Ultrasound imaging of the posterior skull for neurosurgical registration

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ABSTRACT

PURPOSE: Neurosurgical registration using optical tracking in prone position is problematic due to a lack of anatomical landmarks on the posterior skull. The current method of registration involves insertion of screws into the skull. Surface registration using ultrasound has been proposed as a less invasive method of registration. Obtaining full access to the posterior skull would require patient hair removal, which is not favored by patients as it can cause an increased risk of surgical site infection and a less aesthetic outcome. We performed ultrasound scans on participants with no hair removal to evaluate the visibility of the mastoid processes and occipital base of the posterior skull in ultrasound imaging.

METHODS: Participants were scanned using a linear and a curvilinear ultrasound probe. Scans were taken at the maximum and minimum frequency of each probe. Ultrasound scans captured the region around each mastoid process, the external occipital protuberance, and the occipital base of the skull. Scans were recorded using the Sequences extension in 3D Slicer and replayed for visual analysis.

RESULTS: At its minimum frequency, the linear probe was found to have identifiable bone surfaces with some level of uncertainty. At its maximum frequency, clear identification of the mastoid processes and occipital base was possible. The curvilinear probe did not allow identification of bone surfaces in the ultrasound image.

CONCLUSION: A linear probe at a high frequency provides clearly identifiable bone surfaces, allowing for the selection of points used in an iterative closest point algorithm for surface registration.

Keywords: Ultrasound, scanning protocol, registration, neurosurgery

1. INTRODUCTION

Image-guided surgery procedures use navigation systems to provide real-time tracking and visualization of surgical tools in relation to patient anatomy. Navigation in neurosurgery is predominantly performed using optical tracking. Optical tracking relies on maintaining a constant line of sight between the tracking camera and references on the patient and surgical tools. These procedures require the process of registration. Registration is defined as the transformation of tracking and imaging data into a single coordinate system. One method of registration for neurosurgical procedures is surface registration. Surface registration methods analyze surface contours through the collection of point clouds, typically done by a tracked pointer, and use an iterative closest point algorithm [1]. This is a noninvasive method of registration that has been used in neurosurgery when patients are in supine position. In supine position, prominent anatomical features, such as the nose bridge and orbitals, are easily accessible by a tracked pointer. However, when patients are in prone position, maintaining line of sight using optical tracking can be difficult because commonly used registration points on the anterior of the skull are obstructed from view, and there is a lack of landmarks on the posterior skull. Due to the lack of prominent anatomical features on the posterior skull, the current standard for registration in of patients in a prone position requires the insertion of metal screws into the posterior skull. These screws are then used in a landmark registration. However, this is an invasive procedure that requires additional preoperative computer tomography scans thus increasing the patient's exposure to radiation.

Ultrasound may be able to provide sufficient access to areas of the posterior skull that can be using in a surface registration and eliminate the need for screws. The use of ultrasound could access regions below layers of skin, fat and muscle that were not previously accessible by a tracked pointer. This could allow access to regions of the posterior skull that differ from the spherical shape of the posterior skull. The feasibility of ultrasound for surface registration was tested as a less invasive alternative to the use of metal screws. Testing on a plastic skull model, or phantom skull, found that with an approximated initial landmark registration, and the use of ultrasound to perform surface registration, an average target registration error of 1.6 mm was obtained [2]. However, that phantom study, assumed full unhindered access to all regions of the posterior skull. The skull phantom had no hair, fat, or muscles and was only covered by a thin layer of plastisol, simulating skin, which was easily scanned by ultrasound. The scanning protocol was not realistic, as a human skull has hair, skin, muscle, and fat layers before encountering bone. Additionally, the echogenicity of these layers would be unique for each person, and differ depending on the region being scanned.

In neurosurgical applications, hair can be particularly problematic for ultrasound scanning. The presence of hair over the skull area can cause attenuation of ultrasound waves due to trapped air [3]. This issue will differ from person to person depending on the patient's density of hair in areas of interest and the thickness of the patient's hair. In a realistic scenario, to obtain complete access to the entire posterior skull, patients would be required to either shave their head, or clip their hair to a length of about 0.5 mm. However, shaving has been found to increase the risk of surgical site infections [4]. McIntyre and McCloy, in a study examining the removal of hair for surgery, concluded that hair should not be removed unless it interferes with the approximation of the wound edges [5]. Additionally, patients would likely rather not shave or clip their entire head to improve aesthetic outcomes post-surgery, unless it is necessary for the procedure.

We present a study with human ultrasound scans of the posterior skull, wherein we aim to determine if bone surfaces around the mastoid processes and the occipital skull can be identifiable with clarity in ultrasound images without hair removal. This will provide insight into designing a realistic ultrasound scanning protocol for the registration of patients in prone position that can provide improved aesthetic outcomes and reduce the need for shaving or clipping of patient hair.

2. METHODS

2.1 Experimental Setup and Hardware

This analysis was performed using 3D Slicer (www.slicer.org), the Plus Server application (www.plustoolkit.org), a Telemed MicrUs ultrasound (Telemed Ultrasound Medical Systems, Vilnius, Lithuania), a Telemed L12-5L40S-3 linear ultrasound probe, a Telemed C5-2R60S-3 curvilinear ultrasound probe, water, and Aquasonic ultrasound transmission gel (Parker Laboratories, INC., Fairfield, New Jersey) (Figure 1A). The ultrasound was linked to a computer running 3D Slicer, and the Plus Server application *[6]*. Since only image data was being collected the participant's head was not held in a fixed position (Figure 1B).

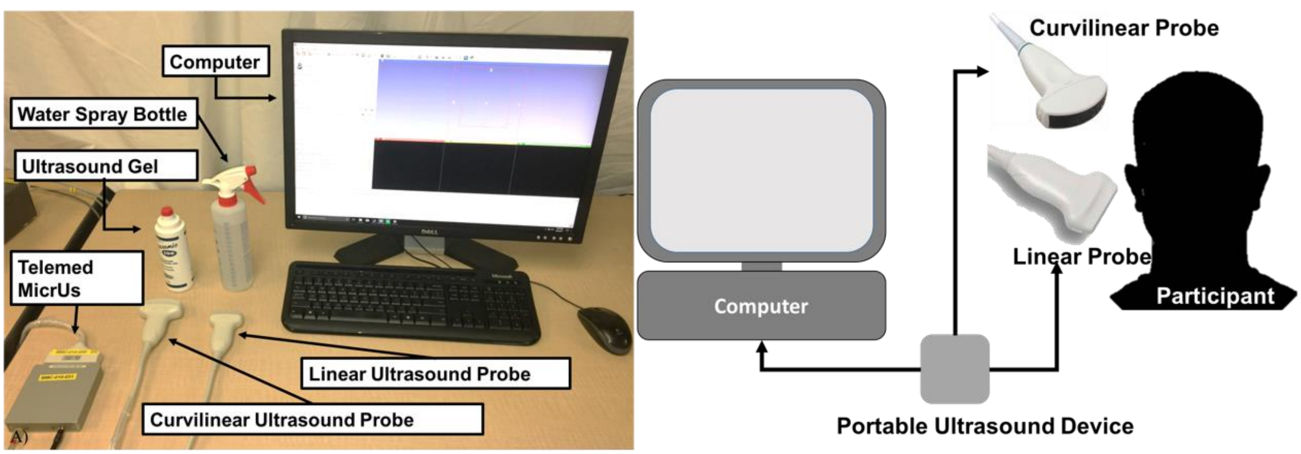

Figure 1. A) Experimental setup and equipment for performing ultrasound scans on participants, B) System set up for the experiment.

2.2 Ultrasound Scanning of Participants

Before the ultrasound scanning could occur, it was essential to improve sonic coupling and eliminate as much air as possible trapped between the ultrasound probe, hair, and the skin surface. To improve sonic coupling, the areas of interest on the participant's head were wetted and ultrasound transmission gel was applied. This decreased attenuation of the ultrasound waves during scanning to give improved ultrasound images.

The iterative closest point algorithm requires distinct regions with unique specificity to perform optimally. The inclusion of unique landmarks will increase the chance of obtaining a more accurate registration. Therefore, participants were then scanned in three distinct regions: around each mastoid process, and the occipital base of the skull including the external occipital protuberance. These regions were selected as they are anatomical bone surfaces that differ from the spherical shape of the posterior skull (Figure 2). These surfaces may be able to provide unique surface contours to break symmetry and ambiguity when minimizing translational and rotational error. Ultrasound scanning information was recorded using the Sequences extension in 3D Slicer. This extension allowed us to record and replay data for analyzing the ultrasound scans of each participant [7].

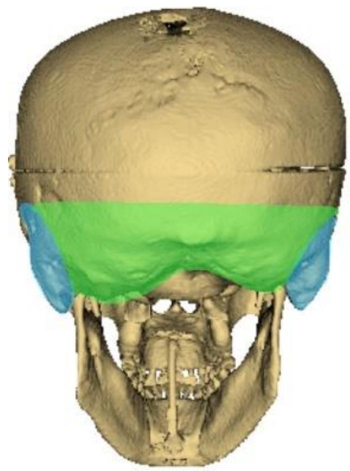

Figure 2. Mastoid regions (blue) and occipital region (green) covered in ultrasound scanning.

Since different ultrasound probes are designed for different application, two different ultrasound probes were used to scan each region of interest. In addition to the physical design of ultrasound probes, the frequency of the ultrasound waves contributes to differing results. Scans were conducted using a linear probe and a curvilinear probe in each area. Scans were taken at the maximum and minimum frequency of each probe. The linear ultrasound probe had a maximum frequency of 12 MHz and a minimum frequency of 5 MHz. The curvilinear probe had a maximum frequency of 5 MHz and a minimum frequency of 2 MHz. Between each scan the areas of interest were wetted again, and ultrasound gel was reapplied.

2.3 Identification of Bone and Evaluation of Ultrasound Images

Each recorded ultrasound scan was then viewed to determine if bone surfaces were identifiable. A bone surface in an ultrasound image should appear as the brightest pixels with a drop-off of pixel intensity or shadowing below. This phenomenon occurs because ultrasound waves are not capable of penetrating bone. Each scan was then evaluated to determine if bone regions were clearly identifiable, not identifiable or if there is uncertainty about bone surfaces.

Since ultrasound waves cannot penetrate bone, bone surfaces appear as a bright white line in the ultrasound image. In addition, the inability of these ultrasound waves to penetrate bone leaves a shadow below the line where the pixel intensity drops off. Clearly identifiable bone surfaces would appear as a thin bright line in an ultrasound image; the thinner the line appears the more clearly identifiable the bone surface is. The uncertain identification of bone occurs when (i) the brightest surface in the ultrasound image is thick, indicating that there is a larger variability in the potential placement of surface points, or (ii) other structures such as muscle can appear as an alternative bone surface. If no potential bone surface was found then it was classified as not identifiable.

3. RESULTS

One phantom and five human participants were scanned with ultrasound (n=6). The participants varied in gender, hair length, and hair thickness (Figure 3).

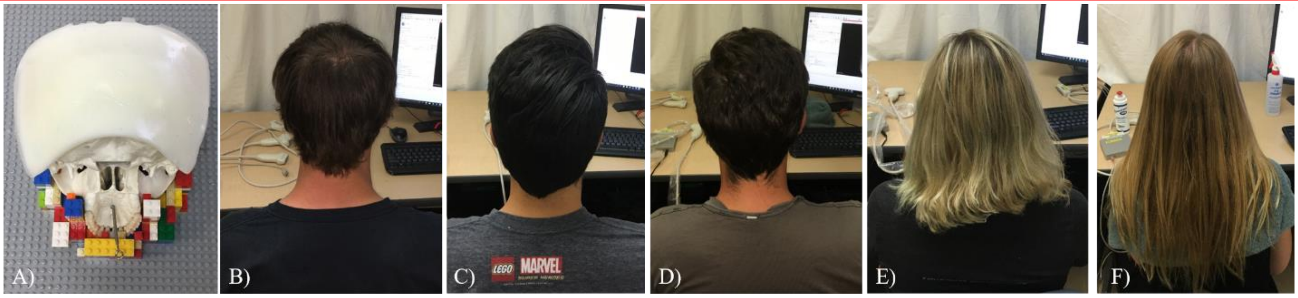

Figure 3. A) Phantom Skull used in scanning with the plastisol cover, B) Participant 1, C) Participant 2, D) Participant 3, E) Participant 4, F) Participant 5.

The results from the ultrasound scanning were recorded into two separate tables. Table 1 shows the results for identification of bone surfaces on the mastoid regions of the skull. There was only one table to represent the mastoid regions since the left and right areas around the mastoid processes are highly symmetrical on each participant. Table 2 shows the results for identification of bone surfaces on the occipital region of the skull. The occipital region of the skull included scanning around the occipital base of the skull and the external occipital protuberance. Each table includes a breakdown of the clarity of bone surfaces in the ultrasound image for two different ultrasound probes at two different frequencies for each.

Table 1. Classification of the ease of identification of bone surfaces over both mastoid regions of the skull.

Participant	Linear probe		Curvilinear probe	
	12 MHz	5 MHz	5 MHz	2 MHz
Phantom	Clearly Identifiable	Clearly Identifiable	Uncertain identification	Not Identifiable
Participant 1	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable
Participant 2	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable
Participant 3	Clearly Identifiable	Clearly Identifiable	Not Identifiable	Not Identifiable
Participant 4	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable
Participant 5	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable

Table 2. Classification of the ease of identification of bone surfaces over the occipital region of the skull.

Participant	Linear probe		Curvilinear probe	
	12 MHz	5 MHz	5 MHz	2 MHz
Phantom	Clearly Identifiable	Clearly Identifiable	Uncertain Identification	Not Identifiable
Participant 1	Clearly Identifiable	Clearly Identifiable	Not Identifiable	Not Identifiable
Participant 2	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable
Participant 3	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable
Participant 4	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable
Participant 5	Clearly Identifiable	Uncertain Identification	Not Identifiable	Not Identifiable

4. DISCUSSION

The scans that were identified as being clearly identifiable would be useful for surface registration of the posterior skull. This is because the clearly identifiable structure leaves little ambiguity in the manual placement of surface points within the ultrasound image for registration. The most clearly identifiable images were collected on the phantom model

(Figure 4A). If bone surfaces were not identifiable in the ultrasound images, then the probe or scanning protocol was not usable or could result in prolonged scanning. When a bone surface is not identifiable then there is no surface to utilize for surface registration and the physician performing the registration could require more time to scan and locate bone surfaces that are identifiable. This presents two potential problems: (i) surfaces found are not unique enough to break rotational symmetry for surface registration and (ii) an increased surgical time. In a study by Korinek and colleagues, they found that a prolonged operative time was a predictive risk factor for neurosurgical surgical site infections [8]. Therefore, searching for alternative identifiable bone surfaces is not ideal. An uncertain identification can also be detrimental for surface registration. An uncertain bone surface can introduce large amounts of variability in the selection of surface points for registration that may go un-noticed by the physician. This variability will alter the registration and result in increases translational and rotational error. In neurosurgery, where it is critical that the registration be accurate as to avoid critical internal vasculature, the uncertain identification of bone surfaces is not ideal and should not be used for surface registration.

The ultrasound scans completed using the curvilinear probe did not produce any clearly identifiable bone surfaces. The ultrasound images collected with the curvilinear probe showed some shadowing, indicating that bone was present, however, the surface of this bone was not identifiable (Figure 4B). Initially the curvilinear probe was considered as it is more commonly used for procedures that require looking at a greater depth while covering a wide area [9]. Scanning he human participants, meant scanning through hair, skin, fat, and muscle before encountering bone. Since the desired bone surface would be deeper than on the phantom model the curvilinear probe was considered. However, bone surfaces may not have been situated deep enough below the skin surface to appear clearly in the ultrasound image. In comparison, the linear probe is commonly used to access superficial areas. The bone surface is shallow to the skin surface and is likely the main reason why the linear probe performed better. Altogether, the linear probe was found to produce better ultrasound images of bone surfaces (Figure 4C).

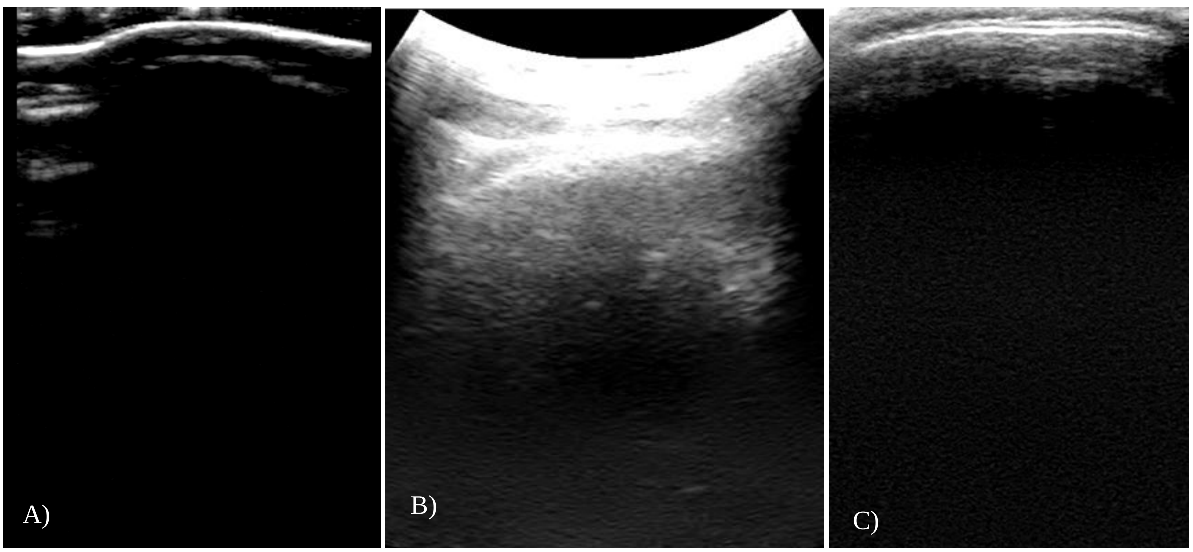

Figure 4.A) Ultrasound image of the phantom using a linear probe with frequency setting at 12MHz, B) Ultrasound image using a curvilinear probe with a frequency setting of 5 MHz, C) Ultrasound image using a linear probe with a frequency of 12 MHz.

There was also a difference in the ability to clearly identify bone surfaces depending on the frequency of the linear probe. Tables 1 and 2 showed that ultrasound scans performed using the linear probe at a higher frequency (12 MHz) allowed for the most clearly identifiable bone surfaces. This may be due to the resolution of the ultrasound probe increasing proportionally with the frequency of the probe [10]. Therefore, bone surfaces that can be determined at a higher frequency have a much smaller thickness (Figure 5). This means that manually placing surface points in the ultrasound image would lead to less variation than on a bone surface with a larger thickness. When bone surfaces are uncertain, error is introduced into the placement of surface points within the width of the image and at different thresholds.

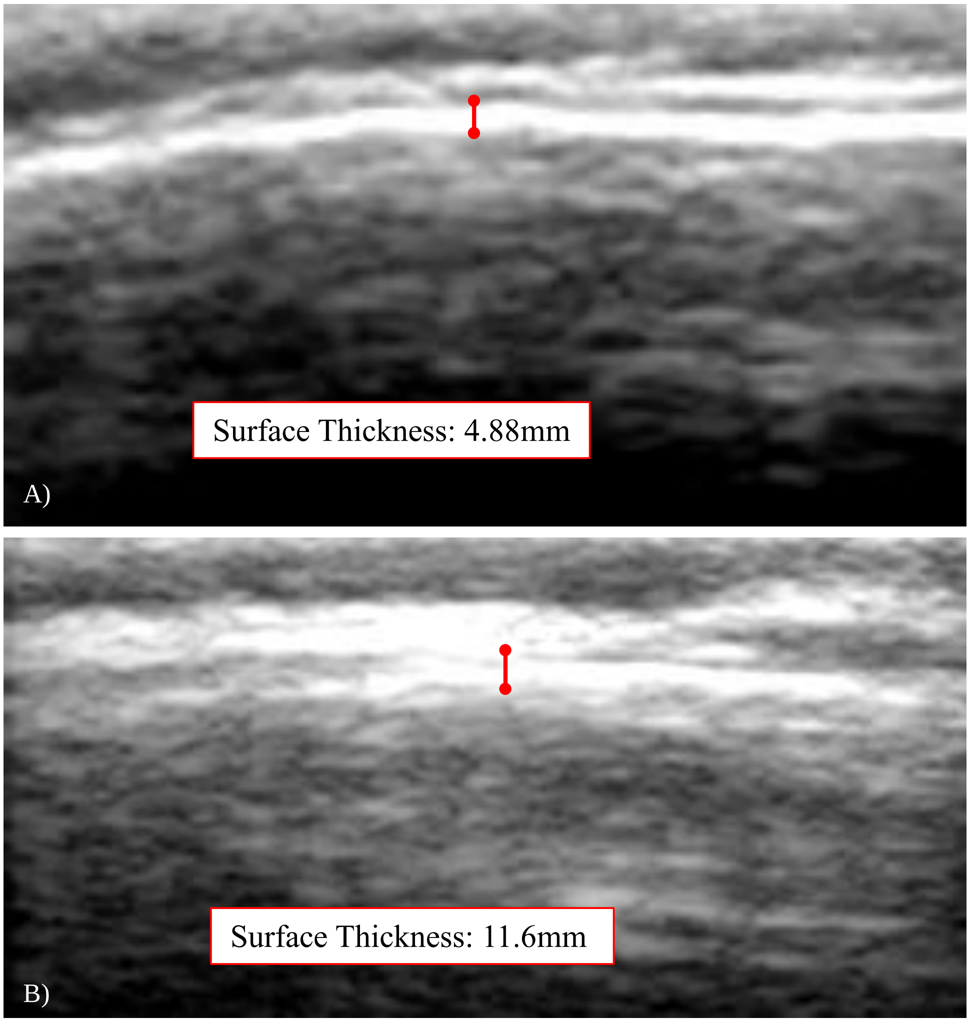

Figure 5. A) Measured bone thickness using a 12 MHz linear, B) Measured bone thickness using a 5 MHz linear probe.

Another problem with ultrasound is that images collected contain an inevitable amount of random noise due to the microscopic reflections produced by internal structures, termed speckle. Nascimento and Ruano discussed how the removal of noise is required to more accurately determine bone surfaces in ultrasound. The ultrasound scans evaluated had not undergone any noise reduction and speckle could have played a role in the uncertainty of bone surfaces. The identification of bone surfaces could have been improved with the implementation noise reduction algorithms, such as Simple Speckle Removal (Nascimento and Ruano 2015) [11]. When developing an ultrasound scanning protocol for registration of the posterior skull, noise reduction will need to be implemented. This implementation will need to ensure accurate identification of bone surfaces while running in a timely manner as not to interfere with the surgical procedure.

5. CONCLUSION

Tracked ultrasound may be used as a less invasive method of registration for patients undergoing neurosurgery in prone position. The use of ultrasound for surface registration on the posterior skull has been demonstrated on a phantom model but did not involve a realistic ultrasound scanning protocol. Shaving or clipping a patient's hair is not ideal for two reasons: (i) it can lead to an increased risk of surgical site infections, and (ii) it results in an aesthetically less pleasing outcome. The use of a linear ultrasound probe at a higher frequency (12 MHz) provided clearly identifiable bone surfaces in all areas for all patients without requiring hair removal. This could be used to develop a realistic ultrasound scanning protocol for surface registration of the posterior skull. A higher resolution and the use of noise reduction algorithms could decrease the width of bone surfaces in the ultrasound image and improve the placement of surface points in the ultrasound image and thus curtail registration error.

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