OPERATOR INDEPENDENT TRANSCRANIAL DOPPLER ULTRASOUND FOR CONTINUOUS MONITORING OF CEREBRAL VESSELS

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INTRODUCTION

Cerebral aneurysm refers to the localized dilation or ballooning of the cerebral artery due to weakening of the wall of blood vessels. Rupturing of cerebral aneurysms will lead to subarachnoid hemorrhage (SAH), which is a serious condition with a mortality rate of 30-60%. The primary treatment for this condition includes open surgery aneurysm clipping. Regardless of the treatment, patients suffering from SAH may undergo vasospasm, which is a condition when cerebral blood vessels spasm, leading to decreased oxygen delivery to brain cells.

Figure 1: Aneurysm

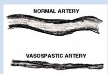

Figure 3: Comparison between a Normal and Vasospastic Artery

Figure 2: Ruptured Aneurysm

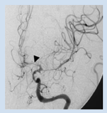

Figure 4: DSA Image of a Vasospastic Artery [1]

It is most likely to occur within 3-7 days after SAH, and rarely occurs after 14 days. Thus, continuous monitoring of the blood vessels within the first 3-14 days after SAH is desired to assess the presence of vasospasm. One characteristic of vasospasm is that the blood flow velocity inside the affected blood vessel increases. As a result, Doppler ultrasound is a good candidate for monitoring vasospasm. It is cost-effective, easy to use and potentially available on a continuous basis. However, the use of Doppler ultrasound suffers from operator dependence requiring a skilled ultrasonographer to make Doppler angle corrections. This implies that the use of TCD as a tool for monitoring requires the ultrasonographer on a continuous basis, which is not typically how the Neurological ICU works. Therefore, the aim for this research is to minimize the continuous need of ultrasonographer in the monitoring process. There is currently no off-the-shelf technology that allows the continuous monitoring of vasospasm. The development of the new TCD, if successful, will be an upgrade of the current TCD technology, which will allow the continuous monitoring of vasospasm after SAH without the need of an operator.

THEORY

The Doppler effect describes a phenomenon that there will be a change in the frequency of a wave perceived by the observer when the source, observer or both are moving relative to the sound wave. Doppler flow measurements have widely been used to determine blood flow velocities in clinical settings. Ultrasound waves are emitted into the blood vessels by the emitting transducer. The back scattering of the red blood cells can be detected by the receiving transducer. If the direction of blood flow makes an angle 'θ' with the direction of the propagation of ultrasound waves, this angle is called the Doppler angle. The Doppler frequency 'f_d' is the difference between the perceived frequency and the emitted frequency 'f_t'. Given that the velocity of blood flow 'v', and the speed of sound in blood 'c', the Doppler frequency can be found by:

$$f_d = \frac{2 f_t v \cos\theta}{c}$$

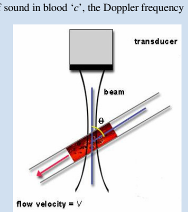

Figure 5: Doppler Ultrasound Parameters

Traditional 2D Dopper Ultrasound has widely been used. One major problem for 2D Doppler ultrasound is that it only provides information in 2D, eliminating the information in the third dimension; as a result, the velocity directly obtained may be the 'false velocity'. 3D Doppler ultrasound can provide a more complete picture of the blood vessel, and can provide information in the 'third dimension' that is not shown in 2D images. We are proposing a solution that allows the automatic measurement of the Doppler angle by using 3D power Doppler and pulse wave Doppler ultrasound.

ALGORITHM

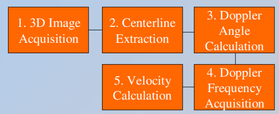

Figure 6: Flow Chart of the algorithm

1. Slices of 2D Power Doppler images were combined to a 3D image for the reconstruction of the blood vessel geometry
   - Power Doppler is used because it doesn't depend on Doppler angle
2. Binary skeletonization was used for the extraction of the centerline from the 3D geometry
   1. Set a threshold value of the image that separates between the vessel geometry (represented by '1') with the background (represented by '·')
   2. The vessel geometry is classified into the interior (represented by '2') or boundary voxels (represented by '1'). A boundary voxel is adjacent to a 'background voxel', and an interior voxel is a non-boundary voxel
   3. The boundary voxels are eliminated
   4. The process continues until no more boundary voxels can be eliminated

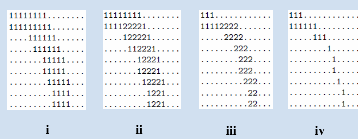

Figure 7: Steps of Binary Skeletonization

3. The Doppler angle at every single point of the centerline is calculated by using simple algebraic calculations
4. The Doppler frequency is obtained from the pulse-wave Doppler images
5. By combining the calculated Doppler angle and the Doppler frequency, the real blood flow velocity can be determined.

MATERIALS AND SETUP

A flow phantom was used for the development of the new Doppler ultrasound technique. It is made of graphite, glycerol, agar and water for moulding the phantom; and a tube made of silicone was placed inside the mould. Blood mimicking fluid was used for the flow medium, and pulsatile and steady flow were triggered separately. The photo of the flow phantom is shown in Figure 8. In order to demonstrate the feasibility of the new TCD on humans, blood flow velocity was obtained from the ICA of a human volunteer. The results were shown in the following section.

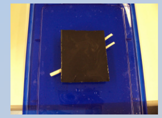

Figure 8: Photo of the Flow Phantom

RESULTS

Case 1: Steady flow inside the flow phantom. The result is displayed in Figure 9.

Case 2: Pulsatile flow inside the flow phantom. The result are displayed in Figures 10 and 11.

Case 3: ICA of a human volunteer. The results are displayed from Figures 12 to 15.

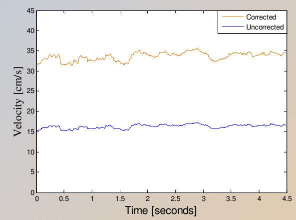

Figure 9: Velocity-time graph of the steady flow inside the flow phantom. It was obtained from using the implemented algorithm.

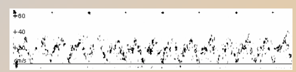

Figure 10: Velocity-time graph of the pulsatile flow inside the flow phantom. It was obtained directly by using traditional 2D pulse-wave Doppler with Doppler angle correction. This graph was used to compare with the velocity-time graph in Figure 11, where the implemented algorithm was used.

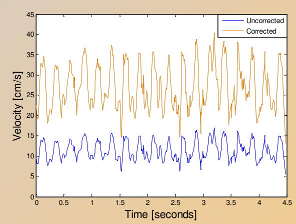

Figure 11: Velocity-time graph of the pulsatile flow inside the flow phantom. It was obtained from using the implemented algorithm.

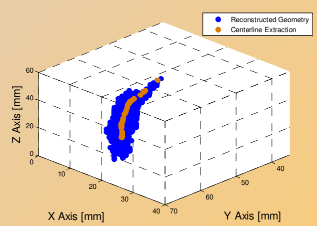

Figure 12: Reconstruction of vessel geometry and centerline extraction of the ICA

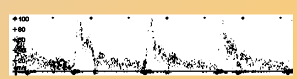

Figure 13: Velocity-time graph of the ICA. It was obtained directly by using traditional 2D pulse-wave Doppler with Doppler angle correction. This graph was used to compare with the velocity-time graph in Figure 14, where the implemented algorithm was used.

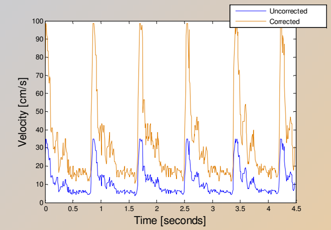

Figure 14: Velocity-time graph of the ICA. It was obtained from using the implemented algorithm.

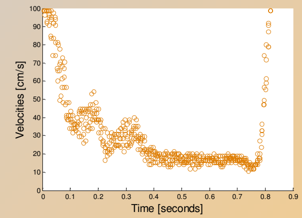

Figure 15: Synchronization of the corrected velocity in Figure 14 into one period

DISCUSSION

- Our results show that, without Doppler angle adjustments, the measured velocities tend to be smaller than the actual velocities, demonstrating the importance of Doppler angle correction
- In order to verify our results, the corrected velocities using the implemented algorithm were compared with the correct velocities obtained from other methods.
- Steady flow inside the phantom
  - The time average velocity obtained from the volumetric flow rate was used for comparison and verification
  - The time average velocity obtained from the flow rate was 30.05 cm/s, and the time average velocity obtained from using our algorithm was approximately 32 cm/s as shown in Figure 9
  - The percentage error is 6.5%
- Pulsatile flow inside the phantom and human ICA blood flow
  - The velocity time-graph obtained from traditional 2D pulse-wave Doppler is used as a comparison and verification
  - Figures 10 and 11 are the comparison for the pulsatile flow of the phantom, and Figures 13 and 14 are the comparison for the ICA blood flow

CONCLUSIONS

Through the use of a flow phantom, an algorithm was developed for the Doppler angle adjustments from 3D Doppler ultrasound images. In addition, the feasibility of the technique on the human ICA was demonstrated. The results obtained from the research is satisfying, and indicate that the operator independent monitoring of cerebral vasospasm is possible.

REFERENCES

[1] R. Loch MacDonald. Management of Cerebral Vasospasm. Neurosurg Rev (2006) 29: 179-193

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