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Three-dimensional reconstruction of transcranial ultrasound images obtained through the temporal bone window using a helmet-mounted mechanical beam-steering device

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Abstract—**Transcranial sonography has been an increasingly widespread diagnostic tool for the diagnosis of neural diseases like Parkinson's disease. However, the utilization of modern 3-D ultrasound techniques has been hampered by the acoustical barrier of the skull bones. We report the development of and preliminary results from an ultrasound helmet which uses mechanical beam-steering to allow 3-D reconstruction of deep brain structures such as the substantia nigra.**

I. Introduction

TRANSCRANIAL sonography (TCS) has been increasingly used to diagnose movement disorders involving the basal ganglia, especially in Europe, ever since the observation that the midbrain has increased echogenicity in the case of certain diseases like Parkinson's Disease (PD) [1]. The exact mechanism underlying the hyperechogenicity remains to be explained, but it has been shown to be a reliable indicator of PD [2-4]. TCS is the only imaging modality that shows these changes; magnetic resonance imaging and computed x-ray tomography do not show any differences.

Simultaneously, 3-D and 4-D ultrasound has been making strides in the advanced visualization of internal organs [5]. However, this 3-D technology has not yet been widely applied to TCS, and all diagnoses are still performed by a trained clinician manipulating the probe to look at 2-D slices of the midbrain.

One difficulty of TCS is the thick skull bone which greatly reduces the ultrasound signal penetration. The five traditional cranial openings available for imaging are the right and left temporal bone window, the occipital bone window, and the right and left ocular bone windows. The temporal bone windows are the most convenient for imaging the midbrain.

In this paper we report the design of a novel mechanical scanner which allows 3-D imaging of the midbrain through the bone window, with the goal of better imaging the hyperechogenicity for increased diagnostic accuracy.

II. Methods and Design

A. Helmet

A mechanically-steerable ultrasound beam was used in this study. This is a different approach to the phased-array electronically-steerable beam design reported by Smith and colleagues for Doppler imaging [6]. Their design attempts to circumvent the bone aberrations by electronically adapting to the varying bone density, whereas our design mechanically adjusts the beam from a manually selected starting location with good imaging penetration.

The ultrasound probe was used in B mode, allowing 2-D slices to be taken at multiple depths and later reconstructed into the 3-D image. The steering mechanism had two major design requirements. First, the tip of the ultrasound probe had to remain pressed against the skin at the location of the bone window. Second, the beam azimuth had to be adjustable in precise regular increments, for accurate reconstruction of the image slices.

We designed an ultrasound helmet which met these requirements (Figure 1). The approximate distance from the probe to the center of the midbrain was estimated to be 85 mm, and the distance between the fulcra was approximately 55 mm. The nigra is approximately 33 mm in diameter, and each minimum vertical external adjustment was 0.1 mm. Thus the vertical voxel resolution inside the brain was 0.12 mm on the near side of the nigra and 0.19 mm on the far side. This voxel size difference between the left and right sides was considered negligible compared to the height of the ultrasound beam, and no significant differences were visible between adjacent scans. Additionally, the slices were assumed to be roughly horizontal to simplify the reconstruction, although the precise angle slowly changed over the course of the scan from approximately -5 degrees to +5 degrees, leading to a vertical distance discrepancy of 2.9 mm (9% of lateral width) between the near and far sides of the nigra at the maximal and minimal angles.

B. 3-D Reconstruction and Visualization

One healthy volunteer was scanned after giving informed consent. The nigra was scanned at both whole-

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brain perspective and nigra-alone perspective. Each scan used an average of 60 vertical slice captures.

In the whole-brain view, the image size was 640x480, including the imaging meta-information (Figure 2). In the nigral-zoom view, the image size was cropped to 200x200.

The slices were visualized using two Matlab toolboxes freely available on Matlab Central: “Vol3d-v2” by Oliver Woodford (based on Vol3d by Joe Canti), and “Slice Browser” by Marian Uhercik. Slice Browser allows viewing of slices side-by-side in two dimensions at a time. Vol3d-v2 plots a 3-D collection of voxels at specified alpha-transparency values. We used the 3-D intensity values to create alpha values by first normalizing the intensity to the [0, 1] range, then squaring the values to make less echogenic voxels more transparent.

The images were cropped, then viewed with the Slice Browser. For the Vol3d-v2 reconstruction the 2-D slice images were also downsampled to 30% of the original size (with anti-aliasing) to match the vertical resolution.

III. RESULTS

The helmet provided a stable holder for the probe and allowed the probe to be moved up and down in small vertical increments. Figure 2 shows typical whole-brain and zoomed pictures, with the butterfly-shaped substantia nigra visible. Figure 3 shows a sample 3-D reconstruction, and Figure 4 shows the same reconstruction in 2-D slice views.

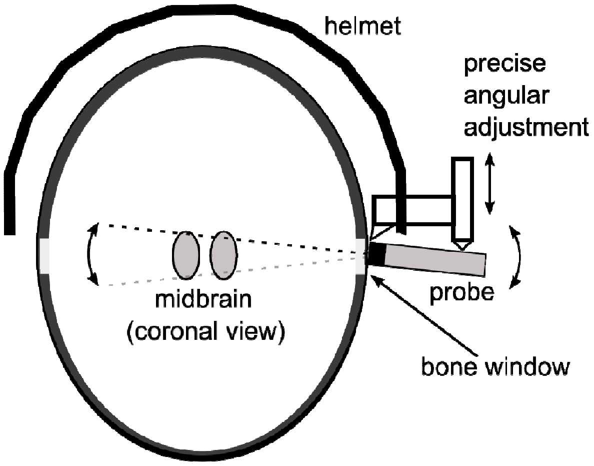

Fig. 1. Schematic diagram of ultrasound helmet with mechanical beamsteering

IV. DISCUSSION

The rotatable partially-transparent 3-D image provided a novel and potentially useful perspective on the overall shape of the nigra. The whole midbrain could be visualized at once, rather than only a 2-D slice at a time.

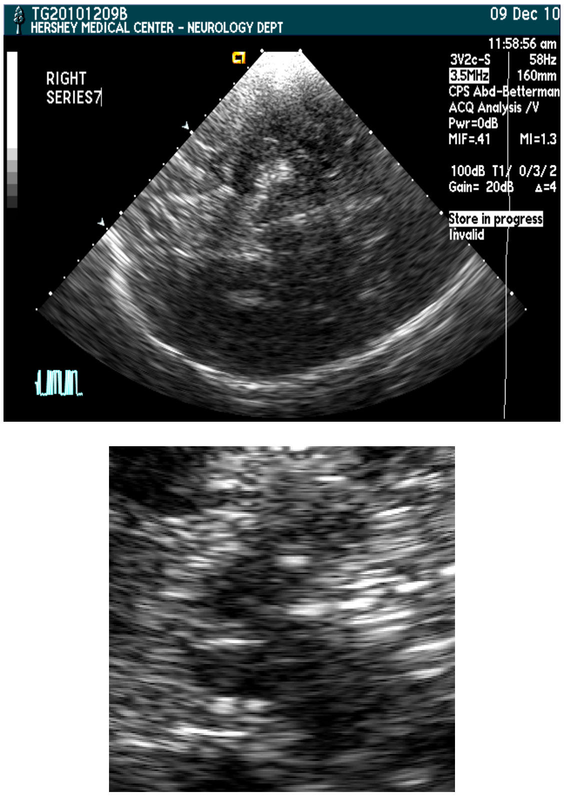

Fig. 2. Sample Images. (Top) Whole-brain view. (Bottom) Nigral zoomed-in view after cropping.

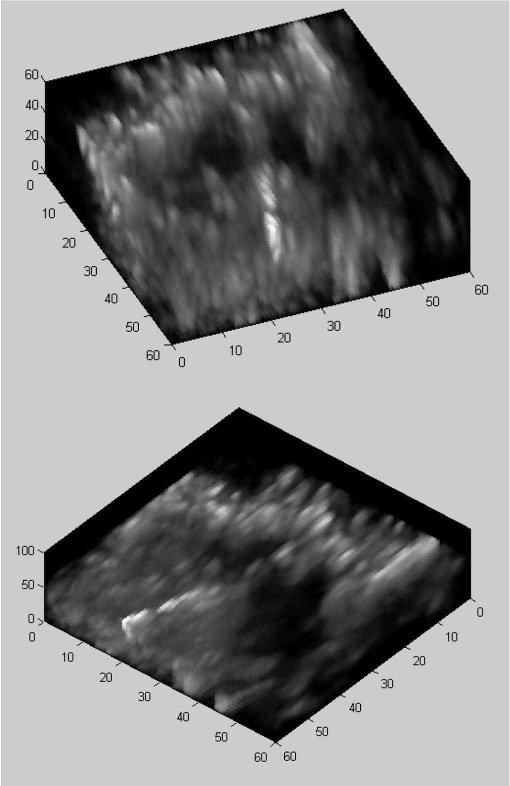

Fig. 3. Sample 3-D reconstruction, rotated at two different angles.

The transcranial ultrasound imaging situation has some unique advantages compared to other imaging which the current device opens the opportunity to exploit in the future. First, the device allows multiple scans in time at a particular given position and direction. This can be used to reduce the signal to noise ratio, both in electrical noise, ultrasound speckle reduction, and subject motion artifacts due to heartbeat or breathing.

Second, the device allows rigid spatial constraints which can greatly simplify image registration, as compared to freehand scans.

Several logical next steps are available for the advancement of this technique. First, as in [6], the beam may be electrically steered and rotated in addition to being mechanically steered, as this would provide additional imaging data at each location. This is important because even tiny probe movements can reduce the quality of imaging through the probe-gel-skin interface and through the bone window. Phased-array nulls in the electronically-steered beam “rake” would cause loss of imaging at certain angles, but the combination of electrical and mechanical steering can provide good coverage of the entire area of interest.

Second, the mechanical motion may be motorized and controlled by a computer for faster and more accurate scanning.

Third, multiple 3-D stacks may be co-registered and merged together as described elsewhere [7, 8]. Further processing algorithms such as despeckling and super-resolution may enhance this composite [9, 10].

Fourth, the 3-D volume may be segmented with edge detection or active contour algorithms, followed by rendering the segments of interest (e.g. the substantia nigra or any echogenic portions of the substantia nigra) [11].

In conclusion, the current device provides a promising model for applying recent image processing advances to the hitherto difficult-to-access intracranial space using ultrasound.

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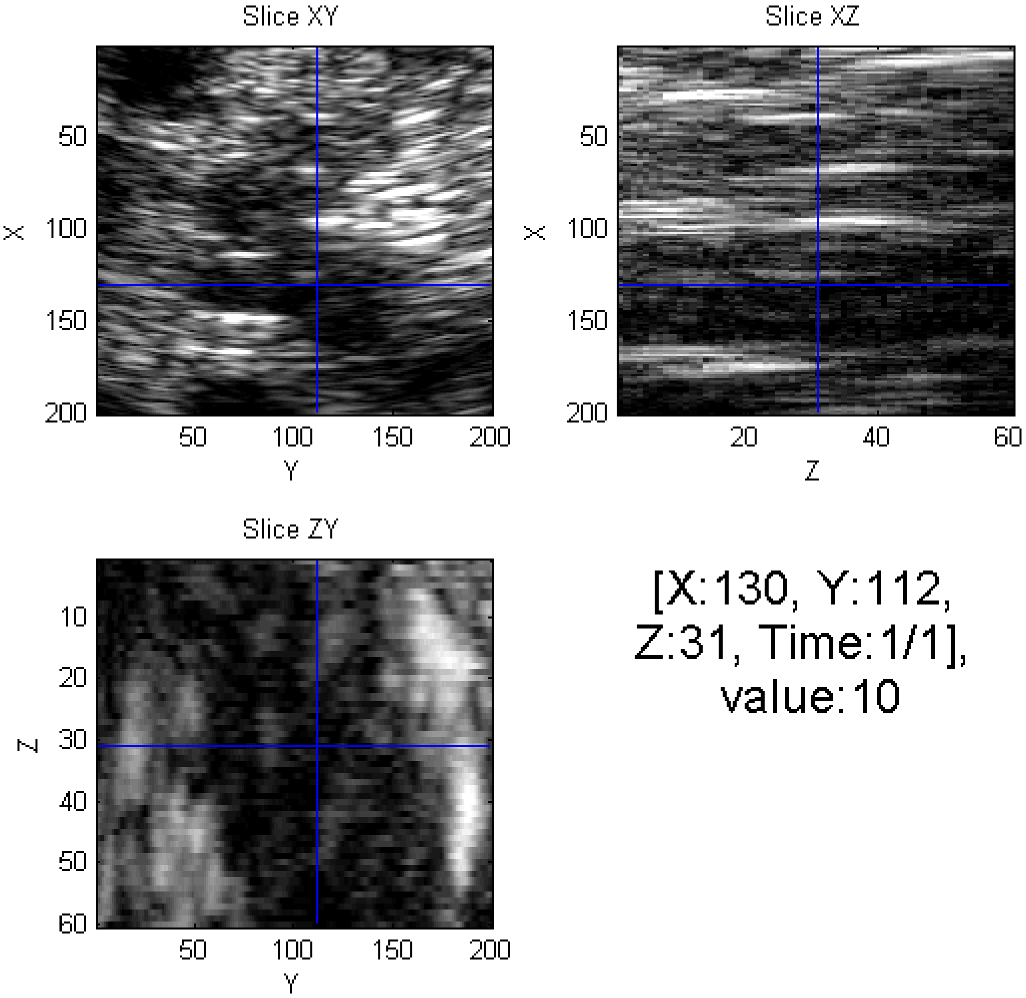

Fig. 4. Slice Browser showing all three 2-D projections of the 3-D stack.

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