Quantification of Circumferential Subpixel Vessel Wall Position and Wall Shear Stress by Multiple Sected Three-Dimensional Paraboloid Modeling of Velocity Encoded Cine MRI.


Introduction

Methods are lacking for accurate, noninvasive circumferential edge detection and wall shear stress (WSS) calculations. We have previously presented a new method where three-dimensional paraboloid fitting of phase velocity data allowed calculation of these parameters (ref 1).

We present a further development of the method, where the use of multiple sectors around the vessel circumference allows to determine WSS and circumferential subpixel vessel wall position at multiple discrete points to avoid the assumption of 1) circular or elliptic shape of the entire vessel area and 2) the assumption of a homogeneous velocity distribution in the boundary layer along the whole circumference of the vessel. This allows measurement of WSS at discrete positions (“sectors”) around the circumference of the vessel wall rather than determination of average values for the whole vessel area.

It is the aim of this paper to evaluate this approach through simulations, in vitro studies and in vivo studies.

Materials and Methods

The method is based on the following basic fluid dynamic assumptions: 1) The blood velocity at the vessel wall is zero, and 2) there exists a boundary layer next to the vessel wall with parabolic blood velocity distribution. If a circular shape is assumed, the velocity at a point in the boundary layer (x,y) is then given by:

\[ u(x,y) = a(x + y + 2) + bx + cy + d \]

Based on an initial definition of the vessel wall, an “edge layer” (distance from wall to pixels included in analysis) and a “fit layer” (thickness of rim of data used for the fitting) is chosen. For a sector of the vessel, the velocity data are then fitted to a 3D by using the equation above. Edge position is derived by setting \( u(x,y) = 0 \) and WSS is derived by differentiating the 3D fit for \( u(x,y) = 0 \) and multiplying by viscosity.

Simulations were performed based on realistic in vivo acquired MR-velocity data to study the effect of varying noise levels on the accuracy of the fit.

In vitro MR studies (MR parameters as for in vivo study) were performed in a steady flow model in 8mm±0.001mm glass tubes (factory specifications) with flow rates of 4.37 ml/s and 6.45 ml/s and fully developed flow that allowed theoretical calculation of WSS. 3D dependence of matrix position relative to vessel position was studied by moving the imaging matrix in steps of 50 mm relative to the vessel.

In vivo studies were performed in 6 young volunteers (mean age 25.8 years) where through plane blood velocity data in the common carotid artery two cm upstream of the carotid bifurcation were acquired using a 1.5T Philips Gyroscan ACS-NT, scanner and a 8 cm diameter circular RF receiver coil. A standard retrospectively ECG triggered gradient-echo pulse sequence with bipolar velocity encoding gradients were used with acquisition matrix 128x128, 64 mm field of view, TR=25ms, two signal averages, TE=8ms, slice thickness 7mm and \( V_{max}=90 \) cm/s.

Results

The simulation results revealed that with 5 % noise added in peak systole, 95 % of the simulation results were within an error of ± 0.9 % for cross sectional area, and ± 3.5 % for WSS. In end diastole the results were less accurate due to the fewer data points and smaller blood velocity and WSS values. A 4 % noise level was found in the actual in vivo data. If the noise level was increased to 15 %, the statistics of the fit were still acceptable.

The in vitro results proved it was possible to determine the internal area of the glass tubes with an error less than 2% of the actual value and WSS values were determined with less than 6 % error. Linear regression analysis showed us that the movement of the image matrix relative to the vessel was depicted very accurately by the 3D fit (p < 0.0001, r=1, SEE= 0.011mm).

In vivo results revealed that varying the sector angle from 180 to 60 degree for the individual fits performed in 15 degree intervals along the circumference did not change the overall luminal area estimate by more than 1-2%. For the WSS determination a “low pass filter” effect was seen for the 180 degree sector angle but very similar values were found for the 90 and 60 degree fits. In fig. 1 an example of the 24 edge fits from one subject in peak systole and end diastole as well as total area estimates for all subjects are presented using 90 degree sector angles. In fig. 2 the minimum and maximum WSS values found are shown as an average for all subjects over time, and an example of the 24 values found around the circumference in one volunteer with standard errors of the fit given for each position.

Fig 2 Min and max WSS vs time (mean of all subjects, left) and min and max circumferential WSS in one subject (right) with standard error of fit

Discussion and conclusion

The multiple sliced 3DP method presented here overcomes some of the most limiting factors for estimation of edge position and WSS using MRI. The fit layer is limited to the parabolic part of the boundary layer at least on pixel away from the wall leaving out problems associated with partial volume effects of the pixels right at the vessel wall. Also no assumptions about homogeneous WSS or circularity around the whole vessel circumference has to be made.

The simulation results indicated that the multiple sector 3DP method is robust to varying levels of noise as are to be expected for in vivo MR data. The in vitro results showed that a very accurate quantitation of edge position and WSS is possible, and that the position of the image matrix relative to the vessel does not change the results. The in vivo results showed that it was possible to estimate luminal vessel area and WSS throughout the heart cycle, and the ability to estimate wall shear stress at 24 positions around the whole circumference with very low standard error of the fit was demonstrated.

The relatively large number of data points (n=m=1 7 for the 90 degree fit angle used) can be further increased with better resolution of the MR images, which will also allow to use the multiple slice 3DP method in even smaller vessels in the future.

References


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