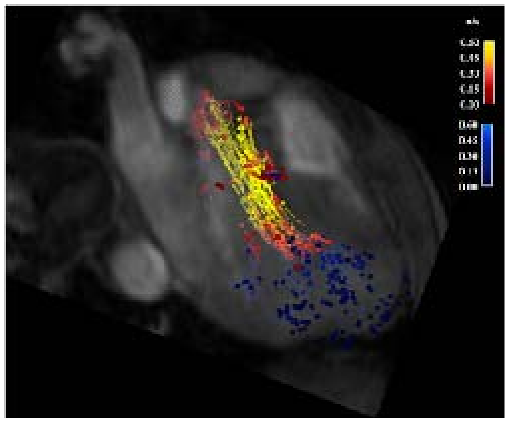
Extreme Visualizations Reveal Secrets of the Beating Heart

By Kara L. Gray, New Horizon Consulting

Over the course of the average lifespan, the human heart will beat more than 3.5 billion times, pumping oxygen-rich blood throughout the body. Modern medical imaging techniques, like ultrasound and magnetic resonance imaging (MRI), have helped scientists to unlock many of the heart's secrets and aided in the treatment and prevention of numerous cardiac diseases.



Blood flowing into the left ventricle from the mitral valve can be separated according to downstream behavior. Flow that will go directly on to the body without delay is color coded in shades of red; blood that will remain in the heart for one or more additional cycles is colored in shades of blue.

However, one of the most intriguing secrets has remained sealed inside: the flow of blood within the beating heart. Until recently, cardiac physicians and scientists could only guess as to how the blood behaves inside the chambers of the heart, based on physiological and anatomical data gleaned from imaging sources. Now, an international group of researchers has married MRI data with EnSight extreme visualization software by CEI, Inc. of Apex, NC to identify flow paths within the left ventricle of the human heart. What they have found opens doors to better understanding the effects of disease and treatments on the flow within.

Ann F. Bolger, MD, of the University of California, San Francisco, has led the multi-disciplinary team, which includes researchers from Linköping University in Sweden, in successfully mapping the multidimensional flow paths, as well as changes in kinetic energy, of blood flowing through the left ventricle. Their work has brought together specialists in cardiology, physiology, advanced imaging, biomedicine and engineering with the support of the Swedish Research Council and the Swedish Heart-Lung Foundation.

Traditional MRI Goes 3D

Bolger says the flow aspect of human physiology has been completely unaddressed, limited by the availability of tools for study, until now.

"We've had good tools for looking at heart muscle and for measuring pressures at specific sites within the heart, and ultrasound methods are very good," Bolger says. "But we haven't had a tool that will let us solve flow problems dynamically, and in three dimensions, in a completely non-instrumented or noninvasive way, that doesn't screw up the exact phenomenon you are trying to study – this is huge."

Bolger's study of cardiovascular flow began in 1992 when she met Bengt Wranne, head of the heart center at the University of Linköping. The two began collaborating on cardiac ultrasound research. The limitations of ultrasound led them to use MRI images, and they rigged the data to fit into one of the first versions of EnSight.

"If it weren't for those first images we saw from EnSight, we wouldn't have been so inspired to keep pushing," Bolger says. "And, it has been a push – we probably find three problems for every solution. Using MRI data, you have to be meticulous and correct for imaging problems. The nice thing about working directly with engineers is that they know how to go looking for these kinds of problems."

For the patient, the process is exceedingly simple – only about one-half hour of image acquisition within the magnet is required to produce dynamic volume data for the heart and great vessels over the complete cardiac cycle. This data includes the time-resolved 3D velocity vector across each of the thirty-two time steps interpolated.

From Patient to PC

Before this "giant dense forest of data" can be converted into EnSight's case format, Bolger and her team conduct extensive data processing to correct for Maxwell and eddy current effects, imaging artifacts that can muddy the analysis. Once the data is post-processed, Bolger and her colleagues analyze the images. By dynamically identifying regions with specific flow behaviors at certain phases of the cardiac cycle, they can pinpoint irregular or shifting flow origins to serve as the emitter for large populations of pathlines. These pathlines allow researchers to visualize the specific flow of interest during the cardiac cycle through any location in the imaged area.

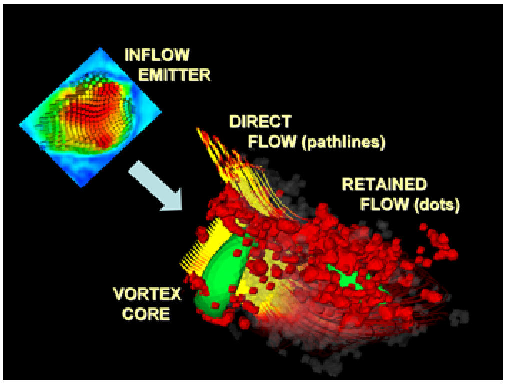
Because of the complexity of the work, the collaboration of the multi-disciplinary team is not only incredibly powerful, but also necessary, in order to arrive at solutions. Insight from the clinicians aids the engineers in handling the data, which allows them to build appropriate and accurate models. The ease and simplicity of EnSight makes this collaboration possible by providing pristine images based on collaborative input.

"We have a call-and-response relationship," Bolger said. "For example, I can request that we measure the energy that is lost throughout the flow, and the engineers can get that data out of EnSight, if I can give them the exact flow of interest. The ability to visualize these new parameters is where the rubber meets the road."

The Beating Heart

Bolger notes that at times their work can get very theoretical, and the ability to visualize the complexity of 3D flow is a major breakthrough. Clinicians are accustomed to mostly 2D representations of the human body, which is why Bolger's EnSight presentations are often met with gasps from the audience during clinical conferences.

"The ability of EnSight to make these particle traces and to present intuitive, dynamic pictures of them – and to allow a person to transform, rotate, and look at them from all perspectives – is so powerful," Bolger says. "During a conference presentation, if someone asks 'what about the vortex?' I can reach over with the mouse and turn the whole image around on screen and everyone gasps!"



This three-dimensional model of the beating left ventricle illustrates direct flow of blood through the volume, vortices (green), and the retained flow positions late in the filling phase of the heart cycle.

Bolger has presented her work using EnSight, along with the accompanying EnLiten model viewer and EnVideo animation player (both also from CEI, Inc., Apex, NC), at conferences of the American College of Cardiology, the American Heart Association Scientific Session, and the Society for Cardiovascular Magnetic Resonance.

EnSight's robust and extensive tool set allows Bolger to readily adapt the output to the question at hand. She sites its ease of use and intuitive operation with producing a short learning curve.

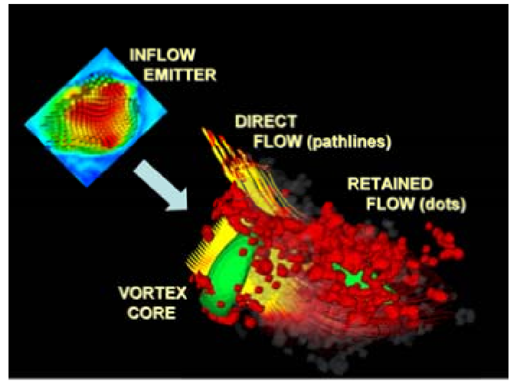
"Because we deal with biological data, and we have a broad interest in all kinds of cardiovascular flows, we exploit an awful lot of those tools," Bolger says. "It's easy to collaborate with EnSight. The animations and visual outputs are very compelling."

However, presenting such compelling images carries with it a heavy responsibility, particularly in the medical field. Bolger feels a strong obligation to ensure the accuracy of her data and analysis.

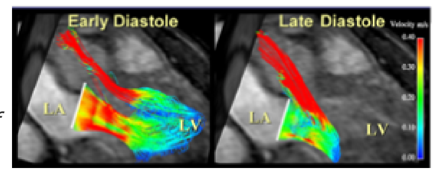
"People will believe what they see in pictures, especially if it looks like something they would have predicted," Bolger points out. "An impressive image can lead people astray. They may be inspired by what they see and go off on a wild goose chase. The last thing we want to do is hurt anyone. Even a delay in getting to the right answer is a big deal."

Engineering Repair and Replacement Parts

The implications of Bolger's work could have some profound impacts on the development of prosthetic heart valves, surgical strategies and the individualization of therapies for various cardiac maladies. Bolger believes that both heart surgeons and engineers will be intrigued by what her group has to show them, considering that many of the treatments doctors rely on have been designed without consideration of flow.



"What if we could analyze a new valve with respect to the flow during the design process, and then again after the valve is in place in the heart?" Bolger says. "The engineers who have devoted lifetimes to designing these fantastic prosthetic heart valves didn't have this kind of 3D flow data. This is huge for them, too."



Velocity-encoded path lines overlaying the cardiac structure (grayscale MRI images) illustrate the variation in flow velocity from the left atrium through the left ventricle of the beating heart at early and late stages of cardiac filling phase cycle.

For prosthetic heart valves and other reconstructive repairs, most doctors understand that preserving the normal flow within the heart is important. The problem, Bolger says, is that many lack a true understanding of what this means and a way to evaluate whether they have done so. In the case of a valve replacement, if the flow within the chambers becomes disorganized, the result is lost energy, turbulence and the possibility of blood clots. On the other hand, restoring a so-called "normal" flow in a sick heart may not only be impossible, but may also not be the best course of treatment for the individual patient.

"It is exciting that we can have better treatment options, and more of them, and also individualize them for each patient," Bolger says. "Now, we can collect flow data on a person scheduled to undergo surgery and forward this information on walls that don't move, valves that leak, etc. in this particular person, and you can customize the surgical plan. This is a possible and powerful outgrowth of this work."

"There are probably 25 different heart valves on the market that can each be put in 3 different ways," Bolger adds. "It would be great to know exactly what to use and how to use it in that individual patient."

Bolger's use of 3D imaging techniques is certainly a novel approach to the study of heart-related conditions, but it also has life-saving implications for millions of people in the U.S. and around the world. Cardiovascular disease is the number one killer of Americans, and Bolger believes that the more we learn about how the heart works, the more successful doctors can be at treating patients with sick hearts.

"Nature is so efficient and so elegant in its solutions. When we show the multidimensional images of intracardiac flow, everyone thinks 'of course that's how it would work,' but we didn't know it before," Bolger says. "We have bridged a major gap in the basic understanding of normal human physiology – how a normal heart works – and, therefore, an even bigger gap in terms of what happens in very ill hearts."

More Information

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