Computer Simulation Helps Predict Cerebral Aneurysms

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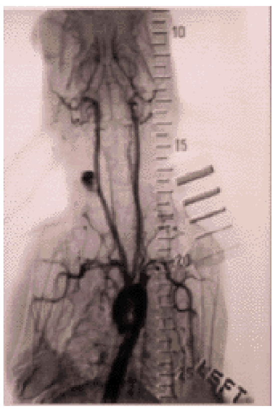

Fig 1. X-ray angiography of artificial aeaurysm (rabbit)

Researchers have recently proven the ability of computer simulation to predict the behavior of cerebral aneurysms. Accurately simulating the flow of blood within the aneurysm helps researchers to predict the growth pattern of the aneurysm and the danger of rupturing. As this tool is further developed into a practical diagnostic tool, it is expected to dramatically improve the ability of surgeons to weigh the results of alternate treatment methods. The simulation method used, computational fluid dynamics (CFD), provides much more information than current diagnostic tools, including particularly shear stress levels at various stages of the cardiac cycle, which help to pinpoint areas of aneurysmformation and growth.

Aneurysms are caused by weakness of the arterial wall resulting in a bulge in the shape of a small balloon. The greatest danger is that the aneurysm could break, particularly if the patient has elevated blood pressure, and produce bleeding within the brain. There are a variety of surgical methods of repairing cerebral aneurysms, including surgical clipping, detachable balloon obliteration and coil deposition within the cavity of the aneurysm. Understanding the hemodynamics of flow within the aneurysm can provide valuable information for the surgeon in deciding which surgical method has the best chance of success and the precise method by which it should be performed.

On a histological level, aneurysms are caused by damage to intima cells in the arterial wall. Damage is believed to be caused by shear stress due to bloodflow. Shear stress generates heat that breaks down these cells. In histological studies, damaged intima cells are elongated in comparison to round healthy cells. Shear stress can vary greatly at different phases of the cardiac cycle, locations in the arterial wall and among different individuals as a function of the geometry of the artery and the viscosity, density and velocity of the blood. Once an aneurysm is formed, fluctuations in blood flow within the aneurysm are of critical importance because they can induce vibrations of the aneurysm wall that contribute to progression and eventual rupture.

CFD is a simulation tool that has long been used in the engineering world to solve fluid flow problems with complex geometries and boundary conditions. A CFD analysis provides fluid velocity, fluid temperature and fluid concentration values throughout the solution domain. The results of the analysis allow a researcher to optimize fluid flow patterns or temperature distributions by adjusting either the geometry of the system or the boundary conditions such as inlet velocity/temperature, wall heat flux, etc. The use of this technology to model hemodynamics within the body is a relatively new area with enormous potential for predicting and solving a wide range of hemodynamic-related pathologies.

This researcher has for the past five years been working with CFD to model blood flow within the human body. While the primary purpose has been to predict the formation and growth of cerebral aneurysms, other areas of application include prediction of stenosis in renal arteries and plaque formation in coronary arteries. The modeling software package (FIDAP CFD software from Fluid Dynamics International, Evanston, Illinois) is a finite element code which gives it the advantage of using non-structured grids. Non-structured grids automate the process of fitting elements to the complex geometries of the human anatomy.

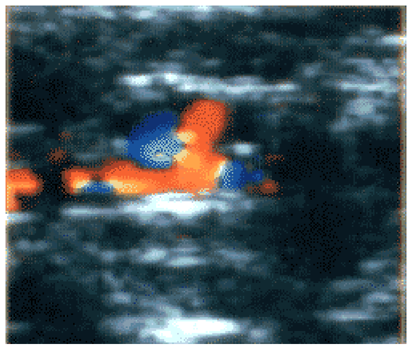

Fig 2. Color doppler aneurysm (animal model)

The behavior of the aneurysms depends on their geometry and hemodynamics. Every aneurysm is studied as a different case, taking into account its own properties such as geometry, blood flow characteristics, blood density, viscosity and velocity.

Recently, a study was conducted at Thomas Jefferson University (T.J.U.) to establish a correlation between the results obtained by CFD computer simulation with the information and the information provided by quantitative color Doppler ultrasound. Since Doppler ultrasound cannot always be accurately performed in humans due to the thickness of the human skull, an animal model was developed in the common carotid artery of New Zealand rabbits. New Zealand white rabbits were selected to create this animal model because the common carotid arteries of this breed have approximately the same diameter as human cerebral arteries.

Lateral aneurysms were surgically produced in one common carotid artery of three rabbits. All animals tolerated the surgical procedures well and were still alive six months after the completion of the study.

One week after the aneurysm was produced, a selective carotid angiogram was performed. Angiographic images obtained from the aneurysms were digitized and used to generate CFD models of the blood flow. Color doppler was also performed using a 7.5 MHz linear array transducer. Multiple axial and longitudinal views of the carotid artery and aneurysm were obtained and flow samples from the aneurysm up and down stream were recorded. Normal density and viscosity of the blood was included to solve the Navier-Stokes equation. The results obtained by CFD based on angiographic data were similar to the results of the color Doppler simulation at each point in the cardiac cycle. From the beginning of the systolic acceleration to the peak of the systole, the blood entered into the aneurysm from the proximal neck side and left the aneurysm along the distal wall of the aneurysm. At t=0.06 sec a small clockwise vortex near the proximal wall of the aneurysm was present. This small clockwise vortex grew as the deceleration continued at t=0.09 seconds and dominated the flow in the aneurysm at t=0.30 seconds, the end of the deceleration period in the systole. From this moment, the clockwise vortex flow was continuously observed inside the aneurysm as seen by the directions of the arrows in velocity vectors, even when there was almost no flow in the main lumen. This is believed to be caused by inertial force inside the aneurysm.

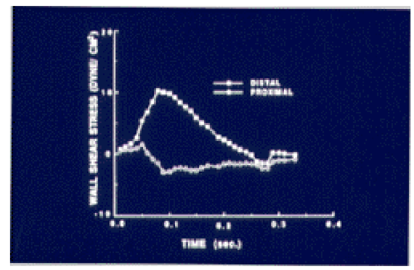

Fig 3. Computer simulation of rabbit model

During the entire cycle, blood continued to impinge on the distal neck. However, during the systolic acceleration, blood impinged in it from the cavity out to the parent vessel, while during deceleration, blood impinged from the parent vessel into the aneurysm cavity. Such rapid changes of the impinging direction, which occurred during a cardiac cycle, should produce a significant hemodynamic stress at the distal neck. In general, the blood flow in the aneurysm changed its direction during a cardiac cycle, rotating counterclockwise during the acceleration and clockwise during most of the deceleration period. The changes in the flow direction result in the directional changes in local wall shear stresses, which may injure the intima, particularly at the distal neck of the aneurysm.

The streamline contour plots produced by the analysis software clearly demonstrate the local flow characteristics inside the aneurysm during the cardiac systole. At the peak of systole, a flow separation at the proximal neck and a small local recirculation near the proximal wall of the aneurysm were clearly seen. As deceleration starts, the small vortex near the proximal neck grows, occupying half of the aneurysm opening at t=0.11 seconds and controlling the aneurysm completely at t=0.30 seconds.

The instantaneous wall shear stress at the proximal and distal necks of the aneurysm were calculated. The instantaneous wall shear stress varies little at the proximal neck. However, at the distal neck shear stress occurs from the maximum value of 10.24 dyne/cm2 at t=0.04 seconds (the peak of the systole) to the minimum value of -2.97 dyne/cm2 at t=0.045 seconds (the beginning of the deceleration period of systole).

Compared to color Doppler examinations, computer simulation produces a more detailed characterization of the sequence of hemodynamic events occurring inside the aneurismal cavity. This is due to the ability of this technique to measure and calculate instantaneous blood flow velocity at different times during the cardiac cycle. Also, computer analysis permits calculation of the wall shear stress distribution. Information regarding directional changes of shear stress is most important since the pseudointima at the neck of the aneurysm are more susceptible to an oscillatory shear stress than to unidirectional shear stress.

The increased wall shear stress in the distal wall of the aneurysms is corroborated by significant thickening in the distal segment of the wall observed in the histological examination of the rabbits. Changes in the pseudointima wall may explain the origin, enlargement and rupture of aneurysms. Rupture, however, does not occur at the neck but rather at the dome of the aneurysm where the wall becomes thick as the aneurysm enlarges. Injury of the endothelial wall is also a serious consideration when surgical clipping or endovascular obliteration of the aneurysm is considered.

For this technique to become a practical diagnostic tool, high performance computers that can provide faster analysis results are needed. Research to date has utilized older Sun Sparcstation Model 2 computers that take 2-3 weeks to analyze hemodynamics for a single patient. The latest model Sun Sparc Ultra computers haved performed this analysis in about one-tenth of this time. T.J.U. researchers, in collaboration with scientists at the National University Autonomous of Mexico (U.N.A.M.) and the Instituto Nacional de Neurologia and Neurocirugia (I.N.N.N.) in Mexico City, have obtained access to a CRAY supercomputer that will provide analysis results in under an hour, about the time frame needed for use in surgical setting. The supercomputer is located at the Direccion General de Servicios de Computo Academico (D.G.S.C.A.) at U.N.A.M.

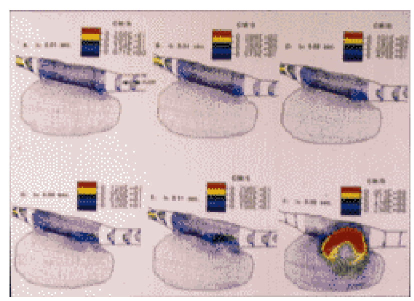

Fig 4. Shear stress graph for rabbit model.