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● *Original Contribution*

VALIDATION OF A POWER LAW MODEL IN UPPER EXTREMITY VESSELS: POTENTIAL APPLICATION IN ULTRASOUND BLEED DETECTION

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Abstract—Vascular ultrasound can provide quick and reliable diagnosis of arterial bleeding but it requires trained and experienced personnel. Development of automated sonographic bleed detection methods would potentially be valuable for trauma management in the field. We propose a detection method that (1) measures blood flow in a trauma victim, (2) determines the victim's expected normal limb arterial flow using a power law biofluid model where flow is proportional to the vessel diameter taken to a power of k and (3) quantifies the difference between measured and expected flow with a novel metric, flow split deviation (FSD). FSD was devised to give a quantitative value for the likelihood of arterial bleeding and validated in human upper extremities. We used ultrasound to demonstrate that the power law with k = 2.75 appropriately described the normal brachial artery bifurcation geometry and adequately determined the expected normal flows. Our metric was then applied to three-dimensional (3-D) computational models of forearm bleeding and on dialysis patients undergoing surgical construction of wrist arteriovenous fistulas. Computational models showed that larger sized arterial defects produced larger flow deviations. FSD values were statistically higher (paired *t*-test) for arms with fistulas than those without, with average FSDs of 0.41 ± 0.12 and 0.047 ± 0.021 (mean ± SD), respectively. The average of the differences was 0.36 ± 0.12 (mean ± SD). (E-mail: aswang@alumni.stanford.edu) © 2012 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Automated algorithm, Bleed detection, Diagnostic ultrasound, Power law, Vascular trauma.**

INTRODUCTION AND LITERATURE

Exsanguination from vascular injuries is responsible for 80% of the early deaths (the first 15 min to 4 h) in civilian trauma (Sauaia et al. 1995; Acosta et al. 1998) and is the leading cause of preventable deaths in the battlefield (Gawande 2004; Dorlac et al. 2005). The diagnosis of vascular trauma should ideally be portable, noninvasive, quick and accurate. Portable ultrasound has already proven to be a valuable tool in the battlefield (Starnes et al. 2006). Duplex ultrasound has been shown to be effective for initial noninvasive screening with 95% to 100% sensitivity and 99% to 100% specificity in the diagnosis of vascular trauma compared with the gold standard of angiography (Bynoe et al. 1991; Fry et al. 1993).

However, diagnostic reliability is user-dependent and requires training and experience (Schwartz et al. 1993). Efforts to improve the ultrasound assessment of the vasculature have focused on quantifying sonographic signatures of bleeding. Luo (2007) has developed a quantitative method to scan the length of a vessel and localize the site of bleeding (Luo et al. 2007). Others have attempted to quantify tissue vibrations at the site of bleeding (Sikdar et al. 2006) and to characterize acoustic streaming properties in hematomas (Shi et al. 2001).

Each of these new techniques is a point-by-point method of detection of bleeding, which requires the actual site of bleeding to be imaged. The strength of angiography is that an entire vascular tree is evaluated with each image. Our goal was to develop an efficient, quantitative way to use ultrasound to first survey an entire extremity vascular tree and localize suspicious areas for further examination. Such a technique would lend itself to a systematic and perhaps automated evaluation for bleeding. A recent push for new sonographic techniques

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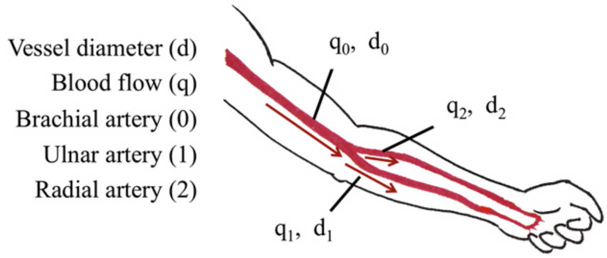

Fig. 1. Schematic of the normal arm with brachial bifurcation: brachial artery (0), ulnar artery (1) and radial artery (2). Each vessel has a diameter (d) and blood flow (q), with direction and magnitude indicated by the red arrows.

has resulted from a Defense Advanced Research Projects Agency (DARPA) initiated project to create an ultrasound cuff that can automatically detect internal bleeding with ultrasound imaging and then achieve hemostasis with high-intensity focused ultrasound (HIFU) (Luo et al. 2007; Vaezy and Zderic 2007). The cuff is being designed to automatically image the length of a limb in all directions and reconstruct the vasculature in three-dimension (3-D). The ability to identify blood vessels that are feeding areas of bleeding would allow such a system to rapidly cut off blood flow to areas of bleeding even if the actual site of bleeding cannot be identified, while limiting the extent of tissue that would be made ischemic if a tourniquet were used.

We hypothesized that the ability to identify deviations from normal blood flow patterns would enable the detection of some types of arterial injuries. Blood flow is conveyed through an arterial tree, which is a series of bifurcating vessels. Each vessel is a parent to two downstream daughter branches and each branch is a parent vessel to two more branches and so on. The power law is a biofluid model that describes the relationship between bifurcation geometry and normal blood flow (Murray 1926). The equations of the power law are:

$$d_0^k = d_1^k + d_2^k \tag{1}$$

$$q \propto d^k \tag{2}$$

$$q_0 = q_1 + q_2 \tag{3}$$

where q is the flow, d is the diameter, k is the power law index, subscript 0 is the parent artery (brachial), subscript 1 is the larger of the two daughter branches (ulnar) and subscript 2 is the sister branch (radial) (Fig. 1). The power law has been validated at branch points in many vasculatures of the body (heart, kidney, eye and lung) but not for those of the upper extremity.

Of vascular injuries, up to 88% occur in the extremities (Fox et al. 2005; Menakuru et al. 2005). Upper extremity vascular injuries constitute a significant proportion of injuries; the occurrence of arterial injuries in the subclavian/axillary was 7%–34%, brachial was 34%–58% and ulnar/radial was 23%–54% (Andreev et al. 1992; Fox et al. 2005; Clouse et al. 2006; Johnson et al. 2007). We, therefore, chose to establish confirmation of the power law in the normal upper extremity first.

Further, it is likely that following trauma, the patient will be subject to dynamic physiologic states associated with shock. Therefore, it is important to establish the invariance of the power law with respect to changing physiology for this approach to have practical utility.

Three-dimensional computational simulations of ulnar and radial injuries were then used to determine the degrees of flow disturbance that would be expected to result from different degrees of bleeding.

Finally, as a provisional proof of concept regarding the ability of this approach to assess flow disturbances, dialysis patients undergoing arteriovenous fistula (AVF) creation were also evaluated. The severity of flow disturbances in these subjects would be expected to mimic those of trauma victims with severe bleeding. The greater challenge of proving the concept in lesser disturbances was limited by the ability to use a technique early in development in patients with uncontrolled acute injuries. Traumatic AVFs are known to complicate many penetrating vascular injuries (Yildirim et al. 2005; Menakuru et al. 2005; Johnson et al. 2007).

MATERIALS AND METHODS

The human studies in this article were approved by the Stanford Institutional Review Board; informed consent was obtained from each study participant.

Normal flow study at rest and exercise

A normal human subject study was designed to determine if a general value for k in eqn (1) could describe the brachial bifurcation geometry and if that value would allow for adequate prediction of bifurcation blood flows. A linear 9–3 MHz transducer on an ultrasound machine (iE33; Philips Medical Systems, Bothell, WA, USA) was used. The brachial, radial and ulnar arteries in 28 healthy arms of 14 young adults (18–35-years-old) were imaged. The transducer was held longitudinally to the vessels and diameters (d) and time-averaged mean velocities (TAMV) were measured at the same location, approximately 3 cm from the bifurcation. Gray-scale B-mode ultrasound was used to measure vessel diameters during systole. Doppler ultrasound was used to measure TAMV (*i.e.*, the mean-velocity through the cross-section of the vessel averaged over several cardiac cycles). The Doppler gate size was adjusted to