CANADA WIDE SCIENCE FAIR

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Chetley L.C.Gervais is the winner of this year's Special Award from the Canadian Acoustics Association for his project - Co-registration of Digital Mammography with 3Dimensional Breast Ultrasound Simulating use of a Full-Field Matrix of Piezoelectric Crystal Transducer Elements - a Phantom Study.

Chet Gervais, 17 yrs old, is now attending Trinity Collge School (TCS) in Port Hope Ontario as a grade 12 student. He has represented Ontario at the Canada Wide Science Fair 2001, 2002, 2003, 2004, 2005 and Canada at the Intel International Science Fair in 2004 and 2005.

He is an Essex Regional Gold medalist 5 times, he has won over 100 Regional, National and International Science Awards including: the Best Jr Engineering project in Canada at the CWSF 2002, a Gold Medalist in Intermediate Engineering at CWSF 2004 , a 2004 Manning Young Canadian Innovator Award Winner, a Senior Bronze Medalist in Medicine at CWSF 2005, and winner of the Acoustical Sociey Award .

At the 2005 INTEL ISEF in Phoenix AZ, Chet won the First Award in Medicine and Health and Kodak Award as part of Team Canada Science 2005 (world first place) . At INTEL he was also recognized by MIT who are submitting his name to the International Astronomical Union (IAU) to have a minor planet named after him!

Canada Wide Science Fair
2001,2002,2003,2004,2005

Chet is also the starting running back for the undefeated TCS Bears football team, an avid soccer and squash player and reader. Chet has a US/World patent pending on his Matrix Probe technology. He hopes it will result in the earlier and more accurate diagnosis of breast cancer.

Chet Gervais' full article is reproduced below.

CO-REGISTRATION OF DIGITAL MAMMOGRAPHY WITH 3-DIMENSIONAL BREAST ULTRASOUND USING A FULL-FIELD MATRIX OF PIEZOELECTRIC CRYSTAL TRANSDUCER ELEMENTS - A PHANTOM STUDY*

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Editor's Note: The submission by Chet Gervais was reformatted and edited to fit in to the Journal format.

ABSTRACT

The Matrix Probe "fusion" prototype co-registered digital mammography and 3D medical ultrasound system demonstrates the successful manual production of a 3D high resolution block of DICOM3 data which can be reviewed in any plane or reconstructed in sequence like a CT or MRI scan. This embodiment eliminates the previous requirement for an external hybrid spatial position sensor, significantly improves image resolution and incorporates the medical DICOM3 image standard. This new biomedical engineering technology allows precise correlation of multi-planar reconstructed 3D ultrasound images with standard digital mammography images improving spatial accuracy during investigation of breast cancer. The Matrix Probe "fusion" device also demonstrates the feasibility of RHESUS - Remote Hybrid Endoscopic Surgical Ultrasound System using the real-time (4D) capabilities of this device.

SOMMAIRE

Le prototype Sonde Matrix "fusion", co-enregistré sous les noms manunographie digitale et système médical d'ultrasons 3D, démontre la production manuelle réussie d'un bloc 3D à haute résolution de données DICOM3 qui peuvent ètre passées en revue dans n'importe quel plan ou qui peuvent être reconstruites de façon séquencielle comme un balayage de CT ou MRI. Cette combinaison élimine la nécessité précédente d'une sonde de position spaciale hybride exteme, améliore de manière significative la résolution de l'image et incorpore l'image standard du DICOM3 médical. Cette nouvelle technologie de génie biomedical permet la corrélation prècise d'images multiplans d'ultrasons 3D reconstruites avec celles de de mammographie digitale standard, ce qui améliore l' exactitude spatiale lors d' investigations de cancer du sein. Le dispositif Sonde Matrix "fusion" démontre également one capacité RHESUS (système chirurgical endoscopique hybride d'ultrasons à distance) du système, c'est-à-dire la possibilité d'employer sa capacité 4D en temps réel.

1. INTRODUCTION

The objective of this study was to design and build a functional integrated synergistic system to produce co-registered 3D ultrasound data sets using a modified mammography compression paddle. Over the past decade the clinical advantages of 3Dimensional imaging in medical practice has become dogma. Multi-planar reconstructed CT and MRI studies are the foundation of modern hospital practice. Sophisticated image storage and archival systems (PACS) and diagnostic radiology workstations enhance the accuracy and speed of medical diagnosis and facilitate surgical treatment.

Recently the advent of "phased array" ultrasound transducers has resulted in the inclusion of 3D imaging capabilities in many high end ultrasound machines. Although these probes produce dramatic images in 3D or even 4D they have shown relatively little clinical medical benefit to patients. One persistent shortfall of all ultrasound imaging, including the current 3D probe systems is that, unlike CT or MRI, the resulting images or "small field" 3D data blocks are not registered in 3D space relative to the patient.

This lack of spatial registration of conventional ultrasound images prevents the accurate correlation in 3D space between objects visualized in one modality, for example digital mammography with breast ultrasound. Current conventional radiology protocols involve imaging a patient mammographically, followed by technician/radiologist review. If a specific area on mammography is of concern or if the breast tissue is very radiographically dense then a breast ultrasound is performed.

With the advent of digital imaging, specifically digital mammography and the widespread use of large field imaging modalities such as CT and MRI, there has been considerable interest in developing a multi-modality imaging system which would incorporate both digital mammography and high resolution soft tissue ultrasound in the production of a single co-registered dual modality image series which is precisely correlated in 3-Dimensional space. The need for this type of system is widely known to all radiologists involved with breast cancer screening and diagnostic investigation of positive mammograms or clinically suspicious findings. Presently the investigative protocols involve performing mammography with the patient in (upright) compression followed by breast ultrasound (supine) without compression. These examinations are generally performed in different rooms and by different technicians. Mammography imaging the entire extent of the breast tissue in the MLO and CC projections and breast ultrasound consisting of 20-30 technician selected small field images with particular emphasis on the region of clinical or radiographic concern. Based on localizing information identifying the approximate position in the uncompressed breast supplied by the technician onto a crude locater icon during each image, the radiologist issues a correlative report relating the two modalities and makes a diagnosis of the significance of the demonstrated abnormalities in the context of breast cancer diagnosis.

There are significant shortcomings to this method of correlated multi-modality investigation. First, it is simply impossible to accurately correlate the location of any lesion seen in a CC mammogram in compression, with a subsequent uncompressed 2D breast ultrasound study comprising a handful of images when both studies are entirely un-registered in 3D space relative to each other. The second and equally important problem with the current standard of care in breast cancer diagnosis is in the actual amount of breast tissue being reviewed by the radiologist prior to issuing a diagnostic consultative report. Assuming a basic effective scan thickness of 1 mm and reviewing 20-30 2D scans per breast ultrasound the radiologist in fact only sees about 1% of the actual volume of the breast being examined during diagnostic review. While it is true that in theory this 1% is representative of the findings present in that breast as determined by an experienced breast ultrasound technician, the fact remains that this tiny fraction of the available information is all that is ever actually seen by the diagnostic radiologist during reporting of any breast ultrasound. To justify this from a patient care perspective, a radiologist needs only to randomly remove 99% of the letters in this monograph prior to reading it and then accurately submit a diagnostic report concerning it's contents as if the patients life depends on it.

There are well know and widely investigated significant False Positive and False Negative rates during the investigation of breast disease by mammography and breast ultrasound. These result in significant patient morbidity and mortality due to missed breast cancers and unnecessary breast surgery for benign disease. These unacceptably high rates of misdiagnosis are exacerbated by poor image quality, dense breast tissue and the inability of the radiologist to precisely correlate lesions seem on both modalities. Once a lesion is correctly diagnosed as requiring treatment this lack of a true 3D spatial relationship between the available ultrasound and mammography tissue images again increases morbidity and mortality due to the inability to accurately establish the relationship between True Positive lesions and surrounding normal and abnormal structures in the breast. This inhibits optimal surgical and radiation treatment of these patients based on a reduced or inaccurate knowledge of their anatomy.

In recent years there has been widespread use of registered images series, such as CT and MRI to create both sequential uniform thickness parallel image full field datasets and subsequently to perform sophisticated segmentation on these image sets to produce spectacular 3D images featuring the selected aspects of that dataset most adventitious to improved patient care. This includes 3D vascular, cardiac and bone window reconstructions which improve diagnosis and treatment. Advanced medical 3D image review software has also been developed which in conjunction with more powerful computer workstations and segmentation algorithms allow rapid and complete review of entire data sets.

Most recently equipment manufacturers have been developing "fusion" imaging systems which link the image information of two complimentary technologies such as CT and PET scans into a single co-registered multi-modality diagnostic imaging device which facilitates improved patient care by linking information from two modalities into the same 3D spatial coordinates. Despite numerous attempts by a variety of developers, to date no practical solution to this problem of mammography/ultrasound "fusion" system has been developed.

In my original project, the Matrix Probe System, I attempted to develop a co-registered data set by putting together a large number of small field images, each of which was registered in 3D space by being tagged with 3D spatial position information using an NDI hybrid external position sensor which monitored the position of reflective tools attached to a plate fixed on to a standard ultrasound probe. This produced a registered 3D databock and demonstrated 3D reconstruction but was not practical for clinical use. The original design was unsuitable for clinical medical use however because of the requirement for an external spatial position indictor, the relatively low resolution of the resulting 3D data block multiplanar reconstructions and the non-DICOM3 image format preventing incorporation of the images into conventional PACS or review using existing sophisticated DICOM3 medical image review software. The images were also not co-registered with simultaneous mammography. A number of investigators have proposed solutions to these problems. They are generally based in attempting to co-register a large number of small field 2D ultrasound images with concurrent mammography and enable an accurate 3D data block reconstruction by post processing of the ultrasound images and mammogram.

There have been a number of attempts to produce a functional digital mammography/breast ultrasound "fusion" imaging system, several of these are detailed in recent bio-medical patents. Generally they consist of mechanical systems which involve a modified or mobile mammography compression paddles which allow both production of a mammography image and subsequent movement, mechanically, of a standard linear high resolution ultrasound probe over a prearranged course to ensure complete co-registered coverage of the full breast tissue. These devices provide solutions to several of the important technical problems of producing co-registered mammography/ultrasound images of the breast but remain intrinsically flawed. This is because any system which incorporates a mechanical scanner subjects the breast tissue to variable and uneven tissue compression resulting in displacement of one part of the breast tissue relative to other parts reducing accuracy of the constructed 3D data block and effective multi-planar image resolution. The time required to complete a mechanical ultrasound during mammography and the heavy and cumbersome nature of the devices required to guide the probe head across the breast are not suitable for clinical practice or use with existing mammography equipment. The objectives of this study were to solve these major bio-engineering problems in an innovative way, to design a new and unique multi-modality fusion device which could be incorporated into existing digital mammography systems and integrate with existing commercial PACS.The system presented demonstrates the feasibility and important patient care benefits of constructing a full field fixed piezoelectric array, electronically controlled to fire sequentially producing a pre-registered series of contiguous parallel 1mm slices in seconds which are co-registered with the patient remaining in compression during a standard digital mammography examination.

2. SYSTEM DESIGN

A novel large format fixed array of piezoelectric crystals is proposed which could be incorporated into a modified digital mammography compression paddle. This array would approximate the size of a conventional mammography compression paddle surface and be designed to be placed in uniform contact with the entire compressed breast during production of the ultrasound data set but which can be removed or rotated out of the way during the mammography exposure without modifying the position or compression of the breast. This avoids the intrinsic problems of variable compression and heavy, complex and unreliable mechanical devices but allows simultaneous production and co-registration of mammography and breast ultrasound data sets creating a functional multi-modality "fusion" imaging system. This design requires incorporation of a sonolucent plastic insert into the compression paddle to maintain compression during the mammography portion of the examination.

The use of this prototype manual system produces a co-registered digital mammogram and high resolution full field set of sequential breast ultrasound images. This achieves all of the bio-engineering objectives of this project and provides a data set which is comparable to that which would be produced by a large field crystal array. This sonolucent insert in the modified mammography compression paddle was constructed from low density polyethylene. This readily available material was salvaged from a spare black wastepaper basket and selected because of the cost and low acoustic impedance of this material - 1.77 Rayl - combined with a relatively low attenuation of x-ray beams 10.7% / 3mm thickness. These compare with the acoustic impedance of polycarbonate thermoplastic - 2.68 Rayl - and x-ray attenuation 14.8% /3mm (standard compression paddle) the significance of these values is that this material, while potentially less optimal than other more exotic plastics such as poly 4-methyl, 1-pentene (PMP) with and acoustic impedance of only 1.84 Rayl , an x-ray attenuation of 9.4% /3mm but retaining a high tensile modulus (stiffness) desirable in a mammography compression paddle. However as home

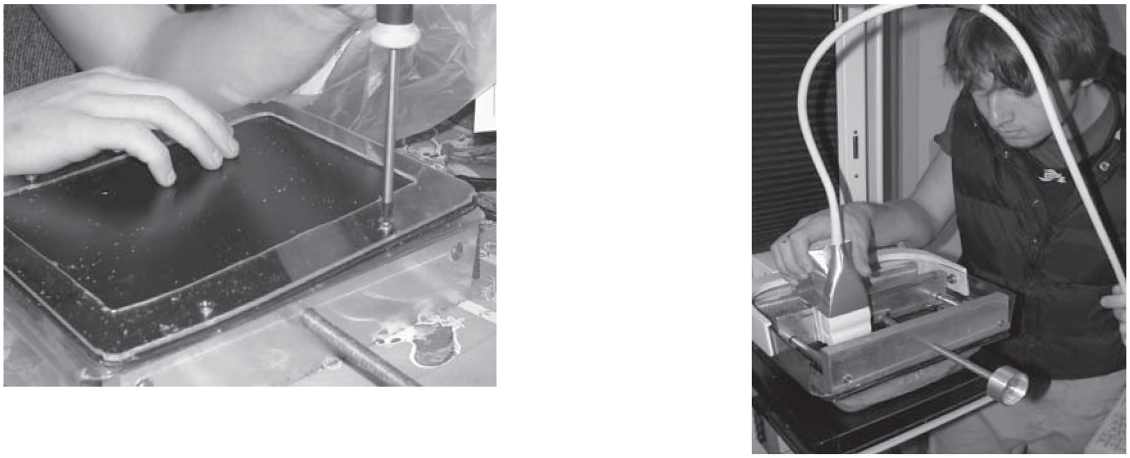

Figure 1: Photographs of construction of sonolucent mammography compression plate insert construction and during production of parallel 1mm large field turkey breast phantom images in compression through the sonolucent plastic insert. This creates a sequential parallel full field set of high resolution breast ultrasound images in DICOM3 medical image format.

wastepaper baskets are not generally constructed of PMP and it is no doubt expensive, use of that or other more "perfect insert material" will be deferred for future research.

3. METHODOLOGY

A realistic organic breast tissue "phantom" was created using a boneless turkey breast into which target objects were inserted to represent solid and cystic breast masses. Wherever possible air, which would disrupt the ultrasound beam was displaced by ultrasound gel and the entire "phantom" was wrapped in a "skin" of latex trans-rectal probe sheath. I had initially planned to use a "stand-off" pad or "water bath" to avoid uneven tissue compression or distortion resulting from the probe head pushing the tissue away as it passed from side to side of the phantom. However, the panoramic imaging software provided with the ATI5000 ultrasound machine requires a stable initial baseline for image creation and without one, the image "wanders". This roadblock actually provided the opportunity for me to move closer to the final Matrix Probe embodying a "fusion" design.

The most difficult problem was how to achieve uniform direct compression of the breast phantom tissue when conventional polycarbonate plastic compression paddles (although rigid and invisible to x-ray beams during mammography) are very resistant to the transmission of sound waves (high acoustic attenuation). Ultrasound impedance increases with material density and rigidity, both of which are desirable in a mammography compression paddle. What I had to find was an available plastic material with low acoustic impedance. After researching the acoustic impedance of plastics I decided that my best candidate was low density polyethylene and sacrificing a waste paper container I obtained my "sonolucent plastic tissue compression interface". Using a Dremel tool, I made a Lexan plastic frame with a polypropylene insert and attached this to my converted standard mammography compression paddle.

By adjusting the height of the ultrasound probe head pre-registration bracket to match the "sonolucent plastic" insert and using ultrasound gel as a probe surface/insert interface to reduce artifact, a "pre-registered" image of uniformly compressed tissue phantom was obtained! This confirmed the feasibility of my Matrix Probe "fusion" combined digital mammography and 3D breast ultrasound "add-on" device for standard mammography systems.

Slice by slice manual image production was time consuming but eventually the entire breast phantom tissue block was

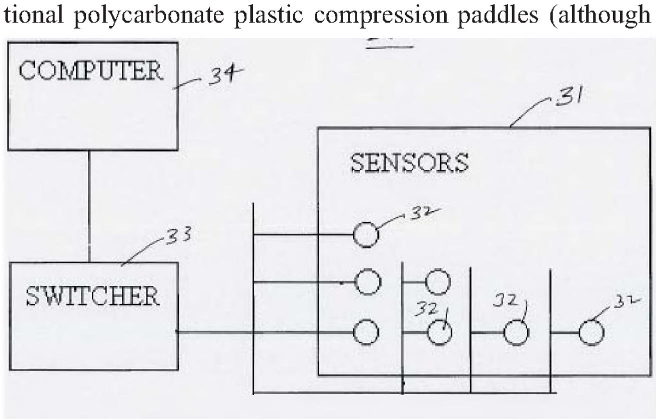

Figure 2: Basic schematic for electronic switching of Matrix Probe array elements.

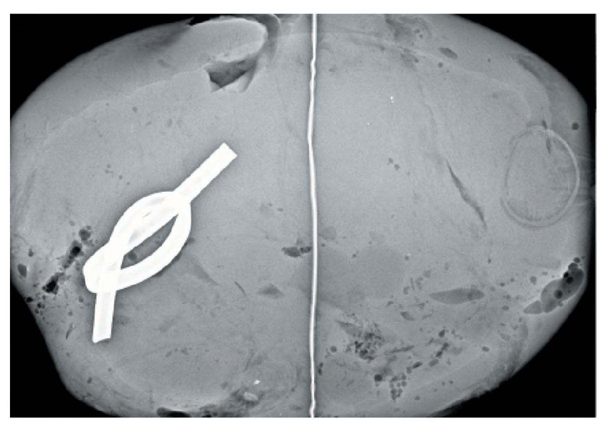

Figure 3: High resolution digital mammography of co-registered turkey breast tissue phantom

imaged. This produced a parallel series of "pre-registered" high resolution ultrasound tissue slices. A DICOM3 header using "patient demographic information" (name, date, type of examination, image number, modality, ID number, accession number) was attached to the image using the existing ultrasound machine "worklist software" allowing these images to be sent to the radiology clinic PACS (picture archiving and communication system).

After the collection of multiple "full-field" DICOM3 image sequences, these were reviewed using the advanced PACS viewing software confirming successful production of sequential DICOM3 medical images. Next, a test of the 4D capabilities of this system was performed using colourflow doppler vascular imaging (vascular tissue phantom created using surgical tubing) and "real-time" endoscopic motion of a probe through the tissue phantom was recorded.

4. RESULTS

I was able to create "full field", high resolution DICOM3 images of the turkey breast tissue phantom which are comparable to those which could be produced by a fixed piezoelectric crystal array (although a single image series which took me 30-40 minutes to obtain could be produced in "real time" 10-15 fps by the actual Matrix Probe device).

In order to complete these goals and demonstrate the potential of this innovation I redesigned and then built (with assistance from the Sandwich S.S. Machine shop teacher, Mr Levesque) a mammography compression paddle with a sonolucent plastic insert. This will be the basis of the Matrix Probe "fusion" add-on mammography paddle which will allow both digital mammography and "instant" high resolution 3D/4D breast ultrasound with the patient still in compression.

Review of these unique sequential "full field" parallel DICOM3 images (using existing diagnostic radiology review software) has significant patient care advantages to Radiologists and surgeons including:

i Far more complete tissue imaging (approximately 100 times more high resolution breast ultrasound imaging information provided to the Radiologist for review than during conventional breast ultrasound imaging). This review is facilitated by existing 3D ultrasound software.

ii The Matrix Probe System images are "**co-registered**" in 3D space, like a CT scan or MRI and can be subjected to multi-planar re-slicing to demonstrate the relationship of any objects within the tissue and to existing normal structures. This confirms the successful creating of a multi-modality "fusion" imaging system.

iii Co-Registration as the breast is imaged simultaneously (in compression) therefore for the first time exact correlation between digital mammography and a 3D breast ultrasound is now possible. This should significantly improve diagnostic accuracy and localization of breast masses and allow earlier and more accurate diagnosis of breast cancer (please see "fusion" compression mammography paddle display).

iv The electronic switching of the proposed Matrix Probe System large field array coupled with a powerful computer work station and appropriate real time auto-segmentation algorithms provides for the opportunity to perform "real time (4D) large field soft tissue ultrasound with the associated potential for guided robotic endoscopic surgery

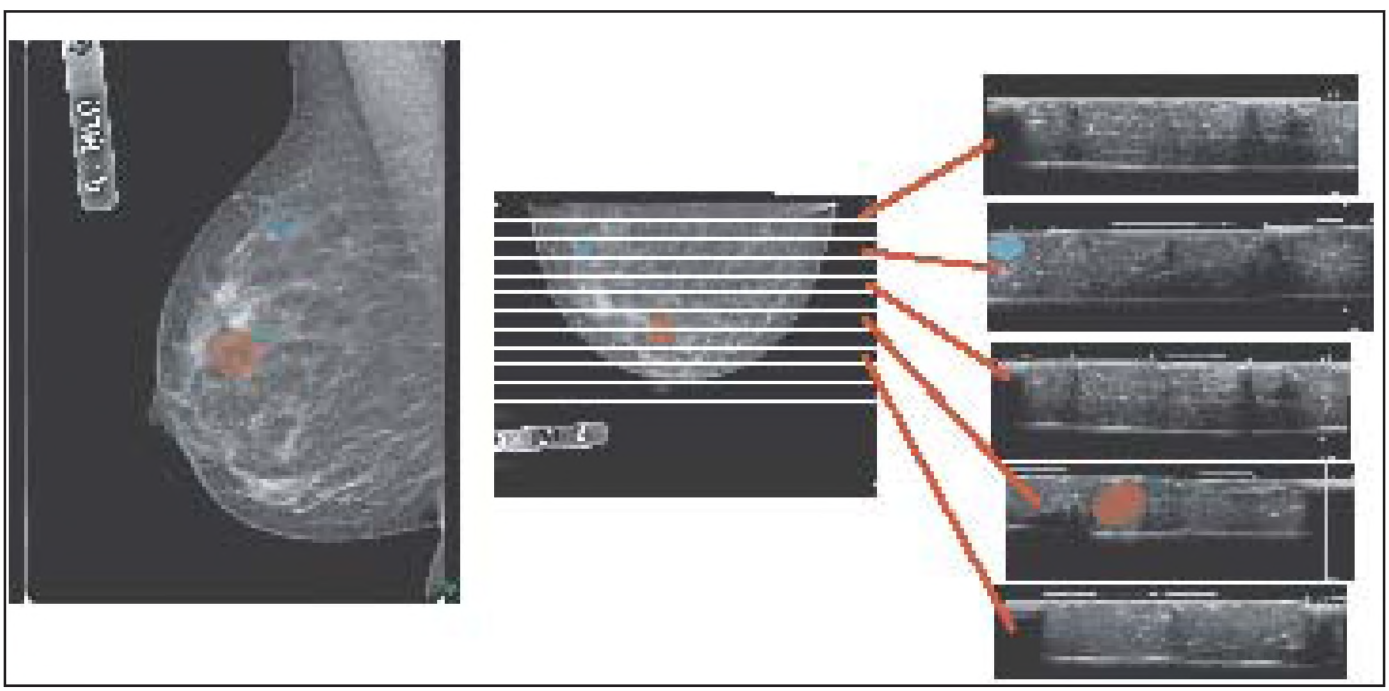

Figure 5: Co-registration of SIMULTANEOUS digital mammography and sequential parallel high resolution DICOM3 medical image format breast ultrasound.

and enhanced vascular imaging in appropriate soft tissues further increasing the medical usage of this device.

5. CONCLUSIONS

This study demonstrates a unique and elegant solution to the conundrum of co-registration of digital mammography and breast ultrasound. It avoids the pitfalls of mechanical scanning devices and demonstrates the potential of "real-time" 4D large field ultrasound. The manually obtained images confirm the feasibility of all aspects of this USA patent pending device. Further research would be facilitated by the construction of a functional large field array of piezoelectric crystal elements.

6. ACKNOWLEDGEMENTS

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8. RELATED REFERENCES

1. R. W. Prager, A. H. Gee and L. Berman. "Stradx: Real-Time Acquisition and Visualization of Freehand Ultrasound." April 1998
2. R.W. Prager, R.N. Rohling, A.H. Gee and L. Berman. "Automatic Calibration for 3D Free-Hand Ultrasound." September 1997
3. A.H. Gee, R.W. Prager, G.M. Treece, and L. Berman. "Narrow-Band Volume Rendering for Freehand 3D Ultrasound." September 2000
4. M. Tuomola, A. H. Gee, R. W. Prager, and L. Berman. "Body-Centered Visualisation for Freehand 3D Ultrasound." October 1999
5. A. H. Gee, R. W. Prager, and G. M. Treece. "Sequential 3D Diagnostic Ultrasound Using the Stradx System." June 2001
6. A.H. Gee, R.W. Prager, L. Berman. "Non-Planar Reslicing for Freehand 3D Ultrasound." January 1999.
7. G.M. Treece, R.W. Prager, A.H. Gee, L. Berman. "Fast Surface and Volume Estimation from Non-Parallel Cross-Sections, for Freehand 3-D Ultrasound." July 1998
8. G.M. Treece, R. W. Prager, and A. H. Gee. "Regularised Marching Tetrahedra: Improved Iso-surface Extraction." September 1998
9. G.M. Treece, R. W. Prager, A. H. Gee, and L. Berman. "Surface Interpolation from Sparse Cross-Sections Using Region Correspondance." March 1999
10. G. M. Treece, R. W. Prager, A. H. Gee, and L. Berman. "3D Ultrasound Examination of Large Organs." December 1999
11. G.M. Treece, R.W. Prager, A.H. Gee, and L. Berman. "Correction of Probe Pressure Artifacts in Freehand 3D Ultrasound- Initial Results." April 2001
12. R. W. Prager, A. H. Gee and L. Berman. "Sequential 3D Diagnostic Ultrasound Using the Stradx System." June 2001
13. A. Fenster, S. Tong, H. N. Cardinal, C. Blake, D. B. Downey. "Three-Dimensional Ultrasound Imaging System for Prostate Cancer Diagnosis and Treatment." November 1998
14. A. Fenster, S. Tong, H. N. Cardinal, C. Blake, D. B. Downey. "Three-Dimensional Ultrasound Imaging System for Prostate Cancer Diagnosis and Treatment." December 1998
15. S. Tong, H. N. Cardinal, R. F. McLoughlin, D. B. Downey, A. Fenster. "ntra- and Inter-Observer Variability and Reliability of Prostate Volume Measurement Via Two-Dimensional and Three-Dimensional Ultrasound Imaging." March 1998
16. T. L. Elliot, D. B. Downey, S. Tong, C. A. McLean, A. Fenster. "Accuracy of Prostate Volume Measurement In Vitro Using Three-Dimensional Ultrasound." January 1996
17. Z. Guo and A. Fenster. "Three-Dimensional Power Doppler Imaging: A Phantom Study To Quantify Vessel Stenosis." May 1996.
18. Y. Wang, H. N. Cardinal, D. B. Downey, A. Fenster. "Semiautomatic three-dimensional segmentation of the prostate using two-dimensional ultrasound images." May 2003
19. N Hu, D. B. Downey, A. Fenster and H. M. Ladak. "Prostate Boundary Segmentation from 3D Ultrasound Images." June 2003
20. A. Landry and A. Fenster. "heoretical and Experimental Quantification of Carotoid Plaque Volume Measurments Made by Three-Dimensional Ultrasound Using Test Phantoms." September 2002
21. K. J. M. Surry, W. L. Smith, L. J. Campbell, G. R. Mills, D. B. Downey and A. Fenster. " The Development and Evaluation of a Three-Dimensonal Ultrasound Guided Breast Biopsy Apparatus." 2002
22. A. Fenster and D. B. Downey. "Three-Dimensional Ultrasound Imaging and Its Use In Quantifying Organ and Pathology Volumes." June 2003
23. H. N. Cardinal, J. D. Gill and A. Fenster. "Analysis of Geometrical Distortion and Statistical Variance in Length, Area, Volume in a Linearly Scanned 3-D Ultrasound Image." April 2000
24 W. L. Smith and A. Fenster. "Optimum Scan Spacing for Three-Dimensonal Ultrasound by Speckle Statistics." December 1999
25. A. Fenster, D. B. Downey and H. N. Cardinal. "Three-Dimensonal Ultrasound Imaging." November 2000

26. A. Fenster and D. B Downey. "3-D Ultrasound Imaging: A Review." November 1996
27. R.W. Prager, R.N. Rohling, A.H. Gee and L. Berman. "Automatic Calibration for 3-D Free-Hand Ultrasound." September 1997.
28. S. Tong, D. B. Downey, H. N. Cardinal and A. Fenster. "A Three-Dimensional Ultrasound Prostate Imaging System." March 1996
29. C. Cardinez, V. Cokkinides, T. Gansler, R. Greenlee, A. Harris, M. B. Hill- Harmon, T. Murray, D. Saslow, K. A. Sawyer, J. Schellenbach, R. Smith, S. Summers, D. Willis, and H. Zoller. "Breast Cancer Facts and Figures 2001-2002." 2001-2002
30. A. Fenster, K. Surry, W. Smith, J. Gill and D. B. Downey. " 3-D Ultrasound Imaging: Applications in Image Guided Therapy and Biopsy." 2002
31. A. Fenster and D. B. Downey. "Advanced Signal Processing Handbook." 2001
32. Y. Saijo, A. F. W. van der Steen. "Vascular Ultrasound." 2003
33. A. Fenster, D. Lee, S. Sherebrin, R. Rankin and D. B. Downey. "Ultrasonics." 1998
34. S. Tong, H. N. Cardinal, D. B. Downey and A. Fenster. "Analysis of linear, Area and Volume Distortion in 3D Ultrasound Imaging." October 1997
35. N. Skubas. "Principles of Echocardiography for the Anesthesiologist." 2003.