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Three-Dimensional Printed Flow Phantom Model of the Carotid Artery in Preterm Infants: Vessel Lumen Diameter Measurements Using Different Printing Materials

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ABSTRACT

Background: Diameter forms an integral part of blood flow measurement. This study aimed to explore different three-dimensional (3D) printed materials to develop flow phantom models of the carotid artery in preterm newborn infants and to investigate best materials for diameter measurement validation. Methods: We produced a 3D printed Doppler flow phantom model with vessel lumen diameter of

2.0 mm with varying vessel characteristics using data from 21 preterm infants (right carotid vessel lumen diameter, wall thickness, blood flow measurements using Doppler ultrasound and distance of the carotid artery from skin surface) examined for research or clinical purposes. Flow phantom vessel lumen diameters were measured by a single operator blinded to flow phantom diameter. <u>Results</u>: 15 diameter measurements were performed. Ultrasound measured vessel lumen diameter measurements resulted in underestimation of the true lumen diameter. The measured mean (SD, range) diameter was 0.163 (0.105, 0-0.420) mm. This study found that difference in vessel lumen diameter measurements were least with the hybrid material (FLXA9895-DM) with shore value of 95 in matte finish. Vessel wall thickness was systematically overestimated in the majority of the measurements {Anterior wall thickness, mean (SD, range) 0.145(0.081, 0.020–0.300) mm and posterior wall thickness, mean (SD, range) 0.103(0.117, minus 0.100–0.370) mm}. <u>Conclusion</u>: We successfully produced a 3D printed flow phantom model of the carotid artery in preterm infants with varying vessel characteristics and identified flow phantoms that produced the least difference in ultrasound measured vessel lumen diameter measurements. Researchers and clinicians can use this information for further studies involving ultrasound diameter measurements.

Keywords: 3-dimensional, 3D printed flow phantom, carotid artery, preterm infant.

INTRODUCTION

Three-dimensional (3D) printing has evolved over the years in different industries and has a growing application in various areas including medicine.(1-4) We previously produced 3D printed flow phantoms of the carotid artery of preterm infant for clinician training and research (5, 6) and compared flow volume measurements using the flow phantom using different ultrasound scanners. (7) The effect of vessel wall thickness, different 3D materials and the vessel wall finish (matte vs. glossy) may produce varying ultrasound imaging qualities especially with regards to vessel wall thickness and vessel lumen diameter measurements, the latter being an important parameter in flow volume calculations. There is a lack of data on the impact of different 3D printing materials and types of wall finish on imaging acquired using ultrasound. Prior unpublished work by this group, where ultrasound measurements were performed using different 3D printed materials (with varied vessel characteristics such as vessel wall thickness, vessel wall materials and vessel wall finish) to evaluate which 3D materials produced ultrasonographic imaging similar to ultrasonographic imaging seen in real life. We have noticed that finishes between matte and glossy are obvious to the eye: the glossy finish is shiny and appears smooth whilst, the matte finish is dull (non-reflective) and can appear rough / textured. Although, it is the same material, the finish appears to have an effect on the ultrasound images. Therefore, we speculate that 3D printing materials with glossy finish are more likely to produce greater ultrasound echogenicity resulting in improved dimension measurements.

One of aims of this work was to investigate different materials and print options to develop an improved / more accurate representation of the neonatal carotid artery. Variables that were used in this work include vessel wall thickness, vessel wall hardness (Shore A value) and vessel wall finish (matte or glossy). Durometer hardness (or Shore hardness) is a dimensionless unit of measure used to define the hardness of flexible elastomers or more rigid plastics. In all measurements, lumen dimeter was maintained at 2.0mm to enable comparison of the printing options.

In the original work(8), vessels with a 0.5mm wall thickness, Shore A-95 value with a glossy finish were developed. Wall thickness of 0.5 mm was chosen as this provided more stability to the vessel when the support material was removed. Anecdotally, the glossy walled vessels were easier to clean without damaging wall integrity. At the time of initial work, we were unable to make softer thinner walled vessels, as the vessels were frequently damaged when removing the support material from the lumen.

The support material is used to fill channels and overhangs in the print job, this needs to be carefully removed whilst not damaging the print. It is challenging to successfully remove the support material when developing soft-walled hollow vessel prints. Our initial flow phantom models made with polytetrafluoroethylene resulted in large hyperechoic vessel wall thickness which was dissimilar to ultrasound imaging of the carotid artery in human infants.(8) Since using different 3D printed materials and as our skills in cleaning the vessels developed, we investigated improving ultrasound appearance to carotid vessel wall thickness encountered in human infants. In an effort to improve the characteristics of the vessels such as vessel wall thickness, vessel wall hardness, vessel wall finish and real life like ultrasonographic echogenic appearance of the vessel wall to make them closer to the clinical case, we investigated vessels printed solely in Agilus30Black (Shore A-30 hardness value), (which was the softest material available to us), and FLXA9895-DM (Shore A-95 hardness value), which is the hardest rubber like material available to us. We therefore used materials at either end of the range.

The aim of this prospective observational study was to compare the vessel lumen diameter and vessel wall thickness in our flow phantom models to the carotid artery of the preterm infants using ultrasound.

METHODS

The phantom was designed and produced in the Clinical Physics Department.

Data Collection for Designing Flow Phantom

The physical characteristics of the right common carotid artery in human preterm infants was collected from twenty-one infants who were admitted to the tertiary level neonatal intensive care unit. As part of standard routine care, cerebral blood flow measurements were also performed in some infants as part of haemodynamic assessment when functional echocardiography and cranial ultrasound scans were performed. Some of the scans were obtained from infants who were recruited to a blood pressure study that had ethics committee approval.(9) The information from this clinical work was used to design the phantom. Vessel wall thickness was explored but particular focus was placed on the vessel diameter, depth and orientation of the vessel from the skin surface so as to replicate the clinical situation as much as possible and to aid with training operators of varied experience to perform measurements using the flow phantom.

Data Used for Designing Flow Phantom

From images obtained with an 7-15 MHz ‘hockey-stick’ linear array probe using Phillips ultrasound system (Buckinghamshire, UK) with the transducer placed over the anterior triangle of the neck, the following data were collected about the physical characteristics of the right common carotid artery (Figure 1):

- d – cross sectional diameter of the blood vessel (cm)
- Tp – proximal depth of the blood vessel from skin surface (cm)
- Td – distal depth of the blood vessel from skin surface (cm)
- L – distance between Tp and Td measuring points (cm)
- Φ – angle formed between blood vessel and skin surface, calculated using the following formula;
- $\Phi = \tan^{-1} (Td-Tp) / L$

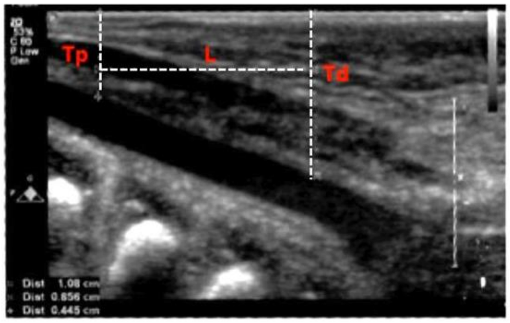


Figure 1: Ultrasound of the right common carotid artery in a preterm human infant, where Tp is the proximal depth of the vessel from the skin surface, Td is the distal depth from the skin surface and L is the distance between Tp and Td.

Flow Phantom Production

Flow Phantom Design:

All 3D printed components were developed using SolidWorks 3D CAD drawing software (Standard, SP0.0, 2022: Waltham, MA, USA) and printed on an Objet 260 Connex 3D printer (Stratasys, Eden Prairie, MN, USA). Five 3-chamber models were developed (Figure 2A-B), the phantom model encasement was 3D printed using VeroWhitePlus, which is a rigid general-purpose material.

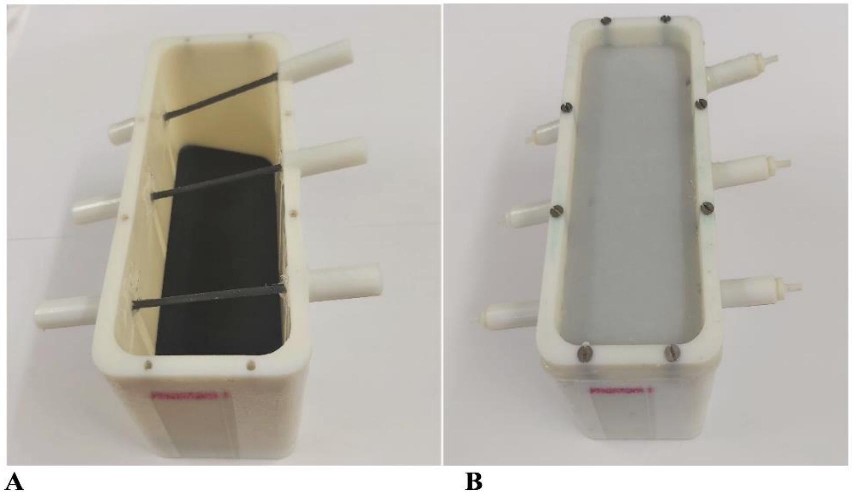


Figure 2: (A) Three-chamber phantom flow model (original printed phantom) – all components shown were 3D printed. (B). Phantom model filled with tissue mimicking material (TMM) and covered with low density polyethylene (LDPE) plastic.

The dimensions of the phantom (150 x 55 mm, 90 mm height) were designed to work with the hockey-stick linear array transducers used in neonatal intensive care. Vessel supports protruded from either side of the chambers, with a central channel to hold the 3D printed neonatal carotid artery. These supports maintained the vessels at the correct position, relative to the phantom surface. Various phantom vessel with an internal diameter of 2 mm were used, reflecting the diameter of the carotid artery seen in preterm infants at Φ of 15°.(8) The internal base of the phantom, consisted of an angled and soft surface made from Agilus30Black (soft rubber like material), to minimise reflections of the ultrasound energy back to the transducer.

Each vessel was 3D printed using a digital material mixture of VeroWhitePlus and Agilus30Black or solely Agilus30Black. The digital material was the result of combining these two materials, in specific concentrations to create a composite material with hybrid characteristics. The vessels used in this study had a Shore-A: 30 or 95 hardness values on the Durometer Shore hardness scale, with varying vessel wall thickness ranging from 0.25mm to 0.5mm. This range of vessel wall thickness was chosen for pragmatic reasons as the support material could be removed without affecting the vessel. The Shore A hardness scale (0-100), is used for measuring softer rubbers and measures the hardness and flexibility of a wide range of materials - lower numbers represent softer and flexible materials, with harder materials at the upper end of the range.

The vessels were encased in an agar and glycerol-based tissue mimicking material (TMM).(10) The phantom vessel was embedded in the TMM at a depth of 10 mm from the phantom surface to the upper point of the 3D printed vessel mimicking real life. The top of the phantom was sealed with a 1.0 mm layer of low-density polyethylene (LDPE) plastic (PSG Group Ltd, London, UK), which minimised desiccation, and thereby increased phantom lifetime. Each vessel was printed with two removable formers (made from VeroWhite) which were positioned centrally in the vessel (Figure 3). The formers could be carefully removed from each vessel (Figure 4).

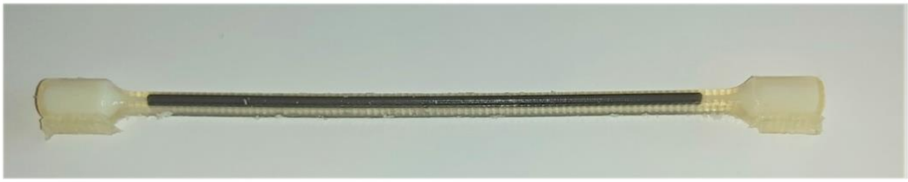


Figure 3: 3D printed carotid vessel removed directly from the printer. Showing the formers within the vessel lumen, with the model surrounded by support material.

Figure 4: The cleaned 3D printed carotid vessel with the formers removed.

The purpose of the formers was to minimise the quantity of support material to be removed after printing. Subsequently, precision ground rods of increasing diameter were inserted through the vessel, to provide assurance that no residual support material was left in the vessels. Additionally, the rods provided assurance that the vessel lumens were of the correct specified dimensions. Vessel lumen diameter was confirmed by inserting ground rods of 2 mm through the vessel prior to placing in the phantom. These rods are used to push / clean the lumen of the vessels – removal of the support material. The printer has an accuracy of 16 microns.

Testing the Flow Phantom:

The flow phantom was set up in the neonatal unit where the ultrasound scanner was housed. Blood mimicking material (Model 707, ATS Laboratories, Norfolk, VA USA) with a density of 1004 ± 10 kg/m^3 was run through the flow phantom. The flow was adjusted by varying the height of the reservoir containing the blood mimicking fluid or by adjusting the outflow valve attached to the end of the line. This produced continuous flow through the circuit.

Flow Phantom Diameter Measurements

Diameter is an important parameter as any error occurring during measurements are squared when calculating flow volume. Therefore, the emphasis for this work was to explore the ideal points from which to measure the vessel diameter with 3D printed materials of varying characteristics which were likely to produce differing echo densities on ultrasound. Hence, flow measurements were not carried out and are beyond the scope of this paper. All diameter measurements were performed with an 8-18MHz ‘hockey-stick’ linear array transducer using GE Vivid S70N ultrasound system (GE Healthcare). This probe has a maximum lateral resolution of ≤ 1 mm (depth <40 mm), and an axial resolution of ≤ 0.5 mm (depth <40 mm). Diameter measurements were performed by a single observer, blinded to manufactured diameter of flow phantoms on the 28th February 2023.

Ultrasound Image Optimisation Used for Diameter Measurements

After placing an adequate amount of water-based ultrasound jelly on the flow phantom, the cross-sectional view of the vessel was obtained, represented by the presence of 2 echogenic areas in the vessel wall (Figure 5A). These brighter areas were seen when the scan plane was perpendicular to the vessel, representing the stronger reflections from ultrasound striking a surface at right angles, confirming that a perpendicular measurement of diameter was being performed. The zoom function in the ultrasound machine was utilised to increase image size. Focus range was adjusted to include the whole vessel with focus midpoint aligned to the vessel midpoint. Gain settings were adjusted to an appropriate level to visualise the vessel lumen. The image was frozen and scanner calipers used to measure the vessel diameter.

Measurement Points for Diameter Measurements

Both the walls of the 3D printed vessel could be visualised. The brightest echogenic signals from the internal walls had a leading edge, centre and trailing edge (these all represented an internal wall signal and did not represent the leading and trailing edge of the vessel wall itself) (Figure 5A). Measurements were performed from the leading edge to centre (Figure 5B).

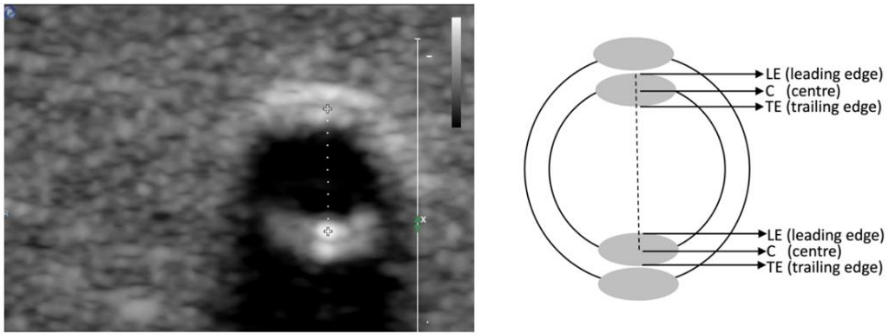


Figure 5: (A) Cross section of the vessel in the flow phantom. (B) Schematic illustrating the leading edge (LE), centre (C) and trailing edge (TE) of the echodensity from where measurements are taken.

Statistical Analysis

Normality of data was examined using Shapiro-Wilk test. Data following Gaussian distribution was summarised as mean, standard deviation (SD) and range. One-way analysis of variance was undertaken for all measurements carried out using all 3 chambers and all 5 phantoms. All statistical analyses were carried out using GraphPad Prism v10.2.3.

RESULTS

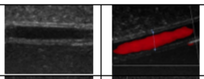
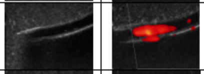
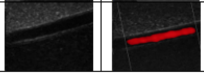
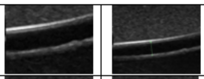
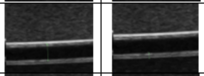
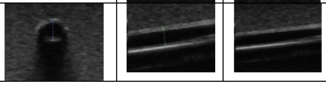
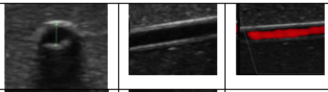
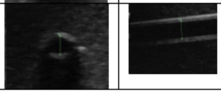
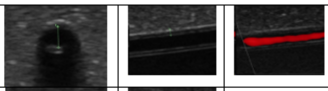
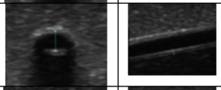
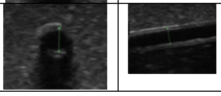
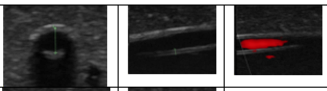
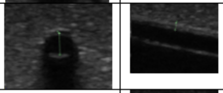
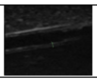
A total of 15 measurements were performed using 5 different flow phantoms with varying wall thickness, wall material and hardness and wall finish (Table 1). All phantoms had a lumen diameter of 2 mm reflecting diameter measurements of the right common carotid artery in preterm infants.

Ultrasound measured vessel lumen diameter measurements resulted in underestimation of the true lumen diameter with the measured mean (SD, range) vessel lumen diameter being 0.163 mm (0.105, 0 – 0.420 mm). Differences in vessel lumen diameter (actual diameter minus ultrasound measured) measurements were least with hybrid material with shore value of 95 in matte finish (Figure 6). Vessel wall thickness was systematically overestimated in the majority of the measurements. The Anterior wall thickness mean (SD, range) measurement was 0.145 mm (0.081, 0.020 – 0.300 mm) whereas posterior wall thickness mean (SD, range) measurement was 0.103 mm (0.117, minus 0.100 – 0.370 mm).

Flow phantom A with matte finish had the least difference in lumen diameter measurements with ultrasound. The difference was lower with the hybrid wall material (FLXA9895-DM) when compared to Agilus30 Black (Figure 6). On the other hand, the difference between ultrasound measured diameter and phantom lumen diameter was largest with glossy finish. All ultrasound diameter measurements underestimated the true lumen diameter.

One-way analysis of variance for all vessel lumen diameter measurements across the three chambers were not statistically significant ($p = 0.16$) as were the vessel lumen diameter measurements across all five phantoms ($p = 0.07$).

Table 1: Vessel parameters along with the difference in measurements for the various flow phantoms.

Flow phantom/ 3D printing information							Measurements from ultrasound scanner				Difference in measurements		
Phantom	Chamber	Lumen diameter (mm) {i}	Wall thickness (mm) {ii}	Wall material	Wall hardness (Shore A value)	Wall finish	Lumen diameter (mm) {iii}	Wall thickness (mm) – anterior {iv}	Wall thickness (mm) – posterior {v}	Images from scanner	Lumen diameter – measured lumen diameter (mm) {i – iii}	Wall thickness – measured anterior wall thickness (mm) {ii – iv}	Wall thickness – measured posterior wall thickness (mm) {ii – v}
A	1	2.00	0.35	Hybrid	95	Matte	2.00	0.44	-		0.00	-0.09	-
	2	2.00	0.30	Hybrid	95	Matte	1.93	0.54	0.56		0.07	-0.24	-0.26
	3	2.00	0.30	Agilus	30	Matte	1.82	0.50	0.48		0.18	-0.20	-0.18
Mean (SD)											0.08 (0.09)		
B	1	2.00	0.40	Hybrid	95	Glossy	1.96	0.49	0.51		0.04	-0.09	-0.11
	2	2.00	0.45	Hybrid	95	Glossy	1.86	0.60	0.49		0.14	-0.15	-0.04
	3	2.00	0.45	Hybrid	95	Matte	1.86	0.48	0.82		0.14	-0.03	-0.37
Mean (SD)											0.11 (0.06)		
C	1*	2.00	0.25	Hybrid	95	Glossy	-	-	-	Vessel blocked – unable to scan	-	-	-
	2	2.00	0.30	Hybrid	95	Glossy	1.58	0.45	0.42		0.42	-0.15	-0.12
	3	2.00	0.35	Hybrid	95	Glossy	1.77	0.43	0.40		0.23	-0.08	-0.05
Mean (SD)											0.33 (0.13)		
D	1	2.00	0.50	Hybrid	95	Glossy	1.80	0.72	0.58		0.20	-0.22	-0.08
	2	2.00	0.50	Hybrid	95	Matte	1.80	0.52	0.50		0.20	-0.02	0.00
	3	2.00	0.40	Hybrid	95	Matte	1.82	0.50	0.50		0.18	-0.10	-0.10
Mean (SD)											0.19 (0.01)		
E	1	2.00	0.50	Agilus	30	Glossy	1.93	0.67	0.54		0.07	-0.17	-0.04
	2	2.00	0.40	Agilus	30	Matte	1.85	0.70	0.30		0.15	-0.30	0.10
	3	2.00	0.35	Agilus	30	Glossy	1.74	0.54	0.44		0.26	-0.19	-0.09
Mean (SD)											0.16 (0.09)		

*Vessel C1 – this vessel stopped working during the measurement – softest and thinnest vessels used.

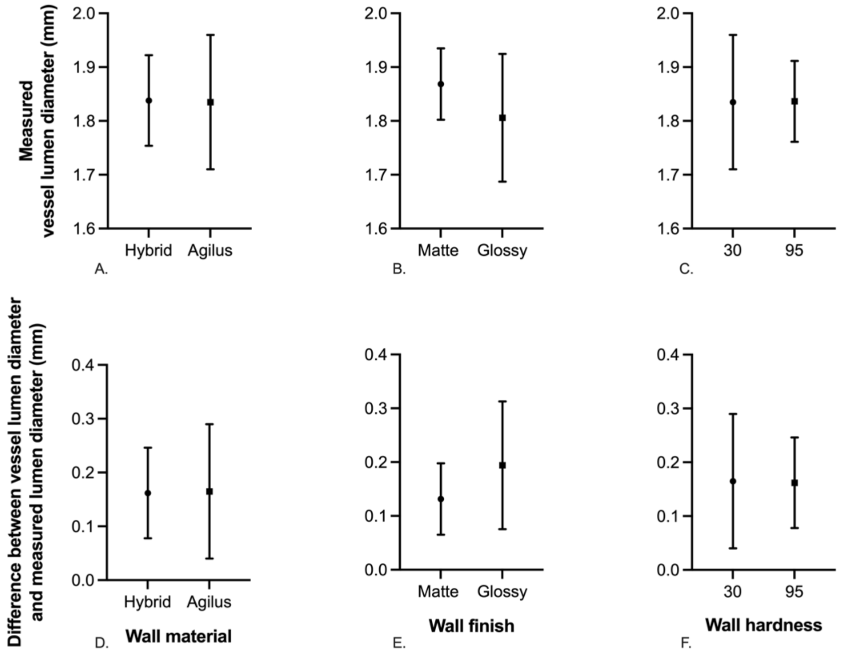


Figure 6: Measured vessel lumen diameter compared with different wall material (A), wall finish (B) and wall hardness (C). Lower panel shows the difference between vessel lumen diameter and measured lumen diameter compared with different wall material (D), wall finish (E) and wall hardness (F). All values are mean with 95% confidence intervals.

Wall thickness measurements were overestimated using ultrasound for the majority of the measurements. Posterior wall thickness measurement differences were generally lower when compared to anterior wall thickness measurements (Table 1). Colour flow was demonstrated in the majority of flow phantoms but appeared to fill the vessel lumen in flow phantom A with no obvious acceleration due to debris related to residual support material.

DISCUSSION

We designed and produced a 3D printed flow phantom model of the common carotid artery in preterm infants using different materials resulting in flow phantoms with varying characteristics such as vessel wall thickness, vessel material, vessel hardness and vessel wall finish (matte or glossy). Ultrasound measured lumen diameters underestimated the true flow phantom lumen and was lowest with hybrid material (FLXA9895-DM) with a Shore value of A-95 in matte finish.

Our prior experience showed that with 3D printed flow phantoms vessels with a glossy finish, elimination of residual support material was more successful resulting in ‘uniform’ vessel margins, with reduced damage of the vessel walls. The acoustic properties of the 3D printed material used in the study has been examined previously(11) and has also been shown that with softer 3D printed material the difference in the speed of sound or impedance is not markedly different. This resulted in accurate diameter estimations at different points and importantly laminar flow without acceleration due to debris. Elimination of support material was more challenging using smaller caliber vessels made from lower Shore A values (softer) and those with thin walls. This was not demonstrated here possibly due to small sample size and single lumen diameter of 2 mm. The diameter was kept constant to examine the effects of the various materials used to produce the flow phantom.

Although, we were able to produce vessels that were more representative of those seen in clinical cases (softer and thinner walls), the printed vessels are a compromise between a vessel that is representative of the clinical case, with one that has good echogenicity and results in accurate dimensional measurements. If the lumen is unable to be measured accurately, it will impact the flow measurement – this will influence and limit the use of 3D printed vessels in training phantoms.

This study has several limitations. We only performed single measurements by a single operator. Emphasis was placed on the diameter measurements, an important parameter in flow volume measurement. Therefore, we did not perform flow volume measurements. The diameter of the lumen was kept constant at 2 mm in order to study the various materials used to produce the flow phantom and limit the influence of varying lumen diameter on ultrasound measurements. We did not explore the distensibility of the 3D materials that one would expect to see with pulsatile flow as this work primarily focused on different printing materials.

This study examined diameter values which were realistically seen in preterm infants. The operator was well versed with performing these measurements both in the clinical and research setting which reduced variance that one may expect to see with multiple operators.

This study found that 3D material of hybrid material (FLXA9895-DM) with matte finish and a shore value of 95 produced the least difference between vessel wall lumen diameter and ultrasound measured lumen diameter. This information could be used for future phantom development and research in this area.

CONCLUSION

We produced a 3D printed flow phantom model of the carotid artery in preterm infants using various 3D materials. Ultrasound measured diameter tend to underestimate the true lumen diameter, but differences from the true value were lowest with the hybrid material and matte finish. Researchers could consider the 3D printing materials and other vessel characteristics used in this study to design larger studies.

DECLARATIONS

Competing interests: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Ethical approval: The majority of scans were done as part of standard routine care for which verbal consent was obtained and some of the scans were from infants recruited to a blood pressure study had received ethics committee approval from the London-Surrey Borders research ethics committee (reference 12/LO/1553) on 21st November 2012.

Guarantor: AS and JR**

Author Contributors: SP, AS, ASA JR, MB, SK researched literature and conceived the study. SK, SP, AS, ASA, JR collected data for designing the flow phantom. SP, SK, AS, ASA JR, MB designed the flow phantom and JR and MB built the flow phantom. AS performed the measurements on flow phantom. SP, AS, ASA, and SK did the data analysis. SP wrote the first draft of the manuscript. AS, ASA, JR, MB and SK wrote the final version of the manuscript. All authors reviewed and approved the final version of the manuscript.*

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