

● *Original Contribution***DESIGN OF ANTHROPOMORPHIC FLOW PHANTOMS BASED ON RAPID PROTOTYPING OF COMPLIANT VESSEL GEOMETRIES**

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**Abstract**—Anatomically realistic flow phantoms are essential experimental tools for vascular ultrasound. Here we describe how these flow phantoms can be efficiently developed via a rapid prototyping (RP) framework that involves direct fabrication of compliant vessel geometries. In this framework, anthropomorphic vessel models were drafted in computer-aided design software, and they were fabricated using stereolithography (one type of RP). To produce elastic vessels, a compliant photopolymer was used for stereolithography. We fabricated a series of compliant, diseased carotid bifurcation models with eccentric stenosis (50%) and plaque ulceration (types I and III), and they were used to form thin-walled flow phantoms by coupling the vessels to an agar-based tissue-mimicking material. These phantoms were found to yield Doppler spectrograms with significant spectral broadening and color flow images with mosaic patterns, as typical of disturbed flow under stenosed and ulcerated disease conditions. Also, their wall distension behavior was found to be similar to that observed *in vivo*, and this corresponded with the vessel wall's average elastic modulus (391 kPa), which was within the nominal range for human arteries. The vessel material's acoustic properties were found to be sub-optimal: the estimated average acoustic speed was 1801 m/s, and the attenuation coefficient was 1.58 dB/(mm·MHz<sup>n</sup>) with a power-law coefficient of 0.97. Such an acoustic mismatch nevertheless did not notably affect our Doppler spectrograms and color flow image results. These findings suggest that phantoms produced from our design framework have the potential to serve as ultrasound-compatible test beds that can simulate complex flow dynamics similar to those observed in real vasculature. (E-mail: [alfred.yu@hku.hk](mailto:alfred.yu@hku.hk)) © 2013 World Federation for Ultrasound in Medicine & Biology.

**Key Words:** Vascular ultrasound, Anthropomorphic flow phantom, Compliant vessels, Rapid prototyping, Stereolithography.

**INTRODUCTION**

For more than two decades, flow phantoms have been playing a pivotal role in fostering the technical advancement of Doppler ultrasound by providing an experimental means of simulating vascular flow conditions similar to those seen *in vivo* (Hoskins 2008). These devices generally comprise a vessel model embedded within a tissue-mimicking material, and a flow pump that is used to drive blood-mimicking fluid through the vessel (Ramnarine et al. 1998, 2001). From a quality assurance standpoint, flow phantoms have been widely deployed as calibration platforms to characterize the performance of Doppler ultrasound instruments (Marinozzi et al. 2012). They have also been used to help identify sources of measurement errors (Lui et al. 2005; Steinman et al. 2001, 2005) and to evaluate the sensitivity of new flow estimation

indices (Dubiel et al. 2006; Raine-Fenning et al. 2008a, 2008b). In addition to these conventional applications, there is an emerging interest in using flow phantoms as investigative tools to explore novel ways of using ultrasound to quantitatively assess complex hemodynamic patterns under different pathological conditions such as stenosis and plaque ulceration (Poepping et al. 2010; Wong et al. 2009). For the latter application, it is imperative to design anthropomorphic (*i.e.*, anatomically realistic) flow phantoms that can precisely mimic the hemodynamics of various vascular morphologies so that new ultrasonic measurement strategies developed from these phantom studies can be translated into clinical diagnoses *in vivo*.

Unlike straight-vessel phantoms that can be readily created using off-the-shelf tubing materials, anthropomorphic flow phantoms generally require reconstruction of vessel geometries that closely follow real vascular anatomy (Hoskins 2008). Such reconstruction conventionally involves the use of investment casting principles

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in which a negative mold of the arterial geometry is created and then used to form a replica of the vessel core for casting within a tissue-mimicking material (Poepping *et al.* 2002, 2004). This technique has been shown to be useful in producing wall-less phantoms whereby the vessel core is removed after tissue casting (Meagher *et al.* 2007; King *et al.* 2010; Watts *et al.* 2007). It has also been used to fabricate thin-walled phantoms that comprise replicas of the vessel wall as opposed to the vessel core (Dingley *et al.* 2006; King *et al.* 2011; O'Flynn *et al.* 2005). Nevertheless, this way of producing anthropomorphic flow phantoms is known to be technically cumbersome, as investment casting is after all a multi-step process that requires skilled craftsmanship (Wong *et al.* 2008). As such, it is inherently difficult to use this technique to pursue large-scale production of a range of phantoms with multi-factor variations in pathological parameters, as would be needed for facilitating longitudinal investigations of novel vascular ultrasound measurement strategies.

The aim of this work is to devise an efficient framework for developing anthropomorphic flow phantoms to support application development efforts in vascular ultrasound. We have been working with the proposition that direct fabrication of authentic vessel geometries can be realized using computer-aided rapid prototyping (RP) technologies like stereolithography in view of their increasing technical maturity in recent years (Lantada and Morgado 2012; Rengier *et al.* 2010). Moreover, it is our hypothesis that anthropomorphic vessel tubes with elastic moduli similar to those of real arteries may be generated with the use of compliant photopolymers that have recently emerged as a new class of stereolithography material (Berselli *et al.* 2011). Note that, in the context of flow phantom design, computer-aided manufacturing has been previously introduced at a limited scale to machine negative molds for investment casting (O'Flynn *et al.* 2005; Poepping *et al.* 2002, 2004) and to create master patterns of artery models for silicone mold imprinting (King *et al.* 2010, 2011; Meagher *et al.* 2007; Watts *et al.* 2007). Computerized milling of wall-less phantoms has also been attempted using rigid materials (Wong *et al.* 2008). In contrast, this work distinguishes itself from these early efforts by providing a novel perspective on how elastic thin-walled phantoms can be efficiently produced without resorting to the investment casting technique.

## DESIGN METHODS

### *Drafting of vessel geometry models*

Our new phantom design framework first involves the use of computer-aided design software (SolidWorks; Dassault Systemes, Waltham, MA, USA) to draft 3-D

models of anthropomorphic vessel geometries. To serve as illustration, generalized models of the carotid bifurcation were developed in this work. As shown in Figure 1a, the lumen diameters used in our models were 6.0, 4.2 and 3.5 mm, respectively for the common carotid artery (CCA), internal carotid artery (ICA) and external carotid artery (ECA). Wall thickness was set to 0.8 mm as consistent with real carotid arteries (Poepping *et al.* 2004). Also, inlet and outlet flow connectors were included in the vessel models to facilitate mounting of the vessel tubes during flow phantom fabrication.

The overall geometry of our demonstration prototypes can be considered as a modified version of a tuning-fork model that was originally reported for magnetic resonance imaging studies (Smith *et al.* 1999). The ratio of the CCA, ICA and ECA diameters was kept the same, but we used different vessel sizes (*e.g.*, CCA diameter was 6 mm compared with 8 mm in the original geometry [Smith *et al.* 1999]) to more closely reflect the mean carotid artery diameter of adults (Krejza *et al.* 2006). Another modified feature is that multiple diseased vascular conditions were concurrently incorporated into the models to demonstrate the ability of RP to fabricate complex vessel geometries that deviate from the typical straight-tube appearance. One of these conditions is arterial stenosis, and it was incorporated into the vessel models by introducing an eccentric narrowing at the inlet to the ICA branch. A stenosis level of 50% was considered in this work, and it was specified according to the definition used for the North American Symptomatic Carotid Endarterectomy Trial (Smith *et al.* 1996). The second diseased condition included in our geometries was plaque ulceration, and two shapes were considered: (i) hemisphere with 3.85-mm orifice diameter (Fig. 1b); (ii) ellipsoid with major-axis length of 7.37 mm, minor-axis length of 2.95 mm and 45° angle tilt toward the ICA distal end (Fig. 1c). In our models, the ulcer was placed on the proximal side of the ICA narrowing (*i.e.*, the side facing the CCA) as this is the site of frequent occurrence of ulceration (Lovett and Rothwell 2003). It should be noted that the two ulcer shapes considered in this work are respectively classified as types I and III (Lovett *et al.* 2004), and they were chosen because they are known to lead to significantly disturbed flow behavior (Wong *et al.* 2009).

Note that carotid bifurcation models were chosen to build our demonstration prototypes because they are of practical relevance to carotid ultrasound studies. In particular, it is well recognized that an effective phantom fabrication framework is warranted to foster systematic development of new clinical strategies in using carotid ultrasound to diagnose various pathophysiological factors (Grant *et al.* 2003; Wong *et al.* 2008). Another point worth noting is that our demonstration prototypes were

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