Complex, Pulsatile Mathematical Model of Arteriovenous Fistula Hemodynamics to Predict Factors Contributing to Steal After Initial Fistula Placement

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INTRODUCTION:
Steal after initial arteriovenous fistula (AVF) placement results in significant morbidity and access failure. Robust mathematical modeling can be used to study and predict changes in hemodynamics. We propose a pulsatile mathematical model of the upper extremity to predict steal based on arterial, fistula, and venous geometries.

BACKGROUND:
Electrical analogs of the upper extremity have been described using both the Wheatstone Bridge model, which accounts for collateral flow, and series type circuit models.1,2 Equations derived from the Wheatstone bridge (#Figure 1) predict the magnitude of mean non-pulsatile flow based on vessel resistance.

METHODS:
A circuit-based Simulink® three-element arterial Windkessel model of the upper extremity was created, incorporating a pulsatile arterial input with arterial capacitance and impedance (resistance). Typical anatomic vascular dimensions (Table I) were converted using basic fluid modeling equations (#Figure 2).

• Collateral flow was calculated as 10% of arterial inflow.
• The pulsatile input was modeled using a 1 Hz sine-wave current generator. In order to condition the signal from the sine-wave generator to output physiologic flow, two diodes were added to the model (#Figure 3).

RESULTS:
Experiment #1: Effects of Fistula Radius on Distal Arterial Hemodynamics:
Observed hemodynamic properties of the distal arterial segment and the AVF as the radius of the AVF was iteratively changed from 0.05 cm to 0.5 cm.

Table I: Experimental Parameters of Upper Arm Models.3

Experiment #2: Effects of Radial/Ulnar Radius on Distal Arterial Hemodynamics:
Observed hemodynamic properties of the distal arterial segment as the radius of both the radial and ulnar artery where simultaneously varied between 0.025 cm and 0.2 cm.

Figure #4: Two-dimensional digitized (CAD) schematic of the simulation model.

A. (Top) Pressure profiles of the input arterial system. (Bottom) Pressure profiles of the output venous system.
B. (Top) Flow profiles of the input arterial system. (Bottom) Flow profiles of the output venous system.
C. (Top) Flow profiles of the AVF. (Bottom) Flow profiles of the venous system.

Figure #5: A two-dimensional digitized (CAD) schematic of the simulated AVF.

A. (Top) Pressure profiles of the input arterial system. (Bottom) Pressure profiles of the output venous system.
B. (Top) Flow profiles of the input arterial system. (Bottom) Flow profiles of the output venous system.
C. (Top) Flow profiles of the AVF. (Bottom) Flow profiles of the venous system.

CONCLUSIONS:
This model predicted that steal after initial AVF placement is dependent upon both the diameter of the AVF relative to the inflow artery, as well as radial and ulnar artery patency. Furthermore, it provides a continuum of data as a preoperative framework to input patient-specific physiology and dimensions to predict distal flow. Further work to clinically validate and refine this model may allow for a predictive tool to decrease or prevent the occurrence of steal after initial fistula placement.

REFERENCES: