Review Article

A Brief Review for Common Doppler Ultrasound Flow Phantoms

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Abstract

In this review, the flow phantoms and the wall-less flow phantoms with recognized acoustic features (attenuation and speed of sound), interior properties, and dimensions of tissue were prepared, calibrated, and characterized by Doppler ultrasound (US) scanning which demands tissue-mimicking materials (TMMs). TMM phantoms are commercially available and readymade for medical US applications. Furthermore, the commercial TMM phantoms are proper for US purpose or estimation of diagnostic imaging techniques according to the chemical materials used for its preparation.

Keywords: Doppler ultrasound scanning, flow phantoms, ultrasonography, wall-less flow phantoms

Introduction

Flow phantoms

Phantoms are usually utilized to check (calibrate) and characterize ultrasound (US) scanning systems and to confirm their performance weather it matches with quality standards [Figures 1 and 2]. Moreover, the phantoms are applied to evaluate the development of modern probes, new medical imaging modalities, and medical diagnostic and image processing techniques.[1-6]

Several techniques have been advanced to pattern vascular acoustically (vessel) structures and with main concern on prime (large) arteries, such as the coronary and carotid artery [Figure 3]. Flow phantoms are classified into three general classes: walled flow phantom, which has a closer similarity to the vessel arteries; basic (simple tubular structure) flow phantom (with no classes); and wall-less flow phantom, which does not have tubing separating the tissue-mimicking material (TMM) and blood-mimicking fluid (BMF). Moreover, several studies revealed the made of phantoms from the real human vessels which harvested from cadavers (bodies). However, the main disadvantages of flow phantoms include the flow patterns, limited longevity, expensive (high cost), and inconstant geometries.[7,8]

Flow phantom is a model of TMM with a vessel-mimicking material (VMM) surrounding it during pumping of BMF.[9-14] The acoustical features of the different ingredients of the flow phantom correspond to the acoustical features of human blood, tissue, and vessel, and as required and identified by the IEC 61685 standard 1999, it can be applied for a proper BMF and TMM.[14] However, when the tubing materials are lacking acoustic properties, the deformation of the Doppler spectrum will lead to the refraction at the vessel wall[15] and attenuation.[16]

Regarding acoustical and physical properties, the most convenient tubing materials are known as C-flex™. This type of tube has an attenuation of 58 dB/cm at 8 MHz and a velocity of sound of 1557 m/s.[16,17] Even the C-Flex tubing has a sound velocity (Vs) identical to human tissue, the attenuation of C-Flex is nearly ten times greater than the tissue.[18,19]

Moreover, the Doppler test flow (in stand-alone systems and the Doppler part of duplex scanners) phantom was used to describe Doppler US systems. The development and compatibility of a Doppler flow test object to the actual values of the IEC

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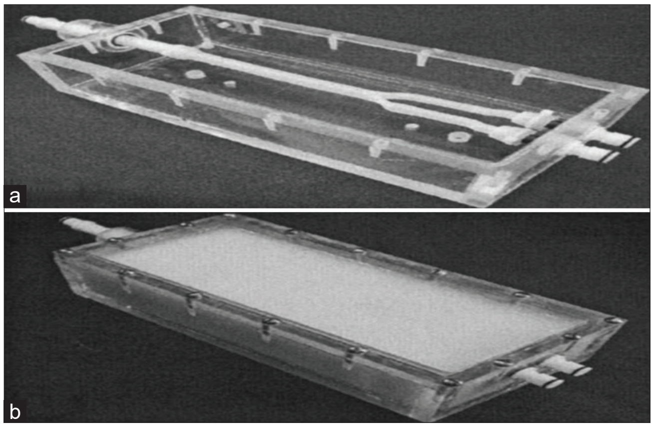

Figure 1: Pictures of (a) a Sylgard carotid vessel mounted in the acrylic phantom box with the metal core prematurely melted out for demonstration purposes, and (b) the completed phantom sealed with a Lexan lid and frame[1]

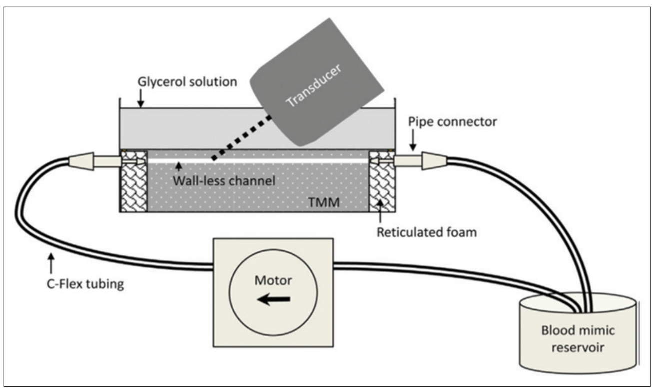

Figure 2: Schematic diagram of the flow phantom illustrating acquisition of Doppler measurements[28]

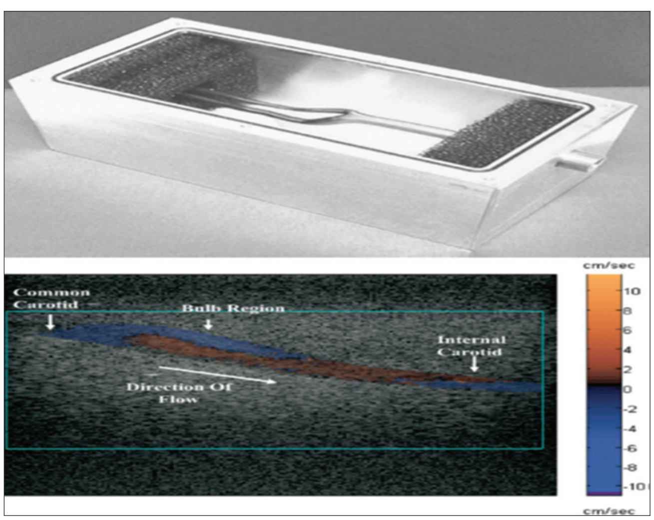

Figure 3: Photograph of a phantom container with reticulated foam surrounding the connectors. Moreover, color Doppler ultrasound image showing the flow recirculation occurring in the bulb region of a phantom carotid artery[32]

1685 was carried out. However, Doppler flow phantom was composed of five main parts: tube (VMM), TMM, BMF, flow pump, and tank. The tube allows a link between the BMF with TMM and the carrying of the blood. The acoustical and physical properties (backscattering, viscosity, sound velocity, density, and α) of these parts were agreed with IEC 1685 values.[16,19-27]

Vascular wall-less flow phantoms

Wall-less flow phantom is a VMM which allows the BMF to an immediate link with the TMM with no tubing material applied to fabricate it. There are several factors to consider for the fabrication of a vascular wall-less flow phantom, such as depth, flow waveform (straight, tortuous, oblique), flow rate, and sizes (diameters) of the vessel. For a clinical *in vitro* application, the ideal vessel diameters between 3 mm and 10 mm are recommended and should mimic human vessels. For preclinical uses, the vessel diameters are ideally between 0.5 and 2 mm and should mimic rat and mouse vessels. For a clinical *in vitro* application, the highest phantom dimension is ideally between 150 and 300 mm; however, for preclinical application, the range is between 50 and 100 mm. The dimensions of preclinical flow phantom are usually less than that of clinical flow phantom.[14,28]

In another study, Allard *et al*. (1999) investigated wall-less flow phantoms that made of 9.52 mm as a vessel diameter. The TMM made of a mixture of 8% glycerol, 3% of the very strong agar gel, and 89% of distilled water, was the acoustic speed of TMM which was identical to that of soft tissue. The metal rod worked like the mold for the vessel. Vessel lumen preserved in its original form throughout time, and the wall-less flow phantom was not absorbing H_2O. To prevent drying of the agar gel and potential deformation, the phantom was maintained in a water bath. Experimental researches were carried out at room temperature in a horizontal constant flow loop sample. A linear array transducer with 4-MHz (L7-4) was utilized to generate Doppler scan images.

In a previous study, Poepping *et al*. (2004) prepared a VMM, which is composed of both silicone (polydimethylsiloxane) and elastomer (Sylgard 184). The setup is integrated by a base and a treating factor permitting the mixture to treat for 7 days at specific temperatures ranging between 25°C and 35°C. Four mixtures of cellulose particles with 50-µm as a scatter with different concentrations by weight (0%, 1%, 3%, and 5%) were added and examined for relevant properties, including the Vs, visual appearance, and attenuation with the B-mode US image. Furthermore, the TMM used a different material mixed with a specific amount by weight, such as silicon carbide (SC), aluminum oxide (Al_2O_3), formaldehyde, high-gel strength agar, glycerol, and distilled water to obtain a proper Vs, backscatter, and attenuation properties. The pulse transmission mechanism was used to measure the TMM attenuation coefficients for Sylgard 184 mixtures. All measurements were conducted through pulse echo single-element unfocused probe and pulse which extend from 2 to 7.5 MHz at room temperature. The attenuation coefficient of TMM at 5 MHz was 0.56 dB/cm and MHz with Vs of 1539 m/s.

Vascular wall-less flow phantom is applied for the evaluation and estimation of Doppler US. Thus, the image distortion results from the tube walls are declined using phantoms. Homogeneous flow phantom was structured by the European Commission Project (ECP) agar-based TMM; it also featured Al_2O_3, benzalkonium chloride, SC, H_2O, and glycerol. This vascular wall-less flow phantom was reported to have the suitable strength (durability) and longevity to flow. However, the agar-based TMM was subjected to rupture at the bifurcation top (apex).[29,30]

Wall-less flow phantoms for a clinical study (7.9 mm) that made of metal core containers with dimensions of 10 cm × 10 cm × 23 cm were mounted in melting temperature of 69°C. Before pouring, the phantom was fixed with reticulated foam and put around the connectors. TMM was composed of agar, then poured into the container, and let it set. However, the limitation of using the agar-based TMM was due to leakage the BMF during a high flow rate. The problem was solved through the expansion of a new powerful TMM relied on the utilization of two types of gels; Konjac carrageenan (KC) was used instead of agar. The ingredients by %weight was K powder, C powder, Al_2O_3 powder 3 μm, Al_2O_3 powder 0.3 μm, H_2O, 400 grains SC powder, glycerol, and Pc powder which used to adjusting the temperature of the gel with %weight of 1.5%, 1.5%, 0.96%, 0.89%, 84%, 0.54%, 10%, and 0.7%, respectively. Several items were estimated as a portion of the ECP which made the TMM. The brand of US scanner equipment (Meagher *et al*., 2007; Watts *et al*., 2007) used for examining the flow phantom was named HDI 5000 Philips Medical US system. The system is provided with linear array transducer L12-5 to scan the flow channels, collect longitudinal imaging of all areas, and measurement of flow. The acoustical properties of TMM were perfect, and it is meeting the requirements of IEC 1685 draft report. At room temperature, it had a velocity of sound of 1550 ± 6 m/s and attenuation (dB/cm) behavior 2.81 ± 0.08 with 5 MHz as a frequency.[31,32]

The great-strength agar is utilized because it produces TMM with firmer and more robust and thus, the likelihood of breakage or tear will decrease when exposed to the strength of high-flow rates. TMM was prepared by mixing H_2O, SC, Al_2O_3, benzalkonium chloride, glycerol, and Struers agar materials continuously with a magnetic stirring rod. It was then cooled to 42°C with the keep of stirring and then poured the mixing materials into the test container. The VMM was made by casting the metallic rod inside the wall-less TMM channel with about 8-mm diameter. US scanner equipment (HDI 5000 Philips with linear array transducer L12-5) used for examining the flow phantom was the same equipment used in the previous studies by Meagher *et al*. (2007). The acoustical properties of TMM were perfect, and it is meeting the requirements of IEC 1685 draft report. At room temperature, it had a velocity of sound of 1541 ± 3 m/s and an attenuation (dB/cm) behavior 0.5 ± 0.03 with nearly 3–10 MHz as a frequency.

Fabrication of wall-less flow phantoms is necessary to prevent problems that resulted by US deformation through the tube wall.[14,28] TMM was created by utilizing two hydrogel materials, namely KC. The KC is composed of two organic materials and was added with H_2O to produce a flexible and strong material. TMM is prepared by mixing SC, Al_2O_3, glycerol, and KC materials. The KC-based TMM had a velocity of sound of 1548 ± 3 m/s and attenuation (dB/cm) behavior of $0.01024f^2 + 0.3639f$, where f is transferred frequency (MHz).[14,32]

Vascular wall-less flow phantom for preclinical study (1 mm) was fabricated. The phantom was made of the plastic box and connected with plastic pipe connectors to allow the connection of the BMF reservoir with a flexible tube. A straight rod supplies a mold to mimic the vessel. Thus, as the rod is removed from the KC-based TMM, it will simulate the vessel VMM shape. Therefore, the blood can be pumped through the VMM. The phantom size is determined by the size of the container and the rod. For avoiding leaking of the BMF, the pipe connectors are fixed with the KC-based TMM using a reticulated foam. However, the main drawback of the KC-based TMM is that it is not adequate for long-term storage.[14] Instruments and recipes required in preparing TMM (KC-based TMM) were listed and mentioned in a previous study [Figure 4 and Table 1].[32]

Currently available wall-less flow phantoms (commercial)

Shelley's TMM (anthropomorphic) carotid bifurcation flow phantom is designed to very carefully and accurately simulate complex geometries' physiological vessel and is compatible with Doppler US. TMM was created using agar-based TMM. Length, width, and height of this phantom are 265 mm × 120 mm × 65 mm, respectively. The scatter particles are added to the VMM to enhance echogenicity and speckle pattern. The acoustical and physical properties were suitable [Figure 5].[33]

Doppler flow phantom with model U-245-based TMM designs for the evaluation and estimation of diagnostic Doppler US. The phantom model U-245 has a long-lasting TMM (urethane) and mix two wall-less flow vessels (agar-based TMM). The vessel size is 8.0 mm and was placed horizontally

Figure 4: Konjac carrageenan-based tissue-mimicking material flow phantom used with the Visualsonics Vevo 770 preclinical scanner[14]

Table 1: A summary for phantom materials

Material name	Materials abbreviations	Manufacture	Concentration weight%	Main function
Water	H_2O	Medical physics laboratory (USM)	84.0	To mimic the H_2O concentration in the tissue
SC (400 grain)	SC	Sigma-Aldrich	0.53	To modify the backscatter and allow it to mimic tissue
Al_2O_3 powder 3.0 µm	Al_2O_3	Sigma-Aldrich	0.96	To affect the attenuation, with a linear dependence as a function of frequency
Al_2O_3 powder 0.3 µm	Al_2O_3	Sigma-Aldrich	0.89	To affect the attenuation, with a linear dependence as a function of frequency
Gelatin (bovine skin)	Gelatin	Sigma-Aldrich	0.92	To increase the robustness and strength of TMM, and to mimic the human/animals tissue
Konjac powder	K	11 street company	1.5	To mimic the human/animals tissue Its acoustically can be distinguished through the clinical application frequencies
Carrageenan powder for gel preparation (Type I)	C	Sigma-Aldrich	1.5	To mimic the human/animals tissue Its acoustically can be distinguished through the clinical application frequencies
Potassium chloride	Pc	Sigma-Aldrich	0.7	To adjust the melting and setting temperatures of the gel. And, used for fertility the TMM
Glycerol	Glycerol	Sigma-Aldrich	9.0	To provide the required speed of sound

TMM: Tissue-mimicking materials, Al_2O_3: Aluminum oxide, SC: Silicon carbide

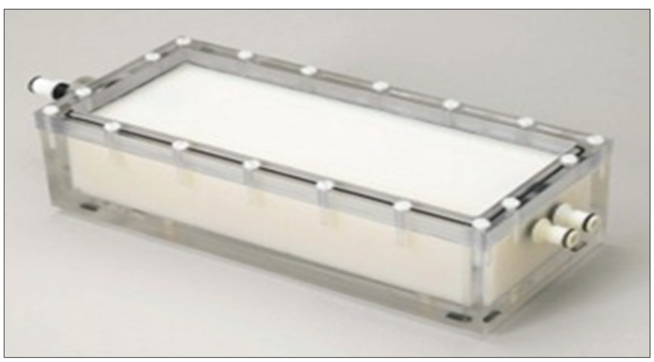

Figure 5: Ideal flow phantom for Doppler and color Doppler flow research and development applications[33]

2.0 cm below the scanning surface mimicking the common carotid artery and a 4.0 mm vessel. The flow phantom was connected to Shelley gear motor pump system; the BMF has filled the pump and produces the most accurate, repeatable, and realistic flow waveforms for Doppler US testing. Overall dimensions (length, width, and height) of this phantom are 17 cm × 10 cm × 21.5 cm, respectively. The acoustical properties were suitable and agreed the requirements of IEC 1685 [Figure 6].[34]

Gear (motor) pump system

Multiflow gear pump system has many properties that make it typical to produce steady and pulsatile flow, such as a fast temporal response, loss of backflow, and capacity to monitor gear pump velocity. A multiflow gear pump system is available which provides several of the flow output, allowing make of flow phantoms suitable with a different range of flow rates.

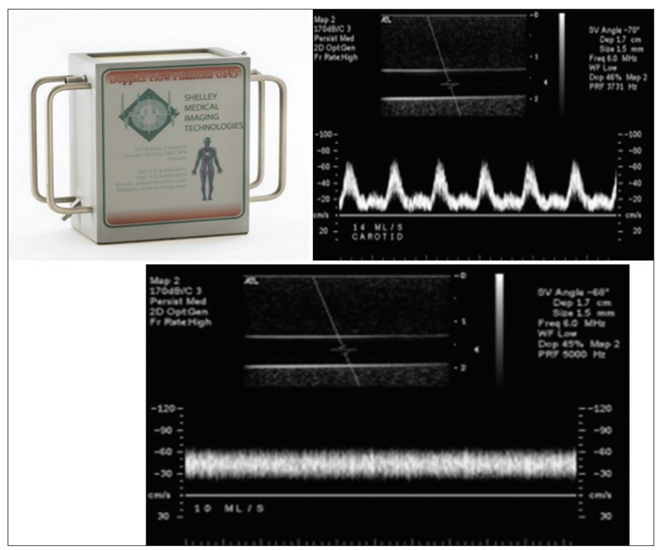

Figure 6: The model U-245 tissue equivalent Doppler flow phantom is for the evaluation of diagnostic Doppler ultrasound[34]

For instance, the flow rate is from a small number of milliliter per minute to hundreds or thousands number of milliliter per minute; also, monitor of pump velocity permits the generating of time-changing or pulsatile fluid flow.[14,16,18,28]

Limitations of the flow phantoms

The main limitation during fabrication of the flow phantom is the repeating pouring of TMM inside the phantom box which takes more than five times and could lead to losing of large amounts of items, because in each time, the air bubbles were produced on the TMM surface, and sometimes, the TMM was immediately cooled during the pouring process, and this produces several layers of TMM and then affects the acoustical features measurements. However, the direct cooled of TMM refers to the effect of the gelatin on the TMM strength.

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Conflicts of interest

There are no conflicts of interest.

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