AIDING THE DETECTION OF VASCULAR TRAUMA IN THE HUMAN UPPER EXTREMITY ARTERIES WITH IMAGE-BASED MODELS OF BLOOD FLOW

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PURPOSE

Trauma patients need medical attention quickly to stop major bleeding. A portable ultrasound ***(US)*** cuff (fig. 1) based on an algorithm to detect major internal bleeding would be useful for medics in the field.

Specific goals

1. Demonstrate a physics-based model to characterize normal blood flow in the upper extremities.
2. Evaluate its ability to detect vascular abnormalities by looking for flows that deviate from the model.

Fig. 1. A portable ultrasound cuff with automatic bleed detection algorithm.

METHODS

The flow model of choice: power law [1]

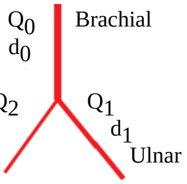
1. $Q \propto d^k$

flow ***(Q)***, diameter ***(d)***, power index ***(k)***

2. $d_0^k = d_1^k + d_2^k$

parent ***(0)***, larger child ***(1)***, other child ***(2)***

Fig. 2.



Adapt law for arms (find k value) with normal human subjects study; n=28 arms

1. US image for diameters & flows at rest & exercise (2.7 watts, 30lb grip). (fig. 3)
2. Find best-fit k value.
3. Confirm if best-fit k power law characterizes flow splits well: predict Q_1 & Q_2 with power law, compare to measured Q_1 & Q_2.

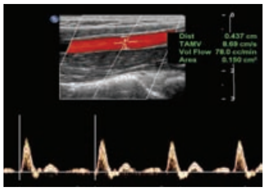


Fig. 3. US imaging for flows, diameters, & flow waveforms.

Parameter for bleed detection

1. Find flow split discrepancy ***(FSD)***.
2. Establish max FSD for normal. (FSD=0 for ideal normal; FSD elevated for a bleed in a branch stealing flow from other branch)

$$\mathrm{FSD} = \left| \frac{mQ_1}{pQ_1} - \frac{mQ_2}{pQ_2} \right|$$

measured ***(m)***, predicted ***(p)***

3D trauma simulations to evaluate FSD's ability to detect bleeds

1. Create finite element model of normal arm flow at rest; implement resistance-capacitance-resistance boundary conditions ***(RCR BCs)***. (fig. 4)
2. Add different size bleeds with zero pressure outlets; track FSD changes.
3. Solve Navier Stokes equations with a stablized finite element method.

Steps for 3D simulation of normal flow [2]

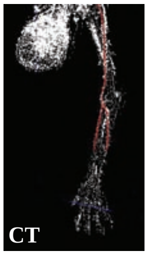


Fig. 4a. Vessel paths from arm CT (pathlines).

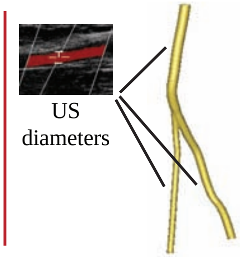


Fig. 4b. Add US diameters to CT pathlines to create arm model.

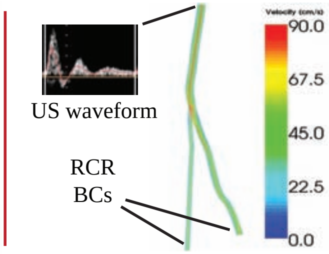


Fig. 4c. Add US waveform & BCs to outlets to achieve normal flow split & physiologic pressures.

RESULTS

Data from normal human subjects study

		Brachial	Ulnar	Radial
Rest	**d (mm)**	3.9 ± 0.1	3.4 ± 0.1	2.4 ± 0.1
n=28	**Q (cm^3/min)**	86 ± 8	43 ± 6	27 ± 3
Exercise	**d (mm)**	4.2 ± 0.1	3.7 ± 0.1	2.6 ± 0.1
n=28	**Q (cm^3/min)**	273 ± 11	160 ± 12	56 ± 5

Fig. 5. Averaged diameters (d +/- SEM) and flows (Q +/- SEM).

Best-fit k determined and it's ability to predict flows shown

1. k values between rest & exercise not statistically different (t-test, p=0.82); thus, data were combined.
2. k=2.75 minimized RMSE; k value similar for other large vasculatures. [1]

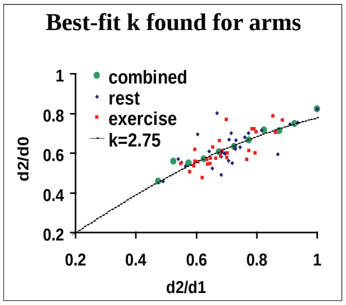


Fig. 6. k=2.75 curve through rest (n=28) & exercise (n=28) data, and combined rest & exercise, averaged in .05 intervals.

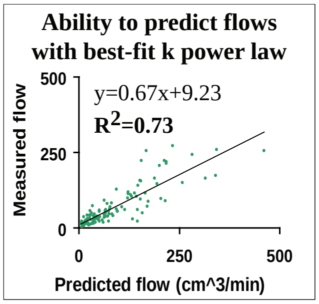


Fig. 7. Good correlation between predicted and measured children flows (Q_1, Q_2) for rest & exercise; n=112.

Max FSD established for bleed detection parameter

1. **FSD < 1.0** for 95% of all 56 measured flow splits (28 rest + 28 exercise).
2. Define **FSD > 1.0** as abnormal.

Trauma simulations determined size of detectable bleeds

1. Larger bleed, larger FSD.
2. A small radial bleed, 1/5 radial diameter, had FSD=1.21. (fig. 8)

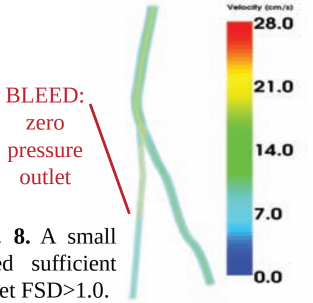


Fig. 8. A small bleed sufficient to get FSD>1.0.

CONCLUSION

1. Normal arm blood flow splits, regardless of physiologic state, can be well characterized with vessel diameters and a k=2.75 power law.
2. FSD was able to quantify flow-stealing affects of bleeds, and a FSD>1.0 was set by normal arm flow data as a parameter for bleed detection.
3. Simulations show that this method could potentially detect a bleed only 1/5 size of a vessel. Followup animal studies, which account for physiological responses to injury, will further evaluate this method of bleed detection.

REFERENCES

[1] Changizi, M and Cherniak C; Modeling the large-scale geometry of human coronary arteries. Can J Physio Pharmacol. 78:603-611 (2000).

[2] Vignon-Clementel, I, et al.; Outflow Boundary Conditions for Three-Dimensional Finite Element Modeling of Blood Flow and Pressure in Arteries. Computer Methods in Applied Mechanics and Engineering. 195:3776-3796 (2006).

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