. The center of each duct was identified on each coronal plane, while the radial plane was used by a researcher to improve understanding of the ductal system geometry and connectivity. An approximate diameter of the duct was given at each center point, although the ducts are not all cylindrical, to give an approximate indication of the duct size. Figure 3 shows the display presented to the researcher, together with the added marks identifying the ductal structures. The 3D model of the ductal systems was exported to 3D Slicer, a medical visualization program created at the Massachusetts Institute of Technology Artificial Intelligence Laboratory (Cambridge, MA) in collaboration with the Surgical Planning Laboratory at the Brigham and Women’s Hospital, such that the arborescent structure could be displayed and studied in 3D. In the 2D views, it was very difficult to differentiate between ducts and blood vessels because both appear as dark linear structures. However, once the structures were mapped in 3D, the different branching patterns and orientations allowed the blood vessels and ducts to be identified more easily because the ducts radiated from the nipple, whereas the blood vessels often followed the circumference of the breast. Because of the time-consuming nature of the manual analysis, tracing was performed by separate researchers (M.H., M.J.G., J.F./F.A.D., and J.A.S.) for each data set (1–4, respectively).

**Results**

**Appearance of Ductal Structures in the B-Mode Images**

Figure 4 shows a standard B-mode ultrasound image of a milk duct in a lactating breast. As reported elsewhere, the duct appears as a band of reduced echogenicity. Although the duct can be easily visualized and its width measured, it is more difficult to gauge the 3D structure of the duct and ductal system: eg, the out-of-plane width of the duct and the relative locations of ducts. In-plane branching can be observed (although not shown in Figure 4); however, out-of-plane branching is more difficult to detect.

**Analysis of the 3D Ductal/Lobular System**

All visible ductal structures were manually mapped for both breasts of each volunteer. The findings for each volunteer were similar and are summarized below.

Figures 5 and 6 show the 3D visualizations of the ductal structures for the right and left breasts, respectively, from volunteer 2. For all volunteers, ducts were predominantly in the inferior lateral quadrant of each breast. Figure 7 shows the regions in which the ducts were predominant for each volunteer. Figure 8 illustrates this, showing the coronal plane for volunteer 3, where the ducts can be seen as darker circular patches.
In all volunteers, one breast contained ducts that were noticeably wider than for the other breast. This was generally in agreement with the volunteer’s statement as to which breast felt fuller and reflected from which side the infant last fed, with the exception of volunteer 4. In that instance, the ducts in both breasts were small and therefore difficult to see, perhaps as a result of the infant being almost weaned and thus the demand, and presumably the supply, of milk being reduced.

In cases of substantially enlarged ducts, the presence of more milk in the breast made tracking of the ducts difficult because the boundaries between ducts were poorly defined in the volumetric images, as shown in Figure 9 for volunteer 1. Therefore, it was necessary to make assumptions about connectivity to perform manual tracing in such cases.

For all volunteers, the sections of the duct that appeared enlarged were deeper in the breast tissue and narrowed to the nipple. Narrower sections were also observed between enlarged sections. These enlarged areas can be seen in the 3D models in Figures 5 and 6. Figure 10 shows a 2D slice for one such case for volunteer 3. In a number of cases, a duct that showed enlargement over an extended range also showed a number of very localized constrictions, as shown in Figure 11 for volunteer 2. The cause of these constrictions is unclear. Further investigation would be required to ascertain the true cause.

**Discussion**

Although the purpose of this study was to assess the feasibility of 3D tracking and display of the ductal/lobular systems over the entire breast volume, this small illustrative study raises a number of interesting anatomic and functional questions about the breast, such as the apparent absence of an ampulla and the noticeable localization of the regions of ductal activity in this group. These observations are discussed below in the context of previous studies. No firm conclusions can be drawn because of the small size of the study presented here, and these issues will need more rigorous investigation to assess the degree of variation between participants in a larger population.

**Table 1. Details of the Volunteers and Settings Used in this Study**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Volunteer 1</th>
<th>Volunteer 2</th>
<th>Volunteer 3</th>
<th>Volunteer 4</th>
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<td>Infant age, mo</td>
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<td>10</td>
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<td>19</td>
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<td>Feeding schedule</td>
<td>5:30 AM, 3:45 PM, 8:30 AM, 2 or 3 times during night</td>
<td>8 AM, 3 PM, 9 PM, 2 times during night</td>
<td>Short feeds hourly during day, no information about night feeding</td>
<td>8 AM, 1 PM, 7 PM, none during night</td>
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<tr>
<td>Time since last feed before ultrasound scan, h</td>
<td>&lt;8, scan at 2–2:30 PM</td>
<td>&lt;6, scan at 2–2:30 PM</td>
<td>&lt;3, scan at 1:45–2:15 PM</td>
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<tr>
<td>Notes</td>
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<td>Volunteer said right breast was more full with milk</td>
<td>Volunteer said left breast was more full with milk</td>
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</table>
Presence of Ampulla/Lactiferous Sinuses

Cooper’s wax-injected dissections\(^7\) revealed widening of the duct beneath the areola, referred to as the ampulla or lactiferous sinuses. He attributed these to the need to store a small quantity of milk to encourage the infant to initiate suckling when first presented to the breast. Unfortunately, neither Going and Moffat\(^5\) nor Ohtake et al\(^4\) made reference to the duct diameter or lactiferous sinuses within their histologically based 3D reconstructions of the ductal structure within nonlactating breasts. Moskalik et al\(^3\) reported locating the ampulla as a method to find ducts within their 3D ultrasound study and suggested that the ampulla would be a good place for an automatic tracking algorithm to detect the duct initially.

However, in our feasibility study, it was found that widening of the duct generally occurred after the first branching point, with respect to the nipple, for most ductal sections identified. Although on B-mode scanning the enlarged parts of the duct may have appeared to be beneath the areola, in agreement with the typical description of ampullae, the presence of a branching point between the nipple and the widening is in disagreement with Cooper’s description of the anatomy.\(^7\) Figures 5 and 6 show the 3D models of the ductal systems, as delineated manually by the researcher, for the left and right breast, respectively, with the associated duct widths included. Ramsay et al,\(^9\) who observed from their ultrasound examinations of lactating breasts that although the duct diameter increased at multiple branching points, typical “saclike” features behind the areola were not observed. They noted that Cooper’s method of injecting wax to visualize the ducts\(^7\) may have forcibly expanded the ducts. The observations in our study are in agreement with their opinion that Cooper’s observation of enlargement of the duct behind the nipple may not be a normal...
anatomic feature but rather a feature of his method. Nevertheless, Cooper’s hypothesis that some milk must be stored within the ducts to provide instant gratification for the infant is illustrated by our observation of enlarged, milk-laden regions within the ductal system.

Existence of Localized and Limited Ductal Activity

In this small study, only about one-third of each breast appeared to store milk, as detailed in Figure 7. A similar observation was made by Going and Moffat, who noted that in the histologic sections of a nipple from a lactating woman, only 4 ducts appeared dilated, whereas the rest were collapsed. They speculated that only 4 ductal/lobular systems were contributing substantially to milk production at the time of mastectomy. However, Ramsey et al made no reference to observing localized ductal activity in their ultrasound study of 21 lactating women. Moskalik et al also did not explicitly refer to any localization of activity, having only scanned a portion of the breast, but they did note that 2 (of 3) ducts appeared noticeably larger, potentially as a result of enlargement caused by, or for the purpose of, milk storage.

The localization observed during this study may have originated from variable compression of the breast within the cone, if the breast was not central within the immobilizing cone. However, the compression applied to the breast by the cone is generally in the superior and inferior sections, which would lead to the observation of enlarged ducts both medially and laterally. Because the regions of ductal enlargement do not correspond to this prediction, it is probable that the localization of enlargement is not a result of the scanning method but of actual breast activity. In addition, the observations of Going and Moffat support the view that not all ductal systems within the breast are active during lactation. The reason for varying activity or storage may be that the capacity of the breast to produce milk exceeds the current demand. The number of ductal systems within the breast, 15 to 20, also seems to exceed the number of openings at the nipple, suggesting that not all ductal/lobular systems can be active in lactation regardless of demand.

Further investigation is needed to assess whether this pattern of limited ductal activity or storage is common and whether the localization of active ducts is generally symmetric between breasts or even follows a pattern among women in general. An investigation of breast-feeding women with twins may also indicate whether more ductal/lobular systems are active when the demand for milk is greater, or whether the...
demand is still met by a limited number of ductal/lobular systems producing more milk. Performing ultrasound analysis during lactation may also highlight whether this observation is one of localized activity or localized storage.

Summary
A 3D map of the ductal/lobular structure of the breast would have applications in a number of clinical areas, including aiding clinical visualization of 3D ultrasound data, detection and diagnosis of breast lesions, definition of surgical excision margins based on the extent of the connected lobe rather than the lesion size, guidance in ductal endoscopy, and alignment of 3D breast scans taken of the same breast at different times. Further applications may be found in the study of the anatomy and mechanisms of lactation and breast-feeding.

This study has built on the work of Moskalik et al., showing that it is possible to perform 3D mapping of mammary ducts from a 3D ultrasound scan of a lactating breast. Although this feasibility study included only a few participants, interesting clinical questions were raised as a consequence of the mapping regarding the pronounced localization of engorged ductal/lobular systems and the presence or otherwise of the ampullae compared with conventional breast anatomy.

Clearly, there is much scope for future research into both the manual and automatic mapping of the ductal/lobular system. Ultrasound visualization of the 3D structure of milk-laden ducts in an uncompressed breast has been shown. Using manual tracing, it was possible to track milk-laden ducts of diameters less than 1 mm. However, it was not possible to delineate all ducts in the remainder of the breast. Improved ultrasound resolution will be necessary if complete ductal mapping from 3D ultrasound is to be used in the nonlactating breast, such as in the detection and diagnosis of breast lesions and guidance of lobe size for surgical excisions.3–5

Figure 9. Coronal section through the right breast of volunteer 1 illustrating the poor definition of the duct boundaries, indicated by the arrows, on the coronal plane in regions with considerable ductal enlargement. The coronal section is shown as if looking toward the volunteer.

Figure 10. Radial section through a breast of volunteer 3 showing sections of ductal enlargement and narrowing. For all volunteers, the duct always narrowed before the nipple.

Figure 11. Radial section through a breast of volunteer 2 showing an enlarged duct with apparent sheetlike constrictions. The cause of these constrictions is unclear.
References


