Design and implementation of a flow phantom for assessing the accuracy of Transcranial Doppler Ultrasound (TCD) devices.

Justyna Janus[1], Fatmah Alablani[2], Edward Pallett[1], Toni M Mullins[3], Emma M L Chung[4]

[1]Medical Physics, University Hospitals of Leicester NHS Trust, UK
[2]College of Applied Medical Sciences, Prince Sattam bin Abdulaziz University, Saudi Arabia
[3]Medical University of South Carolina, USA
[4]Department of Women and Children's Health, King's College London, UK

Introduction

Accurate measurement of cerebral blood flow using transcranial Doppler (TCD) ultrasound is essential, particularly in managing conditions such as sickle cell disease[1-3]. Some TCD systems have been reported to produce slightly higher velocity readings than others, especially near the stroke prevention threshold in sickle cell patients. This study aimed to develop a flow phantom to assess the accuracy of velocity measurements across different TCD devices. We also aimed to compare time-averaged mean velocity (TAMV) and time-averaged mean maximum velocity (TAMMV) estimates based on imaging transcranial color Doppler (TCCD) and non-imaging TCD systems.

Method

A middle cerebral artery (MCA) flow phantom, connected to a programmable gear pump, was developed to evaluate velocity estimates from different TCD devices under controlled conditions (Fig.1). Three measurements were obtained for each of four clinically relevant flow conditions: very low steady flow (CPB), normal pulsatile flow (~55 cm/s), high steady flow (CPB), and very high pulsatile flow (e.g., as seen in sickle cell disease). TAMMV measurements were taken using two TCD systems (DWL and Spencer) and compared with TAMV values obtained by a Zonare (TCCD) scanner and a timed fluid collection method.

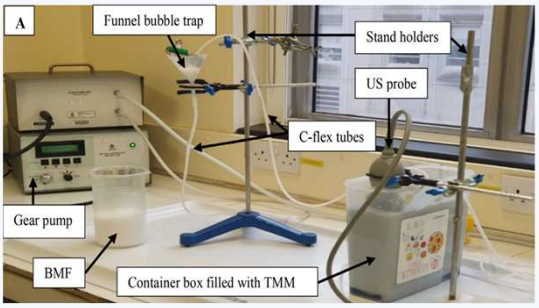


Figure 1. The experimental setup included a flow phantom connected to a gear pump. This was designed to simulate the hemodynamics of the middle cerebral artery (MCA).

Bland-Altman analysis was used to assess the inter-device bias. Paired t-tests were used for group comparisons, with significance accepted a p-value of <0.05.

Results

Phantom validation was performed by comparing waveform shape, backscatter intensity, and velocity with data from a healthy volunteer. The phantom was initially set up based on a typical MCA waveform with a mean velocity of 55 cm/s (Fig.2).

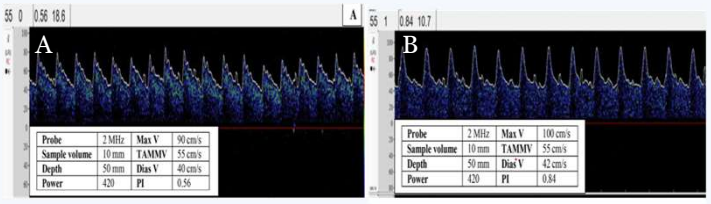


Figure 2. The programmable pump settings were adjusted until the flow rate in the phantom (A) closely matched that of the healthy volunteer (B).

The angle-corrected TAMVs obtained by TCCD did not differ significantly from the true mean flow velocities determined by timed collection at low (p = 0.5) and high steady flow (p > 0.9), as well as at normal pulsatile flow rates (p>0.9). TCCD measurements could not be performed at very high flow rates due to aliasing.

At low steady and normal pulsatile flow rates, the DWL and Spencer systems produced comparable results (p > 0.9). Significant differences were observed at high and very high flow rates, for both steady and pulsatile flow. DWL readings were consistently higher than those from the Spencer device (p = 0.03) (Fig.3).

Flow condition	TAMV estimate			TAMMV estimate		
	Timed-collection (gold standard) (cm/s)	TCCD ultrasound (cm/s)	Bias (%) (LoA) p value	Spencer (cm/s)	DWL (cm/s)	Bias (%) (LoA) p value
Low steady flow	9.05 (9–9.1)	9 (9–9)	0.5 (−0.6, 1.8), p = 0.5	18 (17–18)	18 (18–18)	1.9 (−4.5, 8), p > 0.9
Normal pulsatile flow	33 (32.5–33)	33 (33-33)	0.5 (−1, 2), p > 0.9	57 (57–57)	57.5 (57–58)	0.4 (−1.2, 2), p > 0.9
Flow during CPB	74.5 (74.3–74.5)	74 (74–75)	−0.13 (−1.9, 1.6), p > 0.9	107.5 (107–108)	111.5 (111–112)	3.7 (2, 5), p = 0.03
Very high pulsatile flow	152.4 (152–152.6)	N/A	N/A	195 (195–207)	207 (207- 218)	5.7 (4.8, 6.6), p = 0.03

Figure 3. Mean velocity estimates and agreement for each of the four flow conditions tested. CPB=cardiopulmonary bypass; LoA=limits of agreement.

TAMMV values from TCD systems were consistent with TAMV estimates based on timed collection when applying a scaling factor of 1.74 (assuming a 30° Doppler angle and laminar flow). At higher velocities, however, TAMMV and TAMV began to diverge, and the scaling factor no longer provided accurate alignment.

Conclusions

- ❑ Our in-house MCA flow phantom is a valuable tool for the quantification of differences in velocity estimates between different TCD devices.
- ❑ DWL measurements differed significantly from Spencer at high velocities, which is close to diagnostic threshold for stroke intervention.
- ❑ TCD and TCCD display different measures of velocity (TAMMV and TAMV, respectively); therefore, their diagnostic thresholds are not directly interchangeable.

Differences in velocity measurements between TCD systems at high flow rates may impact clinical decisions, particularly when evaluating stroke risk in patients with conditions such as sickle cell disease. Caution should be exercised when interpreting results near diagnostic thresholds, since measurement bias can vary depending on the system used.

References: [1] Ali MF. Transcranial Doppler ultrasonography: uses, limitations, and potentials. Egyptian Journal of Neurosurgery (2021) 36:20. [2] Alablani F, Janus J, Chung EML, et al. Development of a Flow Phantom for Transcranial Doppler Ultrasound Quality Assurance. Ultrasound in Medicine and Biology. 2022; 48(11):2302–2309. [3] Chou S, Alsawas M, et al. ASH 2020 guidelines for sickle cell disease: transfusion support. Blood Adv 2020; 4:327–355.