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● *Review*

FREEHAND 3-D ULTRASOUND IMAGING: A SYSTEMATIC REVIEW

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Abstract—Two-dimensional ultrasound (US) imaging has been successfully used in clinical applications as a low-cost, portable and non-invasive image modality for more than three decades. Recent advances in computer science and technology illustrate the promise of the 3-D US modality as a medical imaging technique that is comparable to other prevalent modalities and that overcomes certain drawbacks of 2-D US. This systematic review covers free-hand 3-D US imaging between 1970 and 2017, highlighting the current trends in research fields, the research methods, the main limitations, the leading researchers, standard assessment criteria and clinical applications. Freehand 3-D US systems are more prevalent in the academic environment, whereas in clinical applications and industrial research, most studies have focused on 3-D US transducers and improvement of hardware performance. This topic is still an interesting active area for researchers, and there remain many unsolved problems to be addressed. (E-mail: mmoza102@uottawa.ca) © 2017 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Three-dimensional ultrasound imaging, Three-dimensional ultrasound freehand systems, Three-dimensional ultrasound calibration, Three-dimensional ultrasound reconstruction, Three-dimensional ultrasound sensorless methods, Systematic review.**

INTRODUCTION

Medical imaging can be traced back to the discovery of X-rays in 1895, and since then, many modalities, such as magnetic resonance imaging (MRI), ultrasound (US), computed tomography (CT), positron emission tomography (PET), medical X-rays and single-photon emission computed tomography (SPECT), have been invented. Ultrasound imaging appears to be the most prevalent in clinics because of its price, tolerability, space, portability and fast performance. Here, common methods for free-hand ultrasound imaging in the 3-D domain are systematically reviewed.

BACKGROUND

The 3-D domain for US imaging is a promising and burgeoning approach for visualizing and depicting the inside of the human body in 3-D volumes. The first attempts to use US machines to capture 3-D US volume can be traced back to the 1970s. The Kretz Combison 330, unveiled in 1989, was the first commercial 3-D scanner (Prager et al. 2010). The main advantages of the 3-D domain for US systems in comparison to 2-D images can be summarized as follows (Fenster and Downey 2000; Fenster et al. 2011; Gebhard et al. 2015; Gee et al. 2003; Hsu et al. 2007; Mercier et al. 2005; Nelson and Pretorius 1998; Solberg et al. 2007; Yu et al. 2011):

- *Visualization of the entire structure of an organ in three dimensions:* The target object and region of interest (ROI) can be visualized as a 3-D surface or 3-D rendered volume by using interpolation, segmentation and registration methods in 2-D or 3-D space.
- *Less dependence on an operator*: The 3-D visualization of anatomy during a diagnostic examination can be screened directly on the user interface instead of mentally transforming 2-D B-scans to perceive a 3-D view. Consequently, it eliminates operator interpretation dependence in the acquisition process. Furthermore, to work with a 2-D US transducer, the operator must be an experienced operator with knowledge of human anatomy, whereas for 3-D US systems, the acquisition step is much easier and less user dependent.
- *Orientation-independent visualization*: Working in the 3-D domain, it is possible to view any arbitrarily oriented planes, even those that are not possible to visualize by conventional US methods. The 3-D methodology also enables clinicians to discuss,

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Table 1. Quantitative studies of methods in terms of implementation and performance

Reference	Acquisition system	Localization device	Reconstruction method	Visualization software	Accuracy	Performance time	Calibration phantom
Cenni et al. 2016	PC-based US machine + 10.0-MHz linear transducer + 30-Hz transducer HL9.0/60/128 Z, Teemed Echo Blaster 128 Ext-1 Z system	First system: three integrated cameras + OPS (OptiTrack) Second system: OPS (10 optical cameras, Vicon Motion Systems)	VBM	Custom-designed Py3-D FreeHand in Python 2.7	VEA: ~3% VRA: ~1 mm	N/A	Crossed wire embedded in water tank
Daoud et al. 2015	SonixTouch Q+ Ultrasonix + L14-5/38 linear transducer 7.2 MHz	EPS (trakSTAR, NDI)	PBM	VTK + ParaView	N/A	N/A	Double N-wire
Huang et al. 2015	Sonix RP Ultrasonix + linear transducer (L14-5/38) + convex transducer (C3–7/50)	EPS (miniBIRD)	FBM using Bezier curves	Custom-defined	VRA: reduced 0.51–5.07%	Reconstruction in ~20 s and scanning in ~1 min	Fetus CIRS
Wen et al. 2015	DC-7, Mindray Medical International	OPS (Polaris)	VBM using Bayesian-based non-local method	Custom-designed	VEA: ~8%	Reconstruction: ~2142 s	Abdominal CIRS Modal 057
Chen et al. 2014	2-D US device DC-7 Mindray	EPS (Aurora)	VBM using kernel regression model	Custom-designed	RMSE: 6.68	Reconstruction: ~380 min	Standard abdominal (CIRS)
Huang et al. 2013	Sonix RP, Ultrasonix + linear transducer (L14-5/38) + convex transducer (C3-7/50)	MPS (linear sliding track + Digital Scale Units, Model 812–103 + Bluetooth module)	VBM using squared distance-weighted interpolation	VTK + Custom-designed on C++	VRA: improved by 0.46%–2.14% VEA: ~1.46%	Reconstruction: 251 s for 793 B-scans	CIRS Model 044
Neshat et al. 2013	Toshiba PVT-375 BT, 1.9–6 MHz + Aplio XG SSA-790 A + handheld mechanical scanning device	EMPS	PBM	N/A	VRA: ~1.6 mm	Scanning time 6–10 s	String embedded 15% glycerol/distilled water solution
Wen et al. 2013	DC-7 Mindray Medical International Ltd	EPS Aurora	PBM with fast marching interpolation	Custom-designed with C++	N/A	220 * 202 * 145 voxels can be reconstructed within 30 s	Abdominal CIRS
Toonkum et al. 2011	N/A	MPS linear tracking	VBM using cyclic regularized Savitzky–Golay filters	Custom-designed in MATLAB	NMSE: 0.0321	Reconstruction: ~600 s	N/A
Qiu et al. 2011	LANDWIND ultrasound scanner	OPS (NDI)	VBM using improved distance-weighted interpolation	VTK	N/A	Reconstruction: 254 s with four neighbors	Water based with chicken kidney
Yu et al. 2011	Acuson Sequoia C256 + 7 MHz array transducer 7 V3 C	EPS (EPOM Flock of Birds)	VBRM using multiview visualization	Custom-designed in C and MATLAB	VEA: ~5%	N/A	CIRS Model 055
Scheipers et al. 2010	Ultrasonix + L12–5 linear transducer at 10 MHz	Custom-made OPS (Polaris)	Direct frame interpolation VBM using spherical linear interpolation of quaternions	Custom-designed in MATLAB	VEA: ~25 %	Reconstruction: ~100 s	N/A
Dewi et al. 2009	GE LogiQ 9 ultrasound scanner (GE Healthcare) + 2-D transducer linear matrix array 10 L 6.3–10 MHz	EPS (pier, Ascension Tech) + 3-D Free Scan (Echotech 3-D Imaging Systems)	PBM using improved Olympic method	MATLAB 7.0.4	MAE: 0.0069	N/A	N/A
MacGillivray et al. 2009	5- to 10-MHz linear ultrasound transducer (Diasus)	OPS (Polaris)	VBM	Stradwin + ANALYZE	VEA: ~16% of corresponding MR derived	N/A	N/A
Huang and Zheng 2008	Portable US (SonoSite 180 PLUS)	EPS (miniBIRD)	VBM using median filters	Custom-designed on C++	N/A	Reconstruction: ~45 min with 1 GB RAM + 2.8 Ghz CPU	Cross-wire phantom