COMPUTATIONAL MODELS OF BLOOD FLOW IN AORTIC DISSECTION: ENHANCING SIMULATION ACCURACY WITH 4D-FLOW MRI

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1What is Aortic Dissection?
Aortic Dissection (AD) is a deadly Cardiovascular Disease affecting the aorta, the main artery connecting the heart to the rest of the body (Fig. 1).

In AD, a tear forms in the inner layer of the aortic wall, allowing blood to separate it from the medial layer, forming a true and false lumen (Fig. 2).

Life-threatening complications including aortic growth and rupture, organ failure and paraplegia are considered virtually inevitable in the long-term.1

AD is high challenging to diagnose and manage. Intervention-free survival is below 50% at 5 years.2

2Why is blood flow important in AD?
Anatomical measurements from medical images are currently used by doctors and surgeons to predict long-term risk and plan AD treatments.

Anatomical metrics provide only a retrospective measure of disease progression. Their predictive power is inadequate.3

The forces exerted by blood on the inner layer of the vessel wall directly influence AD onset and progression.4 However, the mechanobiological processes driving AD remain poorly understood.

In future, blood flow analysis could be used to improve long-term survival and quality of life by:

- Helping to discover why AD occurs and progresses
- Predicting AD onset in otherwise healthy people
- Supporting clinicians in predicting the potential outcome of various treatments
- Optimising the design of stent grafts

3How do we analyse blood flow?
We use Computational Fluid Dynamics (CFD), a flow simulation technique, and 4D-Flow MRI (4DMR), a non-invasive medical imaging modality. Each has limitations and strengths (Fig. 3), so they are used in combination.

Boundary conditions (BCs) are prescribed in CFD simulations where the modelled region ends (inlet/outlet wall). They can profoundly affect the accuracy of simulation results.

Wall shear stress (WSS), τ, is the frictional force of blood on the vessel wall. WSS and its time-averaged metrics (TAWSS, OSI, ECAP) are of particular interest.

Our aim was to investigate the impact of commonly-applied boundary conditions in a single case of Type-B AD, improving and validating their accuracy using 4DMR data.

4Study A: Inlet Conditions
A time-varying distribution of blood velocity is often extracted from 4DMR and prescribed at the aortic inlet. We sought to address two key questions:

1. With access to 4DMR data, to what extent do imaging errors at the inlet affect simulation results?
2. Without access to 4DMR data, naturally-occurring complex flow behaviours at the inlet are ignored in CFD. How much does this affect metrics linked with aortic growth, such as ECAP?

Inlet velocity distribution and 4DMR errors greatly affected flow metrics linked with aortic growth, such as ECAP, in the aneurysmal FL.

5Study B: Outlet Conditions
The segmental arteries (SAs) are minor branches which have been universally ignored in CFD simulations of the aorta until now.

Up to 21% of cardiac output leaves the aorta through the SAs.5 Does neglecting this flow loss affect simulation accuracy? How much?

After developing a novel technique to model the SAs using WK3 outlet conditions, we performed two equivalent CFD simulations, one with and one without them.

Up to a 75% reduction in transmural pressure, TAWSS and ECAP were observed when SAs were removed from their flow loss analysis.2

6Conclusions & outlook
The choice of inlet and outlet boundary conditions greatly affect flow quantities of potential clinical relevance.

Minor branch flow loss should be considered in aortic flow simulations to ensure accuracy.

Patient-specific inlet velocity profiles from 4DMR should be employed, but further work should endeavour to limit the impact of imaging errors at the inlet.

REFERENCES

AUTHOR AFFILIATIONS

CFD: NO SAs
CFD: WITH SAs
4DMR

Fig. 1: Schematic diagram of Type A AD and a cross-sectional schematic of a dissected artery2

TAWSS = \frac{1}{2} \int \left[ \frac{\partial u}{\partial x} \right] dx

OSI = \frac{1}{2} \int \left[ 1 - \frac{u}{\bar{u}} \right] dx

ECAP = OSI x TAWSS

Fig. 2: Schematic diagram of Type A AD and a cross-sectional schematic of a dissected artery2

Fig. 3: Velocity magnitude contours from CFD and 4DMR in the aorta shown in Figs. 1 & 4 at peak systole

Fig. 4: Aortic modelling region from Fig. 1 with locations from Figs. 5-7 entry tear and BCs indicated

Fig. 5: Each inlet profile (above), mean ECAP along the thoracic FL for each inlet profile against FL growth (right)

Fig. 6: Velocity magnitude contours from CFD with and without SAs, shown against 4DMR data indicating better agreement with SAs

Fig. 7: TAWSS contours in the thoracic aorta with and without SAs (left) and ECAP contours in the abdominal aorta, indicating co-located regions of high ECAP and calcification in CT images (right)

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Fig. 8: Flow MRI imaging of Type A AD, false lumen (FL) and true lumen (TL)

Fig. 9: Flow MRI imaging of Type A AD, false lumen (FL) and true lumen (TL)

High resolution ✓
Obeying physical laws ✓
Accuracy is challenging x
High accuracy ✓
Low accuracy x

Fig. 10: Flow MRI imaging of Type A AD, false lumen (FL) and true lumen (TL)

Fig. 11: Flow MRI imaging of Type A AD, false lumen (FL) and true lumen (TL)