Enabling intuitive 3D Imaging on 2D ultrasound systems: a low-cost solution

By Dr Carl Herickhoff, Matthew Morgan, Dr Joshua Broder, K Tucker Haas & Dr Jeremy Dahl

As a medical imaging modality, ultrasound has unique advantages that make it well-suited for many clinical applications [1,2]. Ultrasound scans use echoes of acoustic waves to determine the depth and location of structures in the body. The exam is commonly performed by a trained sonographer using a handheld probe to acquire planar, two-dimensional (2D) images. Compared to computed tomography (CT) and magnetic resonance imaging (MRI), which respectively use ionizing radiation or high magnetic fields [3,4], ultrasound is completely safe and is also more economical.

In addition, ultrasound images can be acquired and produced in real-time (> 30 frames per second, i.e. much faster than CT or MRI), and ultrasound equipment may be designed in a wide variety of portable-form factors, ranging from cart-based to handheld systems. For these reasons, ultrasound excels in areas such as maternal and fetal imaging, cardiac imaging, and use at the bedside (point-of-care).

However, a few aspects of conventional 2D ultrasound imaging have hindered its use and prevented ultrasound from being fully utilized in healthcare [5]. First and foremost, planar 2D ultrasound has a limited field of view and does not capture volumetric data (as CT and MRI commonly do). Also, the orientation of each 'slice' image depends upon how the user holds and positions the probe on the patient. Only 2D image views or cine clips can be saved by the user, and these can lack appropriate spatial and anatomical context, because the precise orientation of each is not automatically recorded. The user may annotate each images or cine clip immediately post-acquisition [6], but this process can be very repetitive and time-consuming, and such documentation only conveys an approximate orientation of each image 'slice'. Because 2D ultrasound lacks the volumetric-capture capability and standard frame of reference of CT and MR imaging, ultrasound images can be more challenging both to acquire and interpret.

Live, volumetric three-dimensional (3D) ultrasound imaging has been made possible by the development of advanced matrix-array and mechanical 'wobbler' probes, though these specialized probes (and associated scanners) can be quite expensive, with the system cost often exceeding US$ 200 000 (approximately EUR 160 000). Furthermore, while these live-3D ultrasound probes can acquire volumetric images (at or near real-time rates), the orientation of these volumes with respect to the patient still depends on the pose of the probe, which is not precisely recorded.

Because conventional 2D and 3D ultrasound imaging is dependent on probe pose and lacks a natural frame of reference, it has been necessary to establish particular conventions and scanning protocols, and to educate and train users to gain skill in manipulating the probe to acquire and interpret particular views of various target organs and structures [7]. However, ultrasound training can be costly (especially in terms of time involved), and there remains a significant variability in the level of skill—as well as quality and clinical utility of images obtained—among ultrasound users regardless of training. This variability in ultrasound imaging is the issue commonly known as operator dependence [8,9].

DESIGN AND METHODS

Our team has developed a simple and low-cost enhancement to 2D ultrasound systems, enabling capture of volumetric 3D ultrasound images with known patient orientation, in a manner that is less operator-dependent [1]. The method uses a low-cost orientation sensor (retail less than US$10 or approx EUR 8) attached to the ultrasound probe and a simple plastic fixture that only allows rotation of the probe about an axis (i.e., prevents linear translation) once applied to the patient. The orientation sensor is an inertial measurement unit (IMU) commonly used in modern smartphones [10]; the IMU provides orientation feedback as the probe is tilted and the 2D image plane is swept through the body [Figure 1 left]. During the sweep, a collection of 2D ultrasound images are acquired and 'tagged' with associated orientation readings from the IMU; a volumetric image is then reconstructed by inserting pixel data from each planar 2D image into a 3D voxel mesh according to its tagged orientation reading [11] [Figure 1, right] .

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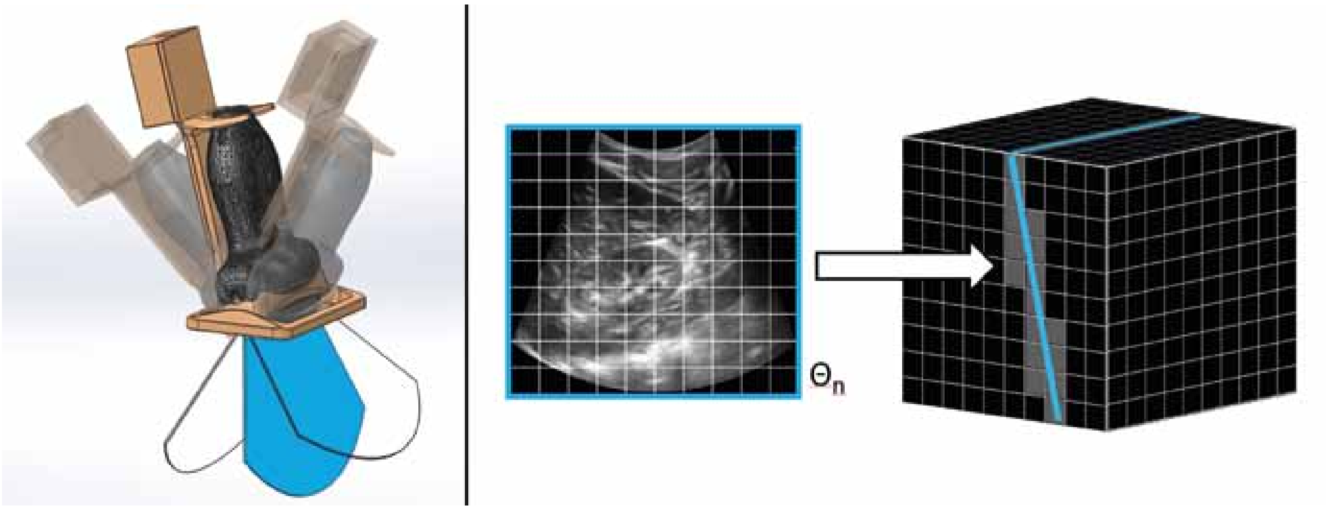

Figure 1: (left) Diagram: 3D volume acquisition sweep with probe fixture and orientation sensor; (right) diagram: 3D volume reconstruction method. The fixture establishes a pivot axis, and the sensor (box at top) returns orientation readings as the probe is tilted and the image plane (below) is swept through the body; each recorded 2D image plane is inserted into the 3D voxel according to its orientation reading.

The orientation of the patient is established by performing a quick calibration step prior to a volume acquisition sweep. The probe and IMU are held in a standard pose relative to the patient (e.g., in a sagittal plane with the probe face parallel to the patient's sternum) and a single reading of the patient's orientation is saved. The IMU readings will then be calibrated [12], and all subsequently acquired 2D images and reconstructed 3D volume will have known orientation with respect to the patient.

Our team has built a prototype system and evaluated its volumetric 3D imaging performance on several phantom and *in vivo* targets, capturing volumes of both B-mode and color Doppler ultrasound data.

RESULTS

Examples of volumetric ultrasound acquisitions using the low-cost 3D prototype are shown in Figures 2 and 3. Figure 2 is a 3D rendering of a B-mode and color Doppler data volume acquired on a custom phantom, consisting of a gel sphere and a flow channel, both submerged in water. The edges of the sphere (B-mode data) are clearly delineated, and the Doppler data reveals the flow channel in the foreground. Figure 3 is an in vivo volumetric B-mode acquisition of the right-upper quadrant of the abdomen, with three orthogonal planes through the ultrasound volume viewed in a multiplanar display. Kidney, liver, and vasculature are seen in the planar views, and a partial segmentation and rendering of the liver vasculature is shown as a 3D overlay on the multiplanar display.

SIGNIFICANCE AND FUTURE DIRECTIONS

The results demonstrate that high-quality volumetric 3D ultrasound images can be obtained by augmenting a 2D ultrasound system and probe with a low-cost orientation sensor and a simple plastic fixture. This low-cost volumetric 3D ultrasound method can be used with existing 2D systems and virtually any 2D imaging probe—including high-frequency/high-resolution probes, which do not tend to have matrix-array equivalents for 3D imaging. Because the method relies only on orientation sensing and does not require expensive x-y-z position-tracking sensors, specialized matrix-arrays, or mechanical 'wobbler' probe technology [13,14], this 3D ultrasound imaging solution is more economical and practical in many clinical settings.

A quality 3D ultrasound volume allows the display of any image plane of clinical interest (which may be scrolled through the volume), and the added knowledge of patient orientation allows multiplanar display of transverse, sagittal, and coronal views with respect to the patient's cardinal anatomical axes. This anatomically-oriented multiplanar display is a common presentation of 3D medical image data (e.g., CT and MRI datasets) that is most familiar to clinicians. Volumetric 3D ultrasound data may also be easily segmented with visualization software packages [15] and displayed as 3D volume renderings, in order to better convey the complex shape, tortuosity, and spatial relationships between anatomical structures. More accurate volumetric measurements can be made from such segmentations as well.

The simple and intuitive acquisition process and quality volumetric capture of a region of interest enabled by this method can help reduce inter-operator variability and allow new, untrained users to reproducibly obtain clinically-useful images. This has important implications for telemedicine and in expanding the use of ultrasound in low-resource and developing-world settings. Thus an unskilled user may quickly and easily acquire a 3D ultrasound and send the volumetric data to an experienced radiologist at a remote location, who can determine and send back a diagnosis. The method could also improve the effectiveness of ultrasound at the point-of-care and in emergency medicine, and thus may reduce both the reliance on CT imaging and its associated radiation exposure to patients.

Future directions for this technology include refinement of a graphical, touch-screen user interface to streamline the volume acquisition and review process, live-updating 3D reconstruction to aid needle insertion and procedure guidance, and ultimately the development of a low-cost commercial product to enable intuitive 3D

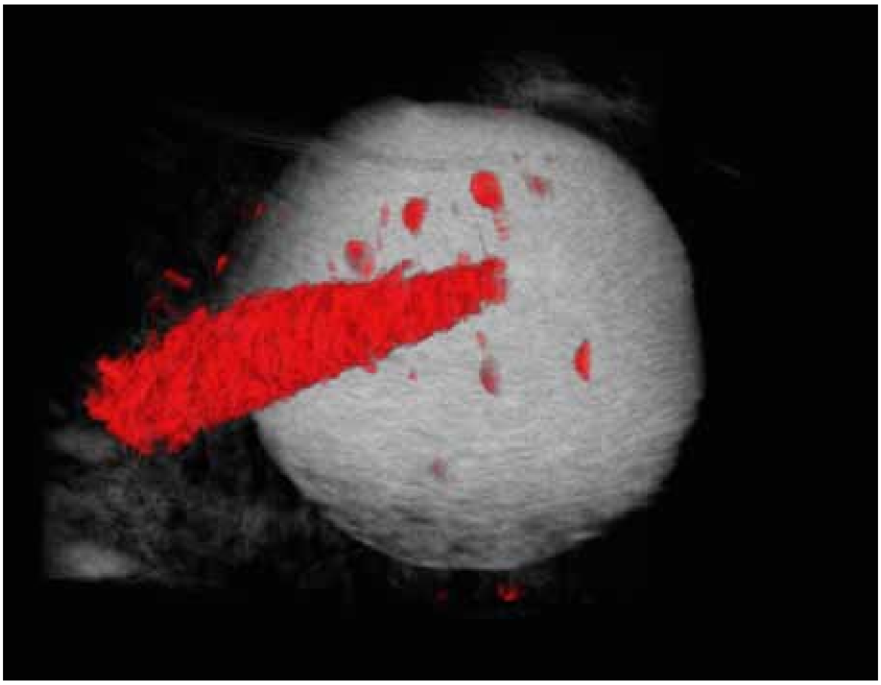

Figure 2: Volumetric ultrasound data of custom phantom target (gel sphere and flow channel) rendered in 3D. B-mode data shows reconstructed sphere in the background; color Doppler data reveals flow channel in the foreground.

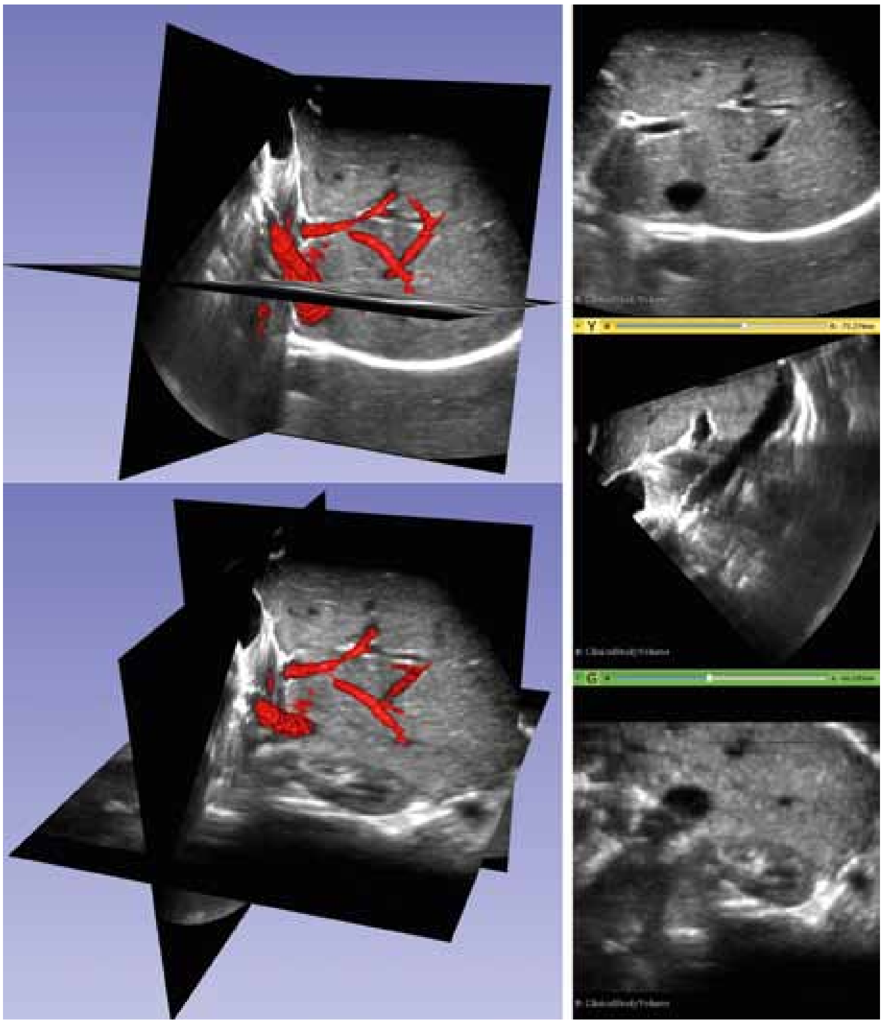

Figure 3: In vivo volume acquisition of abdominal right-upper quadrant: multiplanar display (left) of three orthogonal planes (right). Partial segmentation of the liver vasculature is shown as a 3D overlay (in red) on the multiplanar display.

imaging on existing 2D ultrasound systems in every possible setting.

CONCLUSION

A low-cost device has been developed that enables existing 2D ultrasound imaging systems to quickly and easily acquire 3D volumes of image data with known orientation with respect to the patient. The simple acquisition process, complete volumetric capture, and familiar multiplanar display can reduce inter-operator variability and allow for more intuitive interpretation of ultrasound image data. This practical and economical solution promises to reduce the level of skill and training required to use ultrasound effectively, and help broaden and extend the reach of ultrasound in clinical use.

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