13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

COMPUTATIONAL FLUID DYNAMICS VISUALISATION APPLIED TO MEDICAL MAGNETIC RESONANCE IMAGING

Gordon D. MALLINSON[1] and Brett R. COWAN[2]

[1]Department of Mechanical Engineering
[2]Department of Medicine
The University of Auckland, Auckland, NEW ZEALAND

ABSTRACT

By using phase encoded sequences, magnetic resonance imaging can non invasively detect fluid motion in the human body with excellent accuracy. Resulting data sets describing three-dimensional unsteady motion can be very dense, being at least comparable to state of the art computational fluid dynamics (CFD) data. CFD visualisation techniques have been applied to medical images with the objectives of improving the investigative tools available to the clinician and increasing the speed with which useful information can be obtained from the data sets. This paper demonstrates the nature of the visualisation problem and the kinds of results that have already been achieved.

INTRODUCTION

Phase contrast magnetic resonance imaging has found wide application in medicine for the determination of blood flow rates. Typically these images are acquired in a plane at right angles to the flow, and it is assumed that the in-plane velocity components are negligible so that the data acquisition process is essentially one dimensional.

In vessels with complex three-dimensional flow patterns, such as stenoses (narrowings), tortuous vessels and bifurcations, this approximation is not valid and it is necessary to determine the full three-dimensional motion of the blood. Phase contrast imaging determines the velocity of a medium by the insertion of gradient pulses into standard MRI sequences. The axis on which these pulses are inserted determines the direction of velocity encoding, and this can therefore be modified independently of the other imaging parameters. This enables a single imaging plane to be run consecutively with velocity encoding in each of the x, y and z directions. Several planes can be used to sweep through a volume to generate a complete description of a three-dimensional steady flow.

Repetitive unsteady flows, such as blood flow in the aorta, can be measured by using a sequence of images that are triggered to occur at different times following an event such as the R-wave of the electrocardiogram (ECG) that denotes the onset of contraction.

Typically, an image plane may contain 256 by 265 pixels, each less than 1 mm square. An image slice may be of the order of 2 to 6 mm so that 30 slices might be used to cover a volume of interest, leading to approximately 2 million three dimensional velocity vectors. If 40 time steps are used to cover the cardiac cycle, the total data set contains 80 million velocity vectors. The challenge is to display this complex time-varying information in a format that is useful for clinical diagnosis.

Already studies, such as those by Yang et al (1991), have used vectors to visualise the fluid motion, but there does not seem to have been widespread application of the full range of CFD visualisation tools that are now available. The research reported here sought to ascertain if the MRI data were indeed appropriate for processing by CFD visualisation algorithms.

METHODS

Since MRI data sets are typically arranged as planes consisting of rectangular arrays of pixels that correspond to structured CFD data. Moreover the "grid" is uniformly spaced. Both these characteristics mean that MRI data are well suited to structured CFD visualisation systems such as the *SeeFD* package written at the University of Auckland.

Software has been written to extract phase-contrast images from a database, determine their orientation in space, direction of flow sensitivity and velocity encoding (VENC). This information is then assembled into a form suitable for processing by a medical version of *SeeFD*. If specific regions within an image are of interest, these can be selectively extracted to reduce processing time.

Although still under development in response to clinical need, the system is currently able to produce -

- maps of colour coded vectors
- simultaneous displays of single or multiple image planes, which may also be time varying
- streamlines
- time varying absolute speed plots at user defined locations
- flow rates through user defined selections.

Other more exploratory tools, such as iso-surfaces of speed and vorticity vector maps have been applied in attempts to quickly identify regions of interest.

Although all of these techniques are well known in the CFD field, they are not used in medicine. It must also be recognised that the CFD techniques are being applied in the this context to *un-smoothed experimental data.*

RESULTS

Visualisation results are presented here for a young adult who underwent surgery for coarctation of the aorta at 6 months of age. Five parallel 6mm oblique slices were obtained to encompass the ascending aorta, arch and descending aorta to the level of the diaphragm.

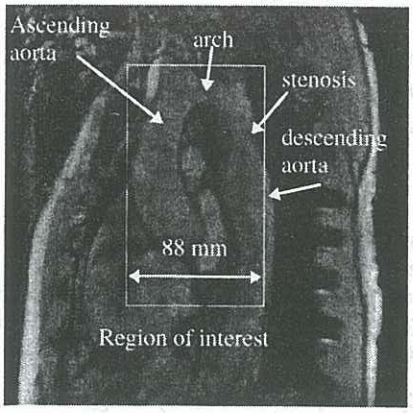


Figure 1: Anatomical image showing the ascending aorta, arch, coarctation repair site and descending aorta (left). Region of interest contains 76×132×5 voxels.

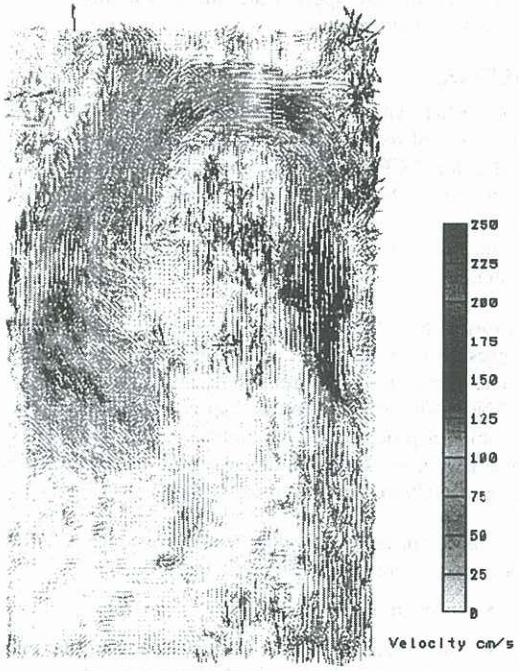


Figure 2: Velocity vector field in the vertical mid plane of the region of interest 200 ms after the onset of contraction.

Flow in the arch and aorta

The anatomical image in Figure 1 shows a region of interest encompassing the aorta, that was used to define the area to be processed into a vector map. This process produced a total of 5 slices, each containing 11,000 vectors and repeated for 31 phases throughout the cardiac cycle. All visualisations for this reduced data set were obtained quickly on an RS-6000 model 355 workstation with 32 Mbyte memory, relatively modest by today's standards.

Each vector in the map shown in Figure 2 represents a 'pixel' of information. The "noisy" vectors in the top right corner of the map represent an air filled region.

For each time frame a three-dimensional velocity field was extracted. Stream lines were traced by assuming that the velocity data were located at the corners of "computational cells". Tri-linear interpolation of the velocity data and fourth order Runge-Kutta integration were used. Bearing in mind that the data are not smoothed in any way and there are only 5 vertical planes of data, the stream lines are remarkably coherent. These are instantaneous stream lines - not particle paths. The software is currently being extended to trace unsteady particle paths.

The representation in Figure 4 is part of an animation, which although not representing true particle motion does indicate the change in speed along the stream lines.

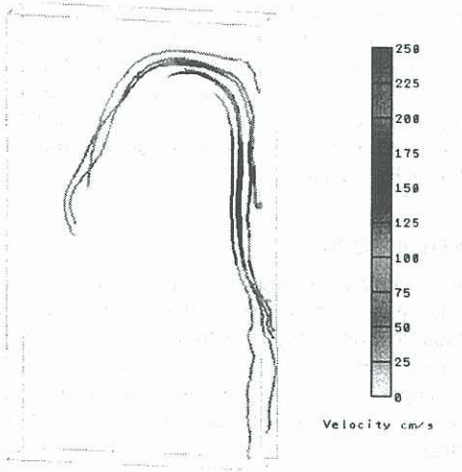


Figure 3: Stream lines traced through the arch into the descending aorta

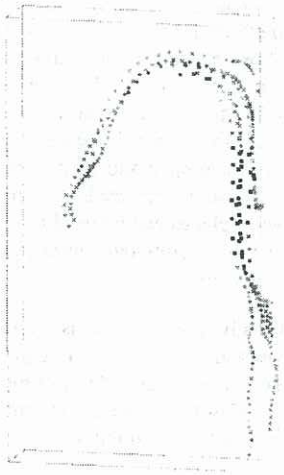


Figure 4: Stream lines in the arch and descending aorta represented by markers that are a fixed time interval apart.

Flow through a narrowing of the aorta

Note (from Figure 1) that the aorta narrows and then expands at the stenosis. This produces a jet of blood, and velocities in excess of 200 cm/sec. It is a region of interest from a clinical view point.

Data representing the flow through the stenosis were extracted, using the region of interest shown in Figure 5 (which is in the top right of the region in Figure 1).

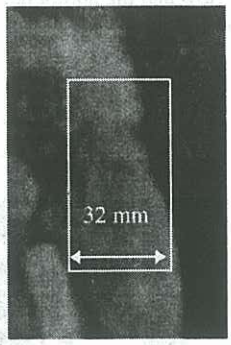


Figure 5: Region of interest used to extract the data visualised in Figures 6 to 8. (28×52×5 voxels)

Stream lines through this region are shown in Figure 6. This figure also shows horizontal maps of the speed of the flow. These maps were helpful in positioning the streamlines which can, if needed, be traced forwards and backwards from points of interest. The stream lines in the Figure were traced from a set of points along a line. These 'rakes' of stream lines are useful to display flow twisting (or helicity) which seems to be induced by the stenosis. The marker representation (Figure 7) shows the form of the velocity profile in the aorta as the line of markers progress along it. A second set of stream lines (Figure 8) released closer to the wall of the aorta appear to be showing fluid leaving the aorta through secondary blood vessels. The ability to observe this kind of structure is evidence of the quality of the measured data.

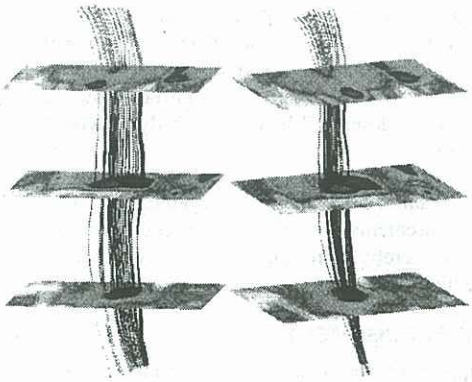


Figure 6: Two views of stream lines in the region of the coarctation jet with superimposed maps of speed, 200 ms after the onset of contraction.

Figure 7: The stream lines in Figure 6 represented by markers separated by equal time intervals.

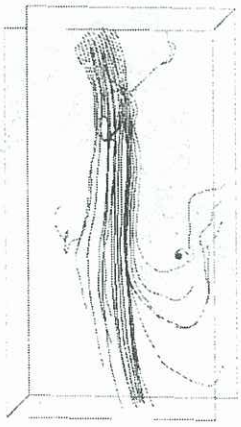


Figure 8: A second set of stream lines in the region of the coarctation jet. These have been released nearer the aorta wall and show flow entering secondary blood vessels.

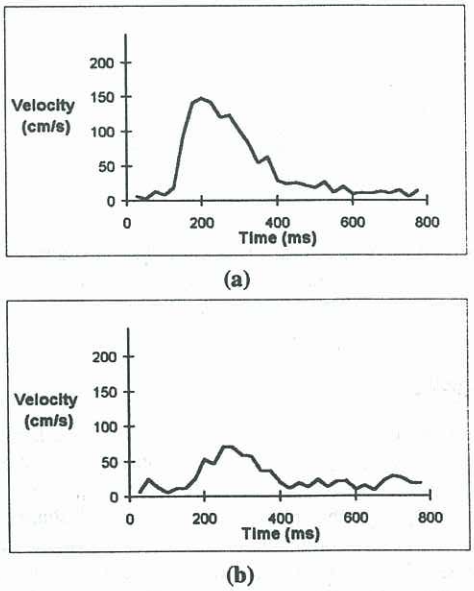


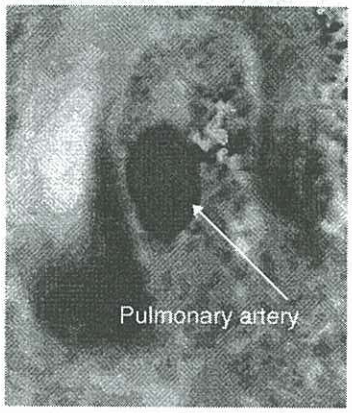
Figure 9: Velocity - time profiles (a) upstream and (b) downstream from the stenosis

One effect of the stenosis is shown by upstream and downstream velocity - time profiles (Figure 9). Upstream the velocity pulse is clean, downstream it is much less distinct. (And, of course it has spread in both directions which accounts for the fact that the areas under the profiles are not the same.)

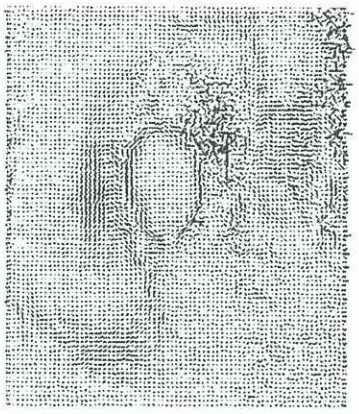
The software allows these profiles to be displayed for locations selected interactively by the clinician. This is proving to be an effective capability.

OTHER VISUALISATION STRATEGIES

With the wealth of information available, it is essential to develop methods for processing the velocity data to produce artefacts which might lead to easy identification of important flow features.



(a)



(b)

Figure 10: Flow in part of the mid plane through the arch and the aorta. (a) Map of the through plane velocity component. (b) Vorticity field calculated from the 3D velocity.

Vorticity

The vorticity vector field may prove useful as a flow edge detection technique. Figure 10 displays information for the region just under the arch. The pulmonary artery passes through this plane. This is the oval shaped dark region in the through plane velocity component map in Figure 10 (a). The vector map in Figure 10 (b) is the vorticity field calculated from the 3D vector field in the plane of (a). As expected, the edge of the pulmonary artery is clearly indicated as is another region of through flow in the lower section of the ascending arch.

Note that the region just downstream from the stenosis in the descending aorta also has components of vorticity in this plane that are evidence of the helicity generated in the jet.

Iso-surfaces

Iso-surfaces of appropriate scalar quantities can usefully be used to display flow structure. Figure 11 shows a speed iso-surface at 150 ms. This clearly shows the region of strong flow and the abrupt delay to the flow just after the stenosis. Again, the surface is remarkably coherent.

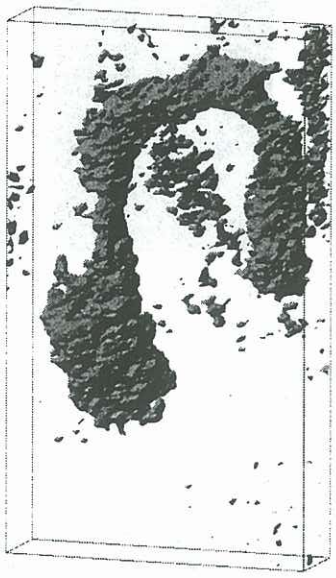


Figure 11: 100 cm/s iso-surface of the velocity magnitude at 150 ms.

CONCLUSIONS'

The results presented here demonstrate the potential that computational fluid dynamics flow visualisation approaches have for the display and analysis of complex three dimensional phase contrast MRI data sets. Although further work is required to develop robust techniques for automatically detecting clinically important flow features, the techniques described here are already proving useful in diagnosis.

The visualisations have also highlighted the detailed flow measurements that may be made, entirely non invasively, thereby increasing enormously the potential to understand fluid motion within the human body.

ACKNOWLEDGEMENTS

The support of the University of Auckland Research Committee and Manukau Radiology Institute Limited is gratefully acknowledged.

REFERENCE

YANG, G.Z, BURGER, P., KILNER, P.J., MOHIADDIN, R.H., In Vivio Blood Flow Visualization with Magnetic Resonance Imaging, *Proc IEEE Visualization* 91, 202 - 207, 1991