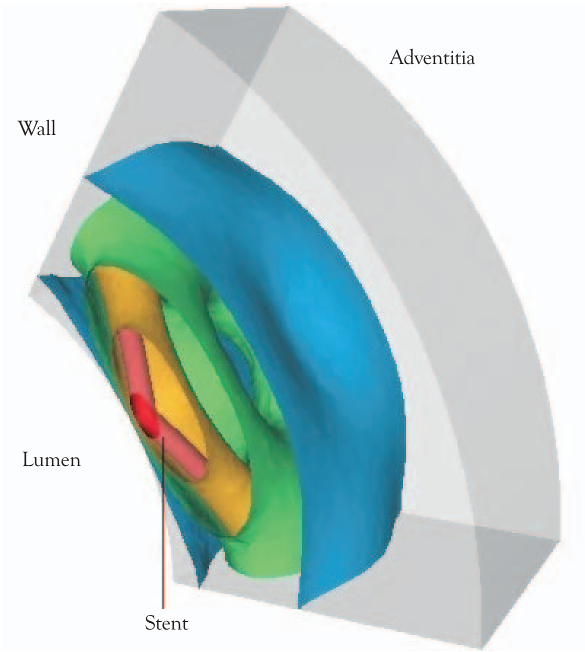
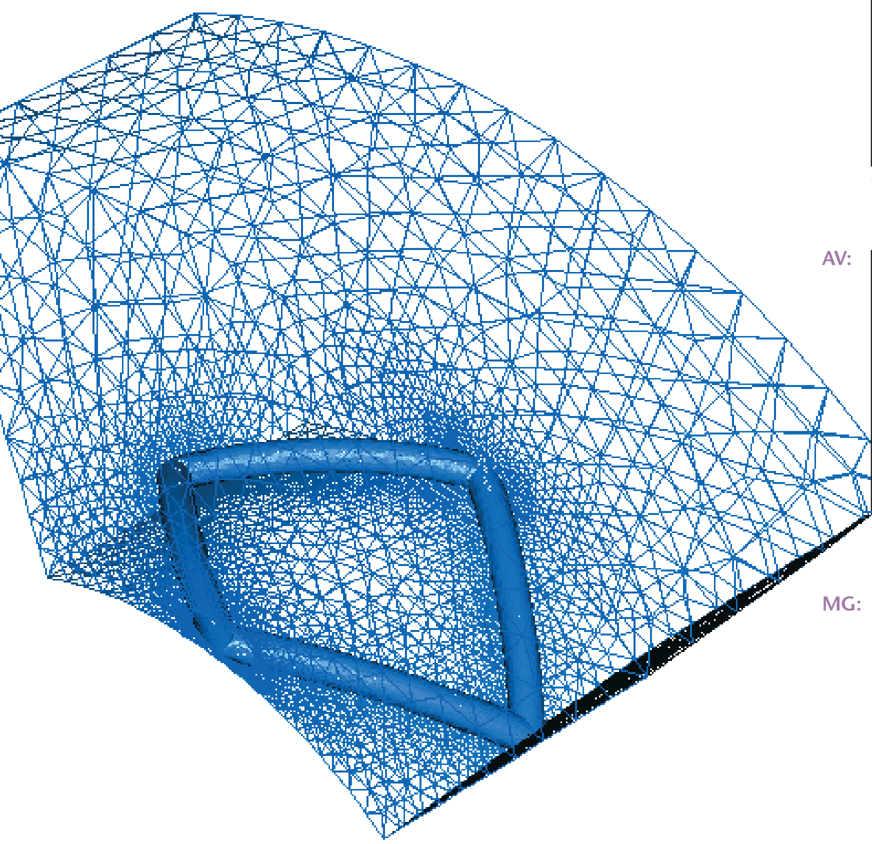
# Visions of CFD in the



Drug eluting stent simulation, showing the mesh (below) and iso-surfaces of Heparin concentration in the stent coating and vascular wall (above); the multi-domain advection-diffusion problem was performed using the MOX-MOCS-INRIA in-house finite element code LifeV (Joint work with M. Prosi (MOX), and P. Zunino (MOCS, Lausanne))

*Courtesy of Politecnico di Milano*

*DURING A RECENT TRIP TO ITALY, Keith Hanna from* Fluent News *visited some of the world's pioneering biomedical engineering organizations and facilities, where he conducted a series of interviews with thought leaders in the developing field of biomedical CFD. Below are excerpts from his interviews with Dr. Andrea Remuzzi (AR), Head of the Department of Bioengineering, Mario Negri Institute, Bergamo, Italy; Dr. Alessandro Veneziani (AV), Professor in Numerical Analysis, MOX (Modeling and Scientific Computing Laboratory), Dept of Mathematics, Politecnico di Milano, and co-worker at the Laboratory of Biological Structure Mechanics, Milan, Italy; and Dr. Mauro Grigioni (MG), Senior Researcher, Instituto Superiore di Sanita (ISS), Rome, Italy.*

**Q. What do you see as the most significant advances in biomedical CFD in recent years?**

**AR:**

Dr. Andrea Remuzzi

It is interesting to note the important transformation of biomedical engineering in recent decades. Twenty years ago we were mostly doing CFD in 2D, then we started to use 3D simulations with idealized geometries, and today we can generate 3D models of large blood vessels that are patient specific. Despite this impressive development of theoretical and technical knowledge, we still need very high levels of CFD accuracy and statistical studies to validate the approach.

**AV:**

Dr. Alessandro Veneziani

Biomedical applications are different from most other CFD simulations. Ten years ago, when we were doing simplified CFD simulations, medical doctors were suspicious of the results. Today, with the prevalence of accurate 3D models, the doctors have changed their views.

**MG:**

Dr. Mauro Grigioni

The recent and rapid improvement in the speed of computers and available memory size in the last decade has led to the emergence of CFD as an alternative, cost-effective means of simulating real biomedical flows. It offers a way to test theoretical conditions that cannot be tested experimentally. CFD has grown from a mathematical exercise to an essential tool for many applications. It is beginning to have a significant impact on the development of biomedical devices, such as prosthetic heart valves, rotary cardiac support

# the Future: Healthcare Industry

devices, and vascular access devices (such as cannulae, catheters and needles). CFD is useful for investigating blood dynamics in implantable medical devices, and its use in diagnostics has developed quickly during the last four years.

**Q. What are the challenges for biomedical engineers in terms of working with medical doctors, surgeons and hospitals?**

**AR:** Currently, CT scans and x-rays of patients are taken and analyzed by physicians so that decisions about surgery or pharmacological intervention can be made. Ideally, we want to get CFD into that loop. Medical doctors tend to also look for statistical validation of clinical data as proof of validity of a procedure, so to make them trust CFD when making clinical decisions, clinical studies with appropriate statistical analysis and validations will be required.

**AV:** Because surgical mistakes can be costly and life-threatening, surgeons by nature are conservative, their procedures are standardized, and they tend to be risk averse. Hence they are reluctant to change their operating procedures or adopt new products. To make such changes, the products must have demonstrable benefits for simplifying their work. Surgeons need to be convinced of the value of CFD, and educated on its benefits before they adopt it as a tool.

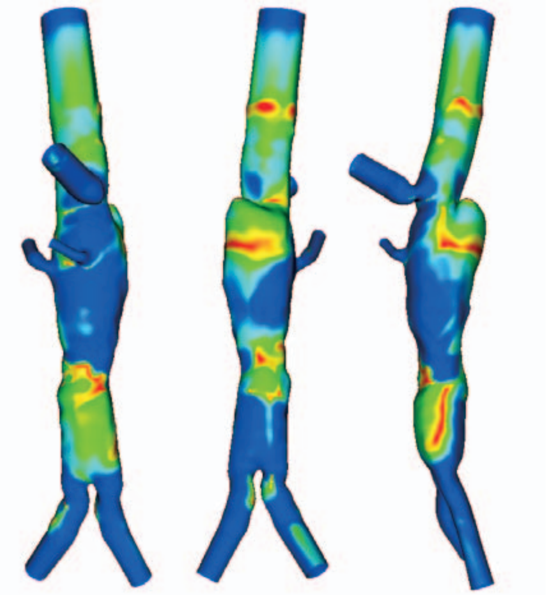
**MG:** Physicians may not be as skilled in understanding the fluid dynamics of a particular device as they are in using the device. By introducing CFD as a postprocessing tool that renders images that the surgeon can understand, he or she will be more likely to consider CFD for more widespread use.

**Q. How has CFD brought benefits to engineers in the healthcare industry?**

**AR:** CFD is currently applied in the biomedical industry for device optimization and production. It is also used as a research tool to analyze complex physiological processes that can be understood with CFD, allowing for the identification of preventative measures, such as pharmacological interventions or surgery.

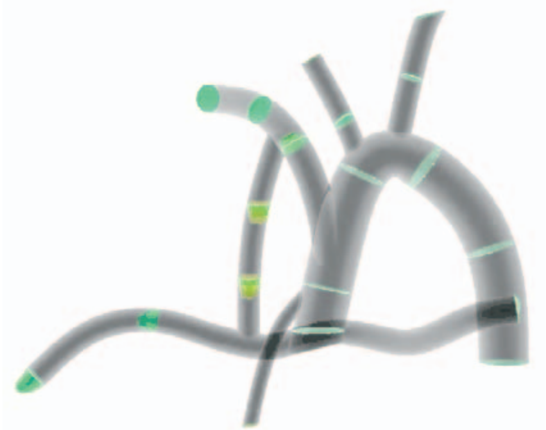
**AV:** Aneurysms are an example of a fluid-structure interaction, and surgeons need to make decisions about surgery with millimeter precision. They occasionally face ethical issues regarding operations on newborn babies, when surgical intervention can be very dangerous. With today's MRI scans that produce slices small enough to resolve the fine details of problematic organs, even in newborns, CFD analysis could be used to better understand the potential risks of the local flow conditions. Another example is the design of prostheses. Analysis of optimal properties of vascular prostheses (like stents) has been supported by CFD.

**MG:** CFD should be seen as a tool that complements experiments, and one that is most useful when accurate physical models are available. CFD helps us understand flow structures where experimental techniques cannot give adequate resolution, and provides more comprehensive flow field information than can be obtained from experiments. It is also an important tool for



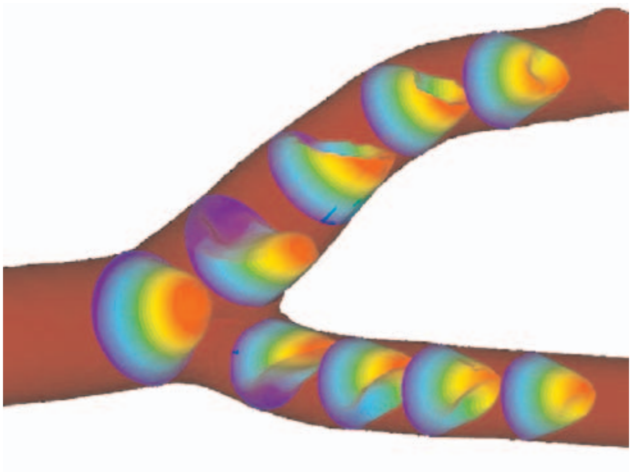
Oscillatory shear index (OSI) calculated on the basis of CFD analysis of blood flow in the abdominal aorta from a patient affected by Takayasu arteritis, or inflammation of the large arteries; the patient-specific geometric model was generated using contrast-enhanced magnetic resonance and automatic generation of a 3D computational mesh

*Courtesy of Mario Negri Institute*

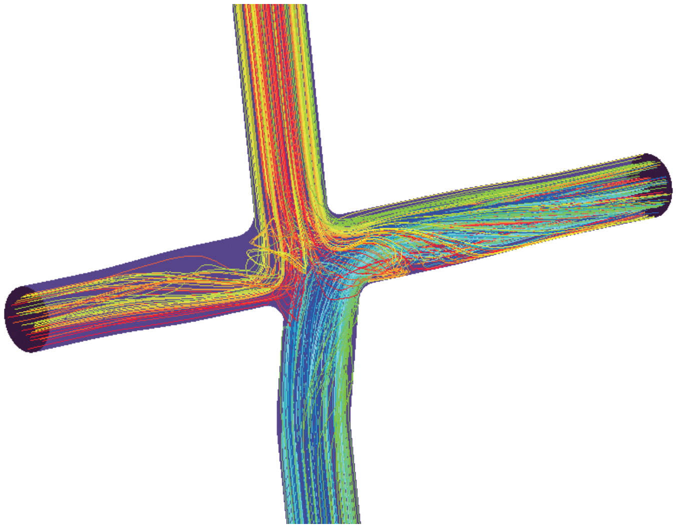


Cavopulmonary connection simulated by FLUENT using pulsatile flow and a lumped parameter model (Joint work with G. Dubini, and F. Migliavacca (Laboratory of Biological Structure Mechanics, Politecnico di Milano))

*Courtesy of Politecnico di Milano*



Carotid-bifurcation simulation (pulsatile flow, Re=300 in a cast produced by D. Liepsch and F. H. Munich); the computation was carried out with the MOX-MOCS-INRIA in-house finite element code LifeV (Joint work with K. Perktold, and M. Prosi, TU Graz)
*Courtesy of Politecnico di Milano*



A CFD illustration of Fontan surgery, where blood returning from the body is redirected to the lungs, rather than to the right side of the heart (Joint work with U. Morbiducci, C. Del Gaudio, and G. D'Avenio)
*Courtesy of Instituto Superiore di Sanita*

flow visualization. In cardiovascular bioengineering, for example, it is used for visualization of the blood flow in prosthetic heart valves, and for investigation of the role of local hemodynamics in the design of components. Despite the potential benefits it can offer, the validation of CFD predictions still represents a very significant question to be addressed in comparison with experimental techniques such as those developed at ISS (LDA: laser-Doppler anemometry, and PIV: particle image velocimetry).

**Q. What are the barriers and multiphysics challenges facing CFD usage in biomedical applications?**

**AR:** Fluid-structure interaction is a challenge in vascular CFD. What makes this approach even more complex is the nature of vessel walls that are viscoelastic. We don't know the wall properties very well in physiological conditions and diseased vessels. Moreover, the cells within the vessel wall are very sensitive to the mechanical stimulation induced by blood flows. Modeling pulsatile flow is also an important challenge. Thrombosis and atherosclerotic plaque formation are difficult to simulate as well, because they involve phase changes in the blood and changes in vessel wall composition. Deposition in arteries is another area that is still difficult to model with CFD.

**AV:** All the material properties in biomedical CFD simulations are "living" – cells, tissues and blood – and they are all very sensitive to flow fields. Something as simple as a drug-eluting stent, for example, poses several multiphysics problems for CFD: the knowledge of structural/mechanical properties, complex geometries, time dependent flows, a range of length scales in the domain, and transport phenomena with pharmacological factors. Effective numerical methods are under development for facing and solving these challenges.

**MG:** The challenge for us is to balance experimental and numerical methods for the design and premarket evaluation of medical devices. There is a need for a mixed model today and in principle, any problem can be solved as long as the boundary conditions are well posed and the physics is captured in the CFD models employed.

**Q. Where do you see CFD in the Healthcare Industry 10 or even 20 years from now?**

**AR:** Today one scan takes a day, and we need several days for CFD analysis. This time is compatible with the planning of surgery, but we hope to shorten this time considerably in the future. Some of the challenges for the future are modeling the biology at vessel walls and simulating oxygen and other small molecule diffusion within blood during drug release into arteries. Our short-term goal is to develop tools for accurate and automatic modeling of blood flow in arteries for patient-specific applications. The modeling of human hearts is still a big challenge. We need to accurately model the coronary artery flow field first, a challenge in itself!

**AV:** Healthcare is a field where CFD can have a social impact, especially with the whole concept of predictive medicine, which is a challenge for the future. Today medical doctors are flooded with a lot of data, and they need better means for interpreting that data. Maybe CFD could be incorporated into medical imaging devices. Diagnostic tools and lab-on-a-chip technology are big areas of opportunity for CFD. I think we need to map CFD predictions onto decision making trees for physicians to study and evaluate. Ideally we want to go from a scan to flow predictions within a few hours.

**MG:** Predictive virtual biomechanical models of a complete human are a possibility in the distant future. In addition, we should also use CFD to instruct the general public with interactive biomedical science tools. Perhaps there is an opportunity to interface CFD with holographic computer-generated visualization techniques. Multi-scale modeling applications would also make possible innovative learning at different levels (shorter and longer university degrees, and specialization masters degrees) in the future. ■

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