# Supporting Novice Prehospital Transcranial Ultrasound Scanning for Brain Haemorrhage

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Abstract: Traumatic brain injury is a significant problem due to difficulties in early diagnosis in the field. Computed tomography is the gold standard for detecting brain haemorrhage, but scanners are bulky and expensive. A cheap, portable scanner such as transcranial ultrasound (TCUS) could allow early triage and intervention. Transmitting images to remote experts for diagnosis means TCUS could be used by any minimally trained person in the field. We propose a virtual 3-dimensional model of the head which shows which areas of the brain have been imaged already, where the probe currently is, and where still needs to be covered in order to generate a complete scan. Using sensors to measure the position and rotation of the TCUS transducer, we can link this to the 3D model of the head and visually display which areas have been imaged. The images can be analysed and composited to form a personalised 3D scan with maximal coverage of the brain, which can be transmitted for diagnostic review, reducing data loss compared with streaming ongoing images. Initial testing of the software has been performed in healthy volunteers and further testing is planned in patients with brain haemorrhage.

## 1 INTRODUCTION

Traumatic brain injury (TBI) is a significant problem, with challenges in diagnosis, especially early diagnosis in the field. Closed head injuries are of particular concern and far outnumber the penetrative head injuries on which official statistics are based. Currently, there are no well-accepted diagnostic tests for use in standard medical practice to diagnose TBI (Centers for Disease Control and Prevention [CDC] et al., 2013). Ideally, brain imaging should be performed as soon as possible because posttraumatic bleeding within the skull is associated with worse prognosis and can be life threatening (CDC et al., 2013). Prompt diagnosis and improved prehospital care can mean that secondary (non-immediate) brain injury can be prevented or limited by good early care (maintaining blood and oxygen flow to the brain, controlling blood pressure and haemorrhage and potentially drilling of surgical burr holes), training and organisation of trauma services, potentially leading to significant reductions in both mortality and long-term disability (Gentleman, 2008; CDC et al., 2013).

Computed tomography (CT) scanning is the gold standard for detecting haemorrhage in the brain, but is not feasible in the field: the scanners are heavy, bulky, expensive and currently not developed in any ruggedized form. A cheap, portable scanner for bleeding in the brain (plus other conditions such as skull fractures, indicators of intracranial pressure, etc.) could alert medics to problems and allow early triage and intervention. We believe transcranial ultrasound (TCUS) has potential in this area and, if used with a communications system to transmit the images to a remote expert for diagnosis, could be used to assess the injured by any minimally trained person in the field. These scanners can fit into cases only a little larger than a laptop, and can therefore be used in ambulances and other prehospital situations. Ultrasound is a useful tool for many diagnostic purposes in trauma and beyond, and it is hoped that this work will add to its utility rather than requiring a different tool for head injuries.

Currently ultrasound is not routinely used clinically for identifying brain structures and abnormalities, although transcranial Doppler, measuring blood flow velocity within cerebral arteries, is a more commonly performed scan (Sarkar et al., 2007). However, following previous work by our group – the Satellite Ultrasound for



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Rural Stroke project (Mort et al., 2015) – we believe that TCUS could provide useful prehospital information when imaging brains looking for haemorrhage. In this project, prehospital ultrasound images were recorded by novice users and streamed live using mobile or satellite networks from an ambulance in remote and rural areas of the Scottish Highlands to hospital-based experts for diagnosis. The quality of the real-time streamed images was rated and found to be good enough for diagnostic purposes in ~93% of cases, although connectivity was variable. This preliminary work identified that novice scanners could, after brief training, record images of the brain's midline, located using the third ventricle. The next logical step was to focus on facilitating the TCUS scanning by novices to ensure that the appropriate information is captured and easily and efficiently transmitted.

If TCUS is to be used to provide information about bleeding in the brain (or its absence), then it is important to ensure that as much of the brain has been scanned as possible so the accuracy of the diagnosis can be quantified. Novice scanners in particular may find this difficult, without the expert knowledge to interpret the images and direct their scanning. It would be useful to provide them with a guide showing what they have scanned and what has not yet been imaged.

The current research is developing a software package to assist the operator in achieving comprehensive ultrasound scanning of the head. We aim to make TCUS scanning simpler for non-medically trained users by providing them with a visual 3D model of the head which clearly shows which areas of the brain have been imaged already, where the probe currently is, and where still needs to be covered in order to generate a maximal scan – something that is important for diagnosing and treating brain injury. By measuring the position and rotation of the ultrasound transducer using movement sensors, we can determine where the probe is pointing at all times during the scanning session. Linking this to a 3D model of the head allows us to determine which areas have been imaged and which have not. The images recorded will then be composited to form a complete 3D scan of the subject's head, using image processing techniques to locate the skull in order to fit the model to the individual's specific head size and shape. This means a personalised 3D TCUS scan with maximum coverage of the brain is created, offering the ability to view the brain images from any point on the head, as if the user possessed a virtual probe that can be placed anywhere on the 3D model. This 3D scan is also a single file that can be transmitted for diagnostic review with less chance of data loss than streaming images from an ongoing scan.

This position paper describes the initial tests in healthy volunteers, and discusses plans for further development and testing.

## 2 METHODS

The software was written using MATLAB R2015a (MathWorks, Massachusetts USA) and produces a real-time display of where the TCUS transducer is currently pointing and has already scanned; plus offline image analysis to locate the skull in the recorded TCUS images and use this to deform a standard 3D skull mesh. The scan model is displayed and interacted with on a laptop, but in future work could potentially be integrated into manufacturers' ultrasound software.

A Philips CX50 portable ultrasound machine (Philips Healthcare, Amsterdam, Netherlands) was used in the testing, with an inertial measurement unit sensor (3-Space Sensor, YEI Technology, Ohio USA) attached to the transducer throughout scanning. One temporary experimental set-up is shown in Figure 1; ideally the sensor chip would be integrated into the probe for easier handling. This sensor records quaternion measurements which are then used by the new software to calculate the plane of the scan, which is then displayed within the skull mesh. There are currently no dedicated TCUS transducers available, so volunteers used a cardiac probe with an appropriately small footprint, which can be used at lower frequencies (1-5 MHz) to penetrate through the skull and image to the opposite side of the cranial vault; software settings of the

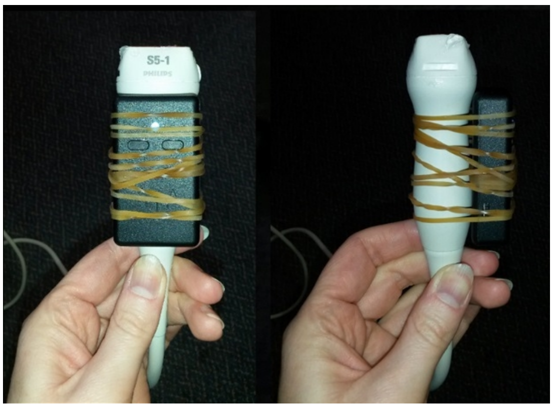


Figure 1: The inertial measurement unit sensor and the ultrasound probe.


Figure 2: The head measurements made in the healthy volunteer study.

ultrasound machine were also optimised as much as possible for head scanning.

The TCUS images were recorded as video clips to capture both the images and any changes in depth, power and sensitivity required to image the various depths of brain for each volunteer. The images recorded will be composited to form a complete 3D scan of the subject's head, using image processing techniques (segmentation) to locate the skull in each image in order to deform and fit the virtual 3D mesh model to the individual's specific head size. This creates a personalised 3D TCUS scan.

Initial testing of the software was performed in healthy volunteers to gather data about the scanning process and visibility of brain structures on ultrasound, plus transducer position data to calculate the brain coverage of scans. Previous studies have shown that between 5–20% of subjects have acoustic windows offering reduced TCUS penetration, which makes imaging more difficult or impossible (Seidel et al., 1993; Sarkar et al., 2007).

Tests were done under laboratory conditions. The dimensions of each volunteer's head were measured using standard neurophysiological landmarks (nasion, inion, preauricular points; see Figure 2). Structural imaging involved scanning through the left transtemporal acoustic window (an area of often thinner bone used to allow greater penetration of the ultrasound waves) to the opposite side of the head with the transducer in the vertical plane, then determining the lateral and vertical range of imaging achievable through this window. Visualisation of landmarks such as the skull base, brainstem, sphenoid bone and choroid plexus was attempted. These steps were repeated in the horizontal transducer plane, and from the opposite transtemporal acoustic window. Imaging then focussed on the midline of the brain, represented by the third ventricle. The distance from skull to third ventricle was measured from both transtemporal windows. Volunteers then scanned a member of the study team with the help of the new head scanning software, after which they were given a short questionnaire about their experience using the program. Feedback was used to improve the program's usability and features.

## 3 RESULTS

The initial testing recruited 12 healthy volunteers: 9 female, 3 male, none of whom had used ultrasound before. Table 1 shows the average head measurements recorded in the study, grouped by gender. This shows that there are differences in head size that support the use of a personalised head model rather than simply using a standard 'average' mesh model.

Table 1: The mean head measurements ± standard deviation (in cm) recorded in the healthy volunteer study.

| Subject type | Nasion to inion | Pre-auricular point to point | Circum-ference |
|---|---|---|---|
| Average | 37.6 ± 1.7 | 35.7 ± 2.5 | 57.8 ± 1.6 |
| Average male | 38.3 ± 0.5 | 37.3 ± 2.6 | 58.7 ± 0.9 |
| Average female | 37.3 ± 1.9 | 35.1 ± 2.1 | 57.6 ± 1.7 |

Two of the volunteers had transtemporal acoustic windows that allowed more limited views of the brain than others. This proportion is similar to what has been reported in the literature. Imaging was still possible, but of reduced clarity.

All twelve volunteers used the new software to help them scan a team member's head. Figure 3 shows a screenshot of the software from such a scan, illustrating the cumulative coverage of the head scans. The average scan time was 8 minutes, 47 seconds (range: 6 minutes, 1 second to 13 minutes, 52 seconds). The computational time of the program

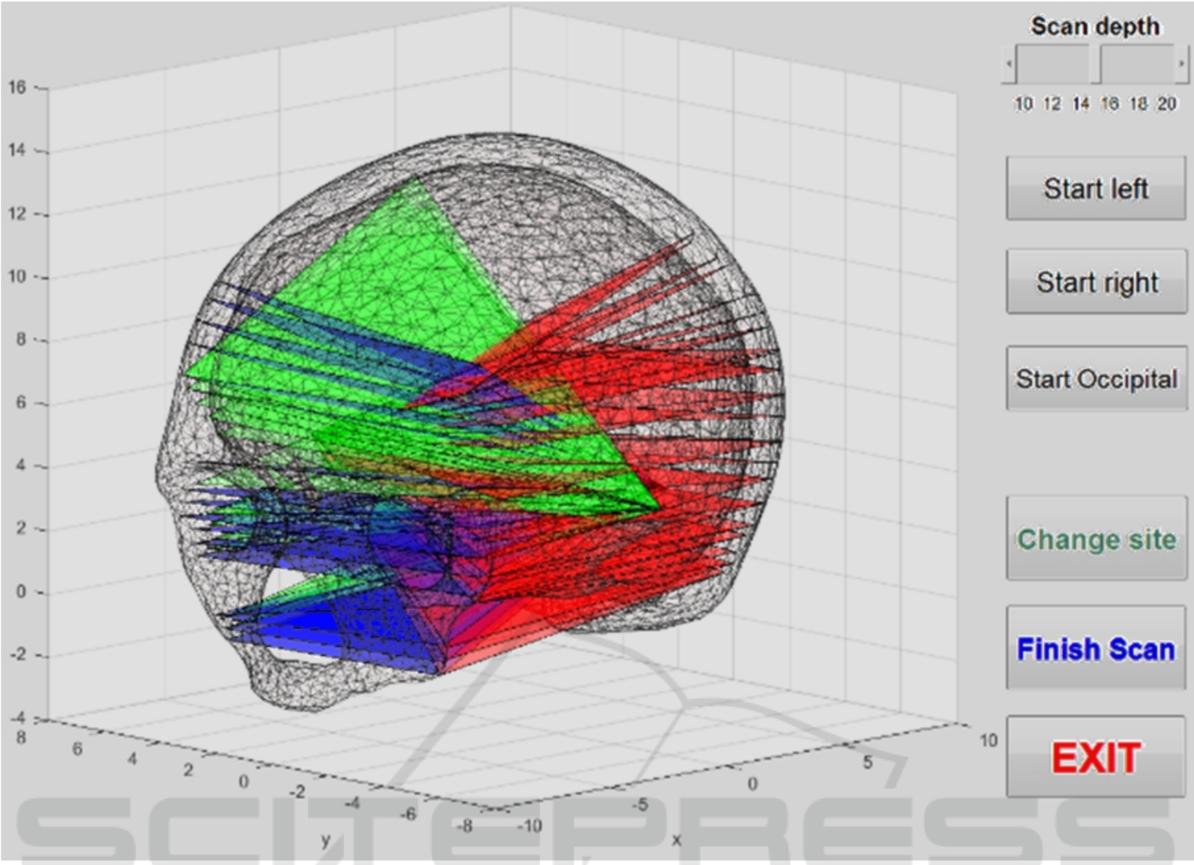


Figure 3: A screenshot of the 3D head model display program showing where scans have been performed from the different acoustic windows (red for the patient's right temporal window, green for their left temporal window and blue for the occipital window).



was not an issue: it averaged approximately 0.3 seconds, with a maximum of 1 second seen during the testing.

All volunteers said they felt they could use the 3D head model program, with 92% saying it was easy to use. Some commented that they found using the probe difficult initially, but this was because they had no prior experience with ultrasound: more than half (58%) said they thought they needed more instructions or help, such as knowing exactly where and how to place the probe (e.g., finding the optimum window, which is actually done by exploring the approximate area and locating the spot that produces the best images; it is difficult to give more than a general guide to location); and being reminded to make sure the probe didn't slide away from the window due to the ultrasound gel used.

All of the volunteers reported that they thought the 3D model accurately represented the direction of the probe and that the model updated quickly enough as they moved. All also thought the model correctly showed areas they had scanned. Only 36% said they were able to scan the areas the model showed were unscanned. This is most likely because there will be areas, such as the very top of the head, where the probe cannot scan because it loses contact with the head when tilted to the necessary angle. The volunteers did not scan from the occipital window (due to the poor images seen from this site when it was attempted), which might have allowed them to scan some areas otherwise unreachable.

Finally, all of the volunteers reported they thought the program included all the functions they might expect to find, given its aims, and all also were satisfied that the program achieved these aims.

The volunteers were asked to rate the program as a whole on a scale of 1 (useless) to 5 (useful), and the mean rating was 4.3, the median was 4 ($25^{th}$–$75^{th}$ percentiles: 4–4.5).

Suggestions from the volunteers as to how the program could be improved included:

• Providing a more in-depth tutorial on ultrasound, the machine and the probe, which is the sort of training that would be provided to end users.

• Having a probe designed specifically for head imaging, with a better shape for reaching all areas; and incorporating the 3D-model into the ultrasound screen so it is easier to see both at once. Addressing both of these points could involve working with ultrasound manufacturers for further development.
• Indicating the places on the model where they are unlikely to be able to image.
• Showing a different coloured plane to indicate where the probe is currently imaging, which has since been implemented.
• Highlighting any abnormalities imaged, which would involve computer-aided diagnosis analysis, discussed in the Future Work section of this paper.
• Automatically detecting when the probe has been removed from the patient's head (currently this is done manually by pressing a button). This is a point for future development, but a partial solution has been implemented, detecting when the probe is held upright, a position in which it would not usually be during usual TCUS scanning.

## 4 FUTURE WORK

The analysis of the ultrasound data is ongoing, looking at forming 3D scans from the 2D images collected, and calculating the variation between the scans of the research team member that were taken by different users.

The patient scanning study is currently starting and involves hospital-based testing of the software package in up to 10 patients with bleeding in the brain. Images of the bleeding are collected for use in two ways: to test the scanning support software in a controlled clinical environment, and to compile a set of TCUS scans featuring haemorrhage, to help investigate the appearance of bleeding in the brain on ultrasound. This appearance will change as the time from the bleeding event increases and the blood clots, so it is important to image several different patients with brain haemorrhage (ideally as a result of different causes), to capture a range of haemorrhage images. These will also be used to explore the potential for automated computer-assisted diagnosis to support TCUS assessment of patients with brain injury.

Details of the diagnosis and timing of the brain haemorrhage will be recorded, as will CT images that form part of the patient's usual care and diagnosis, for comparison. Scanning will take place at the patient's bedside and involve the same structural scanning as in the healthy volunteer study, plus the area of the haemorrhage will be comprehensively imaged. The expert ultrasound operators will provide feedback via a short questionnaire; they will also be asked to assess the resulting 3D image models for utility and quality at a later time point.

## 5 CONCLUSIONS

The software described in this paper is specifically designed to support non-medically trained TCUS users in taking diagnostically useful images, so that no expertise in interpreting ultrasound is required. Brief training on the use of the ultrasound machine and 3D imaging program is all that is needed. It has been initially tested in healthy volunteers, with further testing planned in patients with brain bleeding.

This study recruited volunteers for whom it was their first time using ultrasound, and they took a little time to become comfortable with holding the probe and finding the optimum acoustic windows through which to image. The average scan time of almost 9 minutes would no doubt improve with practice, experience and confidence. The computational time of the program did not produce any appreciable lag and the feedback provides essentially updates in 'real time'. The scan model used in this work was displayed and interacted with on a laptop, but in future work could potentially be integrated into manufacturers' ultrasound software, so that users do not have to view two different screens.

The volunteers reported that the support system fulfilled its aims and appeared to be working correctly. They also made suggestions for improvements, some of which have already been implemented and will be ready for testing in further trials. This study was the first feasibility test and highlighted some problems with the imaging system, such as the existence of areas of the brain that are extremely difficult to scan with the currently available hardware. Using additional acoustic windows could help provide solutions to this problem, as could development of a TCUS-specific probe.

TBI is a significant problem, especially for the military, and can lead to neuropsychiatric and neurological sequelae. The benefits of a field-based lay-user TCUS system are applicable to both military and civilian situations (e.g., prehospital, ambulance-based diagnosis for head injury and stroke). It builds on existing (currently experimental) ultrasound transmission technology to improve its usability and efficiency for use by non-expert medics. The proposed system will make it easy for any minimally trained personnel to collect diagnostically relevant head images, which can then be transmitted in a single package to a remote site for interpretation. In this way, early diagnosis of brain injury in the field – specifically looking for haemorrhage in closed traumatic head injury - can be improved without requiring major training for novice users, because, thanks to modern communication technologies, the images can be transmitted and diagnosis performed by experts at a remote site. The proposed system will also decrease the effects of unstable transmission and packet loss in sending the images to experts, by compositing the data into a single file to be transmitted rather than streaming the ultrasound video, where frames will frequently be lost.

The impact of earlier diagnosis of TBI using such a system as described here could be potentially huge (preventing/minimising sequelae, long term health effects of early/any treatment). It does rely on TCUS being able to reliably detect haemorrhage in the brain, but previous studies have shown there is a strong possibility that the sensitivity will be of a useful level (e.g., Mäurer et al., 1998). These studies were performed some time ago so, with the benefit of today's improved ultrasound technology and ongoing transducer optimisation, we are optimistic that TCUS will prove worthwhile and useful for this situation. We are planning concurrent validity studies with TCUS and CT in patients with stroke in order to provide updated evidence that modern US systems can be used to reliably detect haemorrhage. Although TCUS may be less sensitive than CT for detecting haemorrhage, its portability and low cost make it an attractive technology for battlefield and transit use. Ruggedised systems are already available for use in the field, and are used by air ambulance services around the world.

We believe TCUS has potential and, if used with a communications system to transmit the images to a remote expert for diagnosis, could be used to assess the injured by any minimally trained person in the field.

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