Heart Flow

Computer simulations of blood flow in the heart aid artificial-valve designers

By IVARS PETERSON

Opening and closing with every heartbeat, four valves — thin, flexible flaps of tissue — control the flow of blood through the heart. They move passively, smoothly slipping out of the way when blood pushes forward. Then, when the heart contracts, they snap shut to keep blood from flowing back the wrong way.

"Heart valves are basically very simple devices," says applied mathematician Charles S. Peskin of the Courant Institute of Mathematical Sciences at New York University, "but they're often the thing that goes wrong."

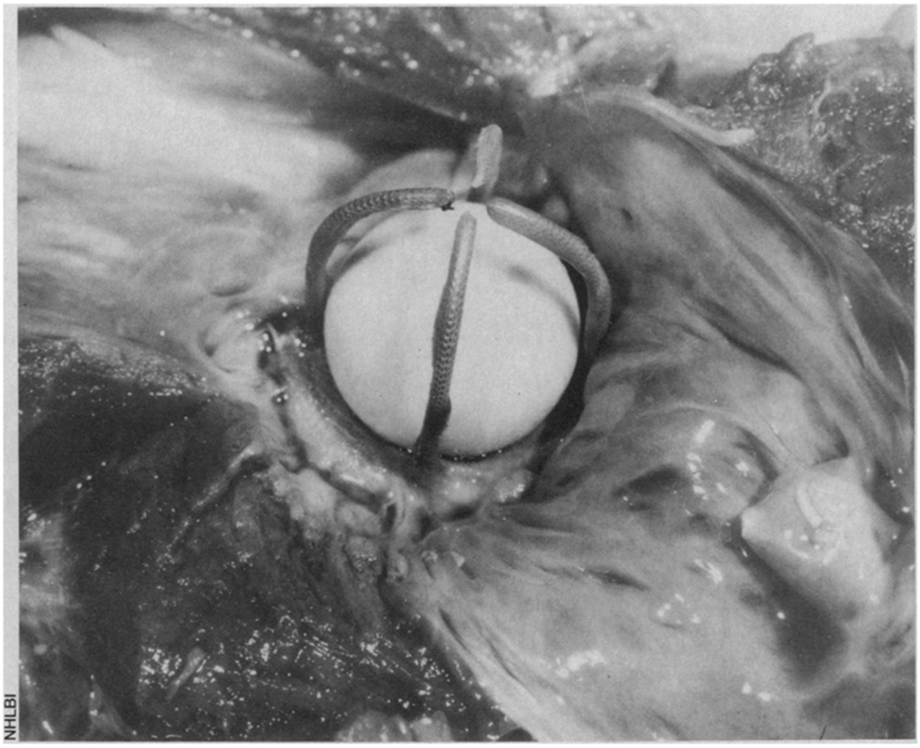
Natural heart valves can suffer from two serious problems. They may become so stiff that a large pressure is needed to force them open and drive blood through. Or they may fail to close properly, allowing a significant backflow.

Since 1960, mechanical valves, some as simple as a ball in a cage or a pivoting disk set in a ring, have been used to replace natural valves. John T. Watson of the National Heart, Lung, and Blood Institute estimates that surgeons worldwide now implant about 150,000 new or replacement heart valves every year.

Many of the early valve designs were little more than educated guesses about what was likely to work well. Although animal and clinical studies showed that these devices functioned reasonably well, it often wasn't clear how effective they would be and what could be done to improve them.

One mechanical valve, for example, changed blood flow patterns enough to induce a loud thump with each heartbeat, which disturbed patients who received the device. Others generated flow patterns that included stagnant pools, which tended to encourage blood clot formation. Medical researchers also tried artificial valves made from animal tissue, but these generally wore out too quickly.

Even now, says Peskin, "the level of technology in this field is much lower than the level of technology in something like aircraft design or oil recovery." Yet all of these fields involve the same kind of fluid mechanics. By bringing in mathematics and computer technology, Peskin says, "the main thrust of my work [is] to create a tool that heart valve designers can use."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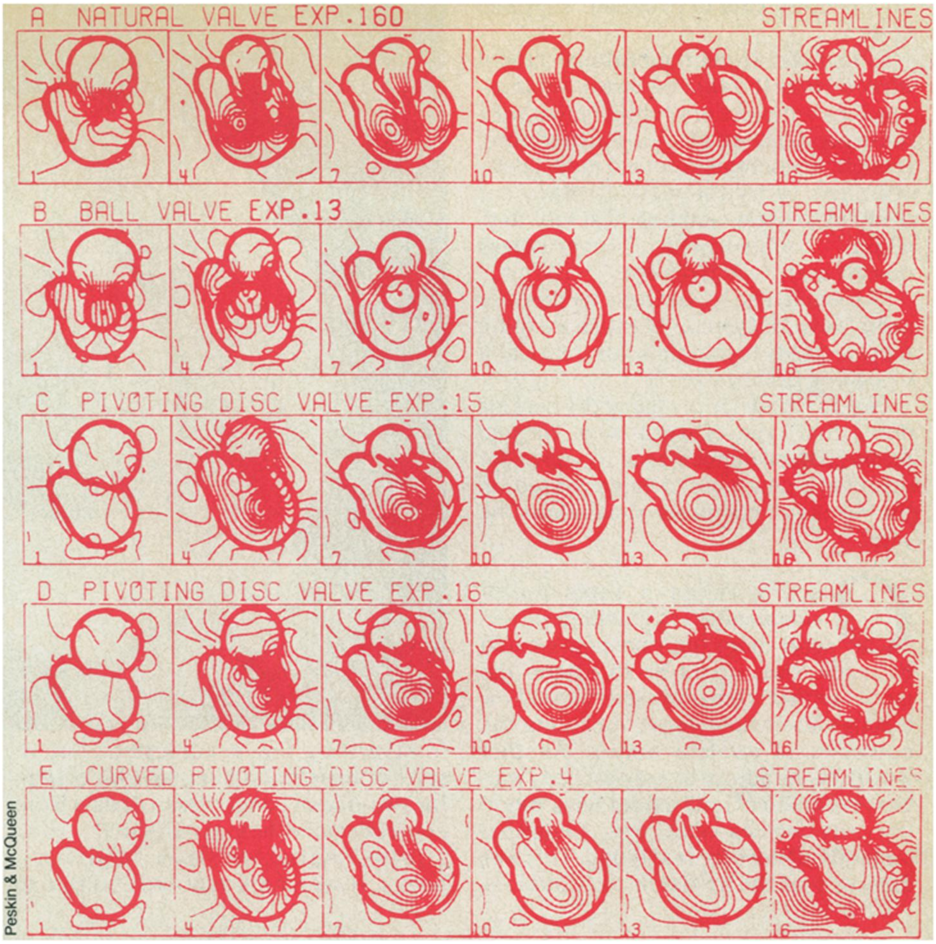
One of the earliest mechanical heart valves was this simple ball-in-a-cage structure, shown here as it would be implanted in a human heart.

Peskin has spent more than a decade developing a computer model for blood flow in the heart. He described his model recently at a meeting in Boston of the Society for Industrial and Applied Mathematics.

Working in two dimensions, Peskin has concentrated on modeling the heart's left side and the movement of one particular valve known as the mitral valve. Unlike other, simpler mathematical models, this version includes the characteristics of both the blood flow and the heart chamber's muscle tissue. Like an elastic band, the modeled tissue responds flexibly to the blood's pressure while it also exerts a force on the flowing blood. In simpler models, the chamber is represented as merely a rigid piece of plumbing.

This is a case of fluid mechanics in which the boundaries confining fluid flow are not fixed, says Peskin. The flow controls the boundary, and the boundary controls the flow. "It's a very subtle, two-way feedback problem," he says.

Hence, coupling flexible boundaries with a moving fluid presents significant mathematical difficulties. The methods that Peskin and a colleague, David M. McQueen, have developed to solve that problem for the heart also apply in many other situations — from the movement of fish in water to the flow of suspended particles in a liquid.



Peskin & McQueen

Each row of computer-generated pictures shows the effect of a particular type of valve on the flow of blood (indicated by the streamlines) during a heartbeat.

In Peskin's heart model, the blood is represented by a large number of discrete points, each with a specific velocity and pressure. These velocities and pressures change as the fluid elements interact with their neighbors in ways that can be calculated using equations from physics. That alone requires millions of computations.

The heart's muscle structure is modeled by a collection of moving particles joined by tiny springs. The properties of these elastic links can be changed over time so that the tissue becomes stiffer at certain stages during a heartbeat. A special mathematical function is used to compute the local interactions between these particles and the fluid.

"The computer solves the equations of motion, predicting what will happen," says Peskin. Each heartbeat takes about 40 minutes of computation on a large computer like the CDC 6600 or Cyber 170.

The net result is a sequence of pictures that can be strung together to produce a dramatic movie of a beating heart. The vivid, two-dimensional images clearly show where flow is uneven, how different artificial valves respond and even the likely effect of a weakened or diseased natural valve.

"The computer makes possible a far more detailed analysis of the flow pattern than was previously available," says Peskin. This technique, he says, adds a new dimension to methods commonly used for developing and testing artificial valves.

With a computer model, there's no need to go through the expensive and time-consuming chore of building and testing each variation of a valve design. On a computer, says Peskin, "we can make variations in the design very easily and try them out. The computer model is flexible enough and general enough that we can put in whatever we want."

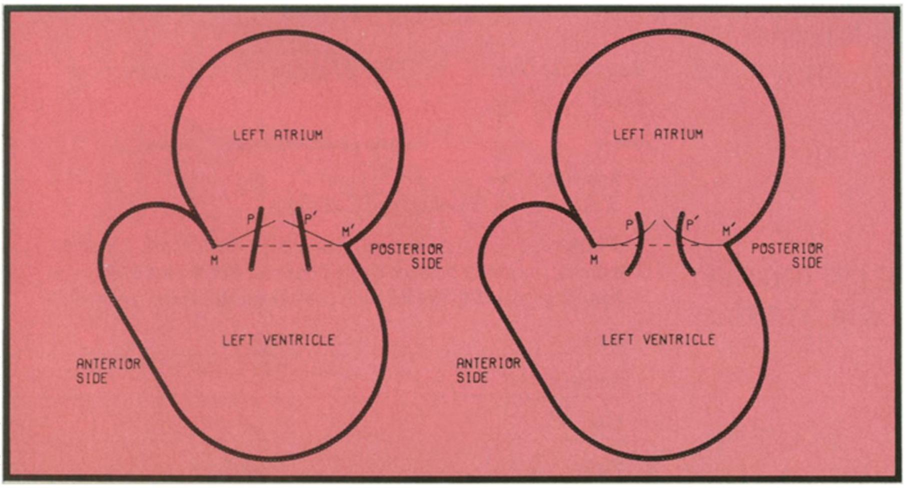
Minor changes in valve design often significantly alter valve performance. "Fluid mechanics is fairly subtle," says Peskin. "It's not always easy to predict the effects without trying it out in some way."

Peskin's model has already been used to improve the design of a commercially available valve. The valve consists of a pair of flat, semicircular, pivoted graphite plates set within a metal ring wrapped in a synthetic fiber. By changing the plate curvatures and pivot points in their computer model, Peskin and McQueen were able to determine the optimum characteristics for smooth blood flow. New York University has applied for a patent on the refined device, and Carbomedics in Austin, Tex., a supplier of heart-valve components, is starting to test it.

Heart simulations may turn out to be useful not only for valve design but also for understanding and analyzing experimental data. Peskin's model, for instance, has helped medical researchers at the Albert Einstein College of Medicine in New York City interpret some experiments done on dogs, in which the variations among dogs partially hid an effect the researchers wanted to study. "It helped make sense out of a much more complicated set of data," says Peskin.

Although computer simulations can never completely replace animal testing, he says, by allowing researchers to learn more from each experiment, they may reduce the number of animal experiments necessary.

Peskin's computer heart, however, is still incomplete. He and McQueen are now constructing a three-dimensional model. To get the computations done within a reasonable amount of time, this version must be run on a Cray supercomputer. "This work would be unthinkable



Peskin & McQueen

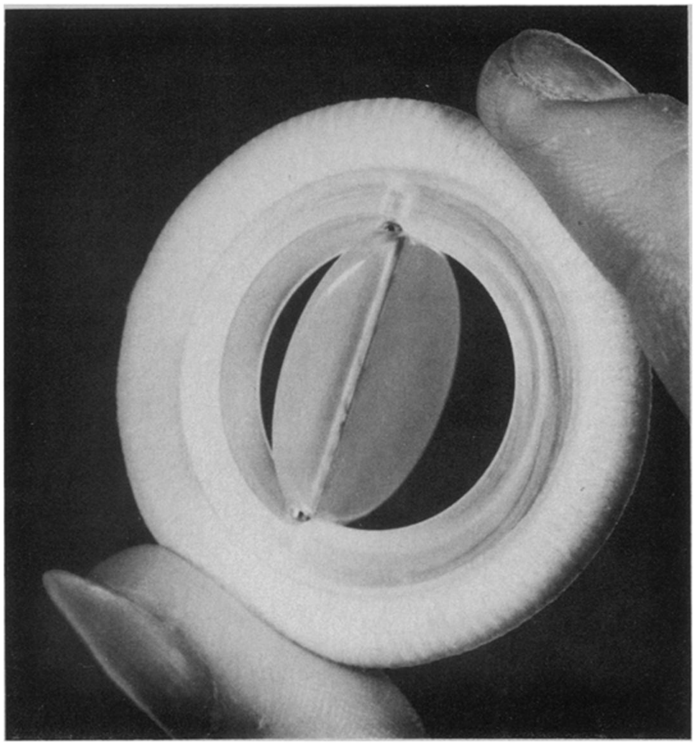
These two-dimensional diagrams illustrate how a "butterfly bileaflet" valve with flat leaflets can be altered by curving each leaflet and shifting its pivot point.

on any other kind of machine," says McQueen.

A realistic, three-dimensional model of blood flow through the heart would allow, for example, the study of valves with more complicated shapes. Furthermore, it might encourage skeptical medical researchers to try the method. Many are hesitant to use a mathematical tool that, while sophisticated, nevertheless doesn't quite match reality.

"We would like to see these techniques used," says McQueen, "because we think they're good techniques for rationally designing heart valves."

Peskin's model is probably the best for doing that type of work, says Watson. Adding a third dimension may help in developing a new class of valves based on the results of computer simulations, he says.



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Computer simulations show that the design of this mechanical valve can be improved by shifting its pivot point and curving the disk. As a result, blood flow is smoother and stagnant pockets are less likely to form.

Once work on a three-dimensional model is completed, several more improvements could be made. One would be to extend the model so that it encompasses blood flow through the whole heart, including the operation of all four valves. Another would be to adjust blood viscosity values. Peskin's current model uses blood viscosity values that are somewhat larger than those for real blood. This was done to keep the fluid flow computations from getting too complicated. But in spite of such limitations, says McQueen, the two-dimensional results fit data from experiments with dogs quite well.

In the long run, with faster, larger computers, researchers may even be able to put together a complete computer model of the heart that includes both its electrical system (SN:3/19/83, p.183) and its fluid mechanics. But that achievement is still much, much more than a heartbeat away. ☐