Guidance for Skull Base Surgery

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1. Project Statement

The goal of our project is to improve the accuracy of computer-aided trans-sphenoidal skull base surgery through the use of intra-operative imaging. This would enable us to better protect critical structures such as the carotid artery during the drilling process. Improving accuracy is particularly important in children because their smaller anatomy renders the trans-sphenoidal approach dangerous and technically difficult. To do so, we build on the computer-aided surgical system developed by Xia et al. in 2008. His system integrated a Stealthstation ® navigation system, a NeuroMate® robotic arm and visualization software 3D slicer to achieve cooperative control and greater safety standards through the enforcement of safety constrants via pre-operatively defined virtual fixtures. However, experiments showed that the system is only able to achieve an average accuracy of 1-2mm, with a maximum error of 3mm. To achieve clinically acceptable errors of the 1mm range, Dr. Kazanzides proposed using intra-operative imaging, specifically, photo-acoustic imaging (PAI), to reduce uncertainty in the registration.

2. Paper Selection

Wang X., Chamberland D. L., Xi G. 2008 Noninvasive reflection mode photoacoustic imaging through infant skull toward imaging of neonatal brains. J. Neurosci. Methods 168, 412–421. This paper was selected because it gives motivation as to why we have chosen photoacoustic imaging as our mode of intra-operative sensing. It describes in detail a system set-up as well as materials and methods that are potentially relevant to our experimental and simulation design. The paper also highlights possible challenges in the application of photoacoustic imaging to imaging of the skull that are relevant to our project.

3. Paper Summary

3.1 Problem Statement: Monitoring morphological and functional information in infant brains is important because it could enable earlier diagnosis and better treatment of neonatal brain diseases. However, there is currently a lack of technology that is suitable for scanning infant brains. Such an imaging modality must have high sensitivity, as well as high spatial resolution. It should also ideally be convenient, continuous, non-invasive, fast and inexpensive. Photoacoustic imaging is a relatively new technology that could in principle deliver the same sensitivity as optical and nuclear imaging, but with improved spatial resolution. Wang et al. are therefore interested in the potential of applying PAI to scanning neonatal brains.

3.2 Goal: The goal of Wang et al. is to study the feasibility of monitoring morphological and functional imaging through an infant skull using PAI. Specifically, in the paper, Wang et al. set out to show that the photoacoustic signals and the images that can be produced as a result of these signals are of high quality.

3.3 Key Results: In the paper, Wang et al. showed that PAI has improved resolution over conventional optical imaging modalities, and that imaging can be done to at least a depth of 21mm beneath the infant skull. They then concluded that PAI exhibits great potential for performing high quality imaging of neo-natal brains.

4. Background: Photoacoustic Imaging

In photoacoustic imaging, non-ionizing laser pulses are directed toward a biological sample, which absorbs the light energy, resulting in thermoelastic expansion. This generates ultrasonic waves, which can then be picked up by an ultrasound transducer. The signals can then be used to deduce the initial distribution of optical energy absorption along the path of the laser.

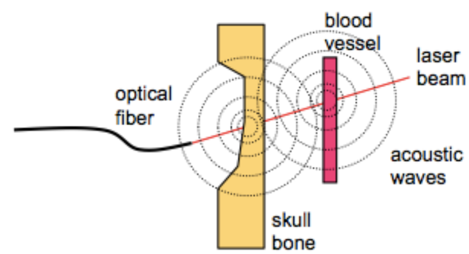

Figure 1: Photoacoustic Imaging; Credit: Dr. Kazanzides

The primary advantage of PAI is that it can be as sensitive as optical imaging because it makes use of optical absorption to determine the contrast. PAI is therefore intrinsically sensitive to the vasculature within the brain. The spatial resolution of PAI is also limited by how the system is set-up, rather than light scattering or diffusion. PAI, as described in the paper, is also non-invasive, non-ionizing, and inexpensive. Furthermore, ultrasound waves need only travel one-way, from the biological sample to the probe, rather than in both directions, as is the case for traditional ultrasound.

However, PAI is not generally used in the skull region because the skull bone attenuates both light and acoustic signals. Wang et al. argue that while this is indeed the case for adult skulls, infant skulls, being much thinner, will not attenuate the light or the acoustic signal to the same extent.

5. Materials and Methods

5.1 Phantom: Wang et al. made use of a newborn infant skull that is 7cm by 9cm with a thickness of 0.6-0.9mm. In many of their experimental set-ups, a simulated vessel is used. This simulated vessel is a 50μm transparent tubing filled with fresh whole dog blood. The vessel is usually embedded in simulated brain tissue. In their experiments, both fresh canine brain measuring 6cm by 6cm by 4cm as well as a 10% porcine gel mixed with whole milk (concentration 50%) were used. These were chosen because they best mimicked the optical properties of human brains.

5.2 Imaging system: Wang et al.'s imaging system comprised of (a) a pulsed laser with a tunable wavelength of

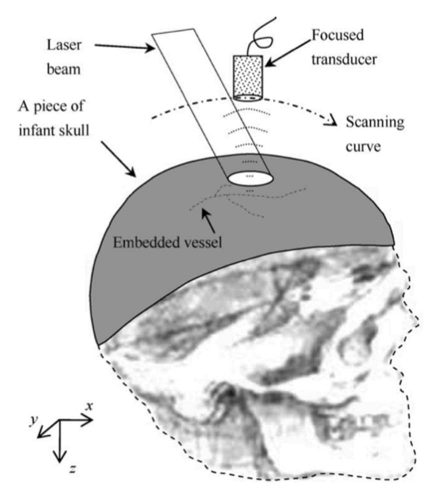

Fig. 1. Geometry of reflection mode transcranial photoacoustic imaging of brain.

Figure 2: Imaging Set-up and Procedure

680-950nm, a repetition rate of 10 Hz, a pulse width of 5.5ns, an incident energy density of 15mJ/cm^2, and an incident diameter of 13mm, (b) a wideband focused ultrasonic transducer. In the experiments, two transducers were used: V311 (Panametrics) with a central frequency of 10 MHz, a bandwidth of 110% at -6 dB, a focal length of 0.75in and an element size of 0.5in, and V307 (Panametrics), with a central frequency of 5 MHz, a bandwidth of 78.25% at -6 dB, a focal length of 1 in, an element size of 1.95 in, (c) a pre-amplifier, (d) an oscilloscope, (e) and a computer.

5.3 Imaging Procedure: During reflection mode transcranial photoacoustic imaging, the laser is shone on the surface of the skull. The transducer is then positioned so that the acoustic beam is detected through the site where the laser is incident. This forms an A-line, which is the signal obtained along the path of the laser at that particular position. To obtain a 2D B-scan, the laser and transducer are moved along an arc that follows the curvature of the skull. The resulting A-line signals are then assembled into a 2D image by lining up the A-lines along the identical y co-ordinates. To obtain a three-dimensional image, the laser and transducer must traverse the surface of the skull (See Fig. 1)

6. Results

6.1 Spatial Resolution: For the V311 transducer, lateral resolution was found to be 420 μm and axial resolution was found to be 50 μm. Lateral resolution was found by finding the full width at half maximum (FWHM) of the line spread function. Axial resolution was found by finding the FWHM of the line target, in this case, the vessel, which was embedded 1.3mm below the skull. Similar results were presented for the V307 transducer. The B-scan images presented in the paper show that the both the skull and vessel could be detected with good contrast-to-noise ratio (See figure 2).

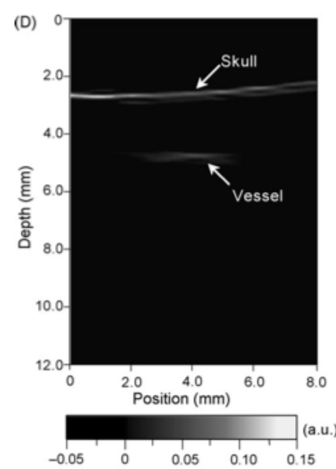

Figure 3: B-scan of vessel

6.2 Ultrasound and light attenuation by the skull: To investigate ultrasound attenuation, Wang et al. measured insertion loss using the standard through-transmission method. They found that there is low ultrasound attenuation by the infant skull. To investigate light attenuation, Wang et al. measured the fluence of transmitted light from the laser beam using a photodetector. They found that across the range of laser wavelengths, 60-70% of the light is transmitted through the skull.

6.3 Imaging Depth: By imaging a vessel placed 21mm beneath the skull, Wang et al. were able to show that despite strong signals from the skull bone and the brain tissues, the vessel can still be clearly recognized with 4:1 signal-to-noise contrast. (See figure 3)

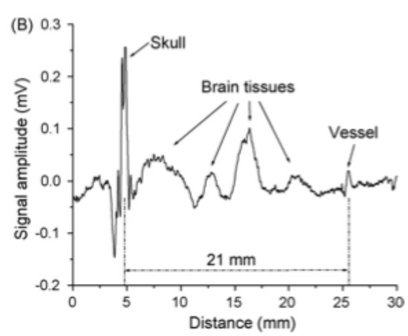

Figure 4: Vessel 21mm beneath skull

6.4 Dark-field Illumination: Dark-field illumination refers to an imaging technique where the light beam used in the illumination is ring-shaped. Wang et al. showed that using dark field illumination suppresses photoacoustic signals from the surface of the skull. However, a drawback of dark-field illumination is that less light is used, which results in less light penetrating the skull.

6.5 C-scan Imaging: Wang et al. imaged three vessels embedded along the x-y plane of the skull using 72 48 μm steps along the x-axis, and 43 50 μm steps along the y-axis. The resulting 3-dimensional C-scan image can be presented at different depths and was able to clearly show the three vessels with good signal-to-noise contrast.

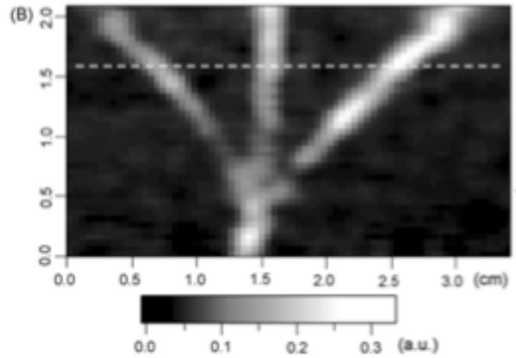

Figure 5: C-Scan Image of 3 vessels

6.6 Functional Imaging: Wang et al. also investigated the feasibility of estimating blood oxygenation level using PAI. While they showed that the measured blood oxygenation level correlated well with actual blood oxygenation level, the experiments were done without brain tissue as the brain tissue was found to distort the acoustic signal.

7. Critical Review

7.1 Good points

The paper made a well-constructed preliminary argument for why PAI could be a powerful tool for noninvasive diagnosis. It was able to bear down on the key points that would make PAI a suitable imaging modality, such as the imaging resolution, and the possibility of functional imaging. Specifically, the argument made use of experimental results that showed clearly that (a) PAI can produce high quality, high resolution images (b) when the technique is applied through a neonatal skull, and (c) that PAI may be able to determine and localize changes in blood volume and oxygen.

The paper also presented a system set-up that was easy to understand and provided the necessary details to replicate the system and the experiments. Though the experiments were simplified, Wang et al. did their best to replicate more realistic conditions through the design of their phantoms and their experiments.

7.2 Relevance to our project

The paper is important to our project chiefly because it provides the motivation as to why PAI should be chosen to do the intra-operative imaging in our system infrastructure. That their experiments were able to clearly image a vessel through the skull shows that PAI is sensitive to vasculature, which gives us confidence that it will be suited to our project.

The detailed description of the imaging system and the phantom and experimental design is also relevant to us because they could be adapted for our use in our experimental and simulation approach. For example, the single-cell transducer and scanning arc used will be adapted in our definition of a realistic sensor mask within our simulations.

Finally, the paper highlights possible challenges for our project. Firstly, the results from 6.2, 6.3 and 6.6 suggest that brain tissue, as well as skull, attenuates the acoustic signal. This could be problematic for our project because we want to be able to clearly detect the signal of the artery at a depth that may be greater than those used in the paper. This could also suggest that one of the dependencies related to the larger goal of our project would be to validate the assumption that the acoustic signal can be detected through a child's skull.

However, there are several key differences between our project and this paper that should be pointed out. Firstly, our project is concerned with skull base surgery in children, who are not necessarily in their infancy. Secondly, our project is not concerned with light attenuation since the laser is shone through the sphenoid area rather than through the top of the skull. Finally, in our case, the carotid artery is embedded further into the skull.

7.3 Limitations of the study

One limitation of the study is that the measurements were done in optimal conditions. For example, in the experiments for measuring resolution, the vessel was placed at the focal distance of the transducer, and the acoustic beam for signal detection was through the center of the light beam. However, in reality, it is unlikely that these conditions hold. To prove that PAI can be use in a clinical setting, the possible variance in the resolution has to be investigated.

Another limitation of the study is that the skull thickness was fixed at that of the infant skull that was used. Something that is interesting and particularly relevant to our project is the effect of variation in skull thickness. For PAI to be used in a clinical setting, the maximum skull thickness and the extent to which acoustic signal gets attenuated by different skull thickness should be studied.

A third limitation of the study is that only one vessel, or three vessels along the x-axis, were used in the experiments. However, in a more realistic brain, there are a lot more vessels present, and they might be present on different layers. This could affect both the light transmission and the acoustic signal, but the effects are not explored in the paper.

A final limitation of the study is that no direct comparisons were made between the quality of the images produced by PAI and by other methods such as other optical imaging modalities, CT scan and conventional ultrasound. Making direct comparisons to other technologies would help strengthen Wang et al.'s argument for the use of PAI.

7.4 Future Work

Future work for the study mostly involves overcoming the limitations detailed in 7.3. For example, to show that PAI is suitable for clinical use, experiments should be done in non-optimal settings to determine maximum depth and skull thickness. Furthermore, as pointed out in the discussion by Wang et al., system parameters should be optimized to maximize both spatial and temporal resolution. Finally, integration of other optical modalities could be done to take advantage of the information from each type of technology.

8. References

All images and data credit to **Wang X., Chamberland D. L., Xi G. 2008 Noninvasive reflection mode photoacoustic imaging through infant skull toward imaging of neonatal brains**. J. Neurosci. Methods 168, 412–421 unless otherwise indicated.