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www.ozeninc.com
info@ozeninc.com
(408) 732 4665
1210 E Arques Ave St 207
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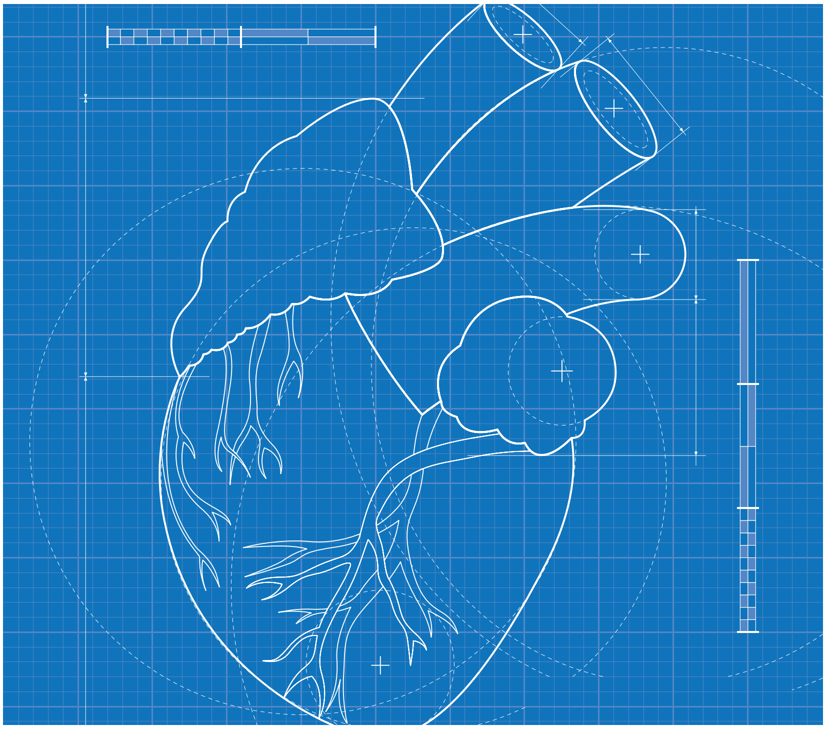
# CARDIOVASCULAR ENGINEERING

**As engineering and medicine converge, researchers are making gains in understanding and treating causes of cardiovascular disease.**

**By Santhosh Seshadhri,** Technical Services Engineer, ANSYS, Inc.



Cardiovascular diseases are the main cause of illness and premature death in the European Union (EU). This class of diseases that affect the heart and blood vessels accounts for approximately 40 percent of deaths, with a combined direct/indirect economic cost of approximately €196 billion per year. National health systems are tasked with providing health services to an increasingly aging population under tight fiscal constraints with the additional challenge of providing personalized healthcare, which tailors treatment to the individual patient. Because predictive models of cardiovascular disease and device intervention are expected to yield substantial health and economic benefits, research in this area has received increasing attention and funding in recent years.

ANSYS is playing an integral role in cardiovascular research, collaborating in EU projects @neurIST, GEMSS, COPHIT, BloodSim, BREIN and RT3S. MeDDiCA (Medical Devices Design in Cardiovascular Applications) is one such multidisciplinary and multi-center project funded by the European Community's Seventh Framework Programme. This Marie Curie Initial Training Network (dedicated to making research careers more attractive to young people) involves a number of universities across Europe that simulate cardiovascular problems of interest with the support of ANSYS engineering tools. A key goal of the MeDDiCA network is nurturing early-stage Ph.D.'s and postdoctoral researchers in a variety of disciplines to help them develop a broad range of scientific and individual skills.

State-of-the-art simulations of the cardiovascular system are based on the integration of observations, theories and predictions across a range of temporal and spatial scales. Interactions can be investigated in silico (via computer) to bring new insight about phenomena observed in vitro (in an artificial environment, such as a test tube) and in vivo (via medical testing of a living organism) and to assist in the formulation and validation of new hypotheses. The nature of such research is highly multidisciplinary, combining aspects of physics, chemistry, mathematics, engineering, computer science, biology and medicine. The following examples of cardiovascular research as part of the MeDDiCA project focus on the heart and the blood vessels.

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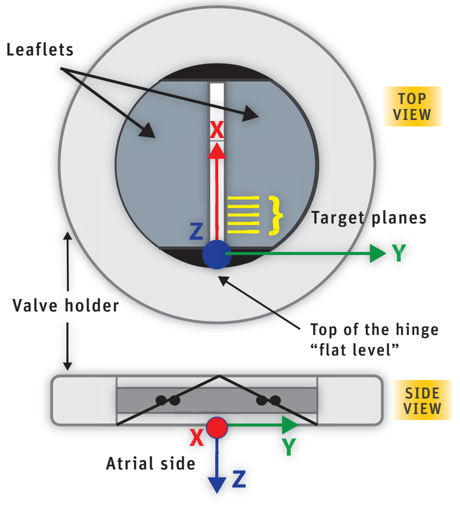
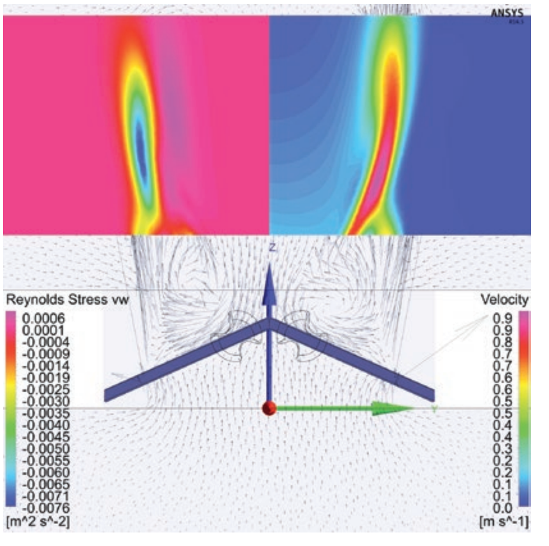


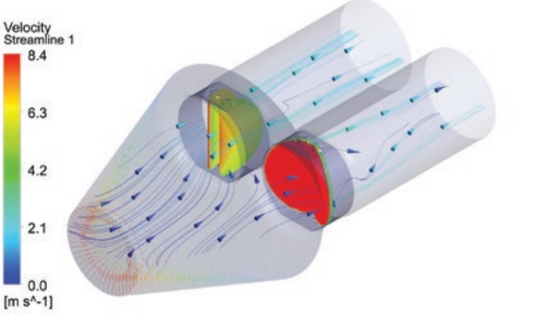




▲ **CFD simulation for velocity distributions of leakage jet of bileaflet mechanical heart valve. Results on the left side are negative because the plane is on the negative side of the y-axis.** COURTESY TECHNICAL UNIVERSITY OF CLUJ-NAPOCA, ROMANIA AND ISTITUTO SUPERIORE DI SANITÀ, ITALY.

## HEART VALVES

Today, physicians routinely replace damaged or deteriorated valves in the human heart. Now that the surgical challenges of the procedure are largely overcome, what remains is a complex engineering challenge: to design a valve prosthesis that matches the function and performance of a healthy heart valve. Bileaflet mechanical heart valves (BMHVs) are utilized often because they do not suffer from durability issues. However, they must satisfy certain characteristics, including backflow leakage during valve closure, which is vital for healthy valve dynamics. This backflow helps to prevent areas of stagnant flow and inhibits microthrombus (blood clot) formation. However, if the magnitude of shear stress due to the retrograde flow is too large, it can lead to platelet activation that causes blood clots or hemolysis (the abnormal breakdown of red blood cells).

To evaluate and optimize the effectiveness of a valve design requires analyzing its flow dynamics. However, it is challenging and time-consuming to obtain detailed measurements solely using in vitro methods. Computational fluid dynamics (CFD) allows researchers to study flow dynamics at high resolution,




▲ **Representation of flow field inside lumped parameter to 3-D coupled model of left heart and arterial system at peak systole (heart muscle contraction). This FSI model represents the movement of both the ventricular walls and the leaflets to investigate valve–valve interaction.** COURTESY TECHNICAL UNIVERSITY OF CLUJ-NAPOCA, ROMANIA.

**With surgical challenges largely overcome, what remains is a complex engineering challenge — to design a valve prosthesis that matches the function and performance of a healthy heart valve.**

particularly in areas that are not visually accessible. Validation with experiments can be necessary to confirm that CFD results are accurate. MeDDiCA researchers have compared observations of the leakage jets for a BMHV obtained in experiments using particle image velocimetry, a method that measures velocities in fluid by taking two images shortly after each other, to findings from CFD predictions using ANSYS software. Researchers determined that comparison of CFD results to experiment is reasonable for the fully closed position of the valve.

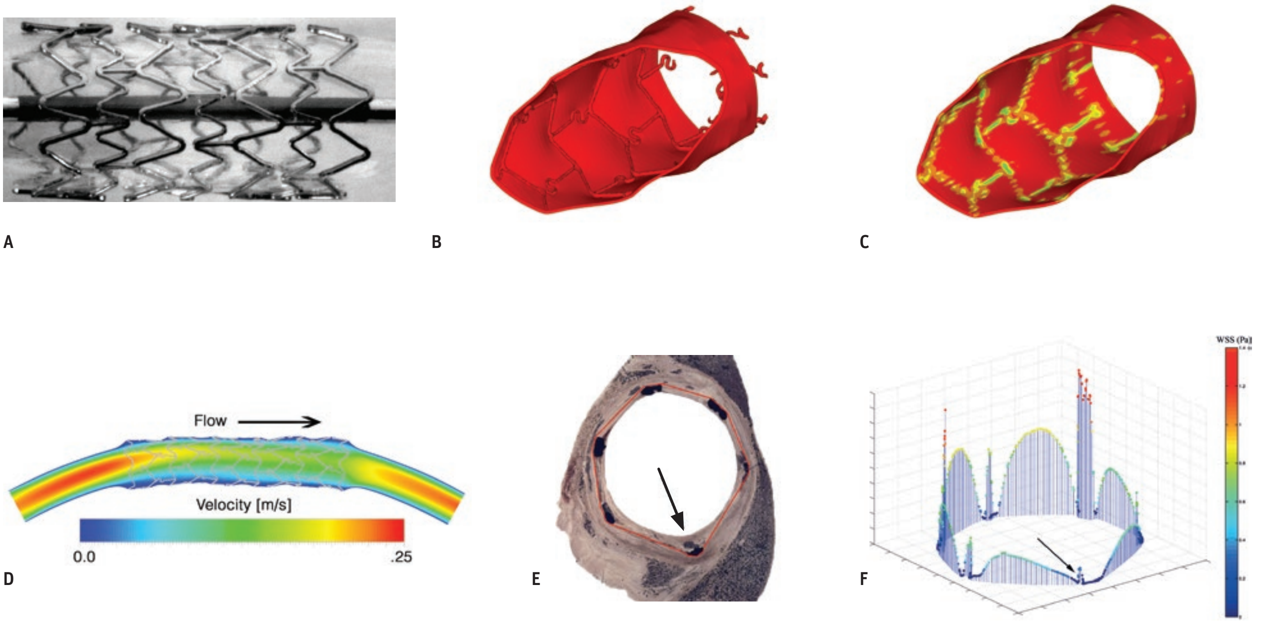
Artificial valve function is driven by interaction between the blood (fluid) and the motion of the solid valve structure. Simulating the dynamic fluid–structure interaction (FSI) of heart valves is challenging, but, over the past decade, simulations have become increasingly realistic, evolving from conceptual 2-D geometries to patient-specific 3-D geometries. Research within MeDDiCA employs a novel multiscale model of mitral heart valve dynamics that incorporates features from the cellular level — the actin–myosin cross-bridge cycle and calcium dynamics that give rise to the heart's beating. To specify boundary conditions, the model uses a geometrical multiscale approach that couples lumped-parameter models (of lower dimension) with 3-D models. Some features are modeled at a high level of detail (3-D domain), while the remaining part of the system is simplified to a lumped-parameter representation

Multiphysics and multiscale modeling allow FSI to be investigated in silico. Modeling helps to assess the fluid mechanics of prosthetic heart valves and to improve the design of these devices by minimizing the potential for blood clots and increasing valve durability. Implementation of moving mesh algorithms in ANSYS CFD software allows researchers to analyze fluid dynamics in a more realistic way compared to non-FSI simulations — for example, to provide information about valve leaflet motion during opening/closing stages and to determine dynamic leaflet stresses. By coupling a multiscale model of left-ventricle contraction to a three-dimensional FSI model of a bileaflet mechanical heart valve, researchers can gain insight into the global biomechanics of the valve, leading to studies that investigate possible sources for hemolytic and cavitation drawbacks.

Researchers used coupling between 0-D models (MATLAB) and 3-D CFD models to exchange pressure and flow values. This multiscale, multiphysics model enables a more-detailed understanding of flow-induced stresses on valve mechanics based on physiological changes to pressures and flows. It allows researchers to study the influence of biological parameters and variables at various scales, and it also provides insight into underlying biological mechanisms that affect functionality of the mitral valve under both healthy and diseased conditions.

## STENTED VESSELS

Arterial restenosis is the recurrence of narrowing of a blood vessel (usually a coronary artery) after corrective surgery to



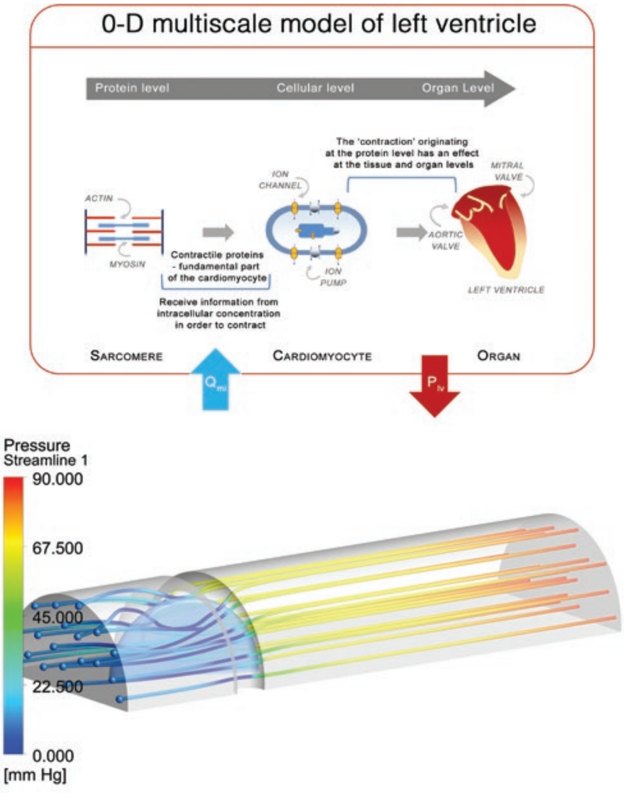

▲ Structural mechanics and fluid dynamics can be used to study the formation of thickened artery walls after a stent implant. A) Bare metal stent. B) Finite element model in initial configuration (7.5 mm length, 2.8 mm diameter cylinder) prior to radial expansion of vessel wall. After expansion and subsequent release of stent, C) stress contours on inner surface of vessel. D) Use of CFD to analyze coronary stent, implanted in porcine coronary artery and reconstructed from micro-CT, for identification of regions prone to formation of in-stent restenosis; velocity plotted on transversal plane of stented geometry. E) Comparison of histology to identical cross-section of numerical domain; traced red line depicts internal vessel structure, which corresponds with numerical model. Arrow indicates same position in histology F) numerical plot of wall-shear stress. COURTESY UNIVERSITY OF SHEFFIELD UK AND POLITECNICO DI MILANO, ITALY.

remove or reduce a previous narrowing (stenosis). It is a significant limitation for long-term success of endovascular interventions (minimally invasive surgery performed though major blood vessels) such as stent implants, in which a wire mesh is guided through the vessel to the location of a narrowing and expanded once in place to improve blood flow. In fact, despite improved success rates of stent implantation to relieve a thickened artery wall (an occlusive atherosclerotic lesion), acute inflammation of the vessel wall and resultant in-stent restenosis still occur in 20 percent of all bare-metal stent cases.

The severity of restenosis is associated with both initial injury of the arterial wall during stent deployment and subsequent biological response over time. Local fluid dynamics might affect the migration pattern of smooth muscle cells and endothelial cells that line the heart and blood vessels during initial healing stages, so wall-shear stress due to blood flow may be a potential accelerator. The interaction between the stent and the vessel is complex; it is challenging to study this process in vivo. Investigating the structural mechanics and fluid dynamics of stented vessels can give insight into the processes governing initiation and progression of restenosis. It also can provide guidance for optimizing stent design.

Placement of a stent into the artery changes both the structural and the hemodynamic environment of the vessel. Experimental techniques can be applied to study stent deformation in vitro, using stereo-optical methods to measure 3-D stent geometry. However, detailed experimental measurement of stress distribution within the vessel wall is not possible, so a finite element (or structural mechanics) model (FEM) is a powerful tool for studying changes in the artery's mechanical environment following stent implantation. Corresponding images of the tissue structure allow researchers to correlate the occurrence of restenosis and vascular wall stress. Additionally, computational fluid dynamics of the altered vascular geometry after stent implantation provides very detailed information regarding flow domain, including local variations in wall-shear stress, which is impossible to measure experimentally in complex geometries and in vivo.

To examine structural and fluid dynamic changes following stent implantation along with their possible association with biological outcomes, researchers simulated a porcine right coronary artery using the in vivo stent geometry reconstructed from micro-CT data (use of X-rays to determine the 3-D structure). Because corresponding tissue images were available, a direct correlation could be made with structural mechanics and CFD results. Using computational analyses, MeDDiCA researchers identified the regions of the stented artery that were subject to higher compressive stress and to a reduction in mean fluid wall-shear stress areas that may be more prone to formation of restenosis. By using stent geometry derived from in vivo data of an implanted stent, the availability of corresponding tissue data allows the




▲ **A multiscale model of the heart is used to compute left ventricular pressure, which, in turn, is employed as a boundary condition for ANSYS CFX software using an immersed boundary approach to simulate the dynamics of the mitral valve.** COURTESY UNIVERSITY COLLEGE LONDON.

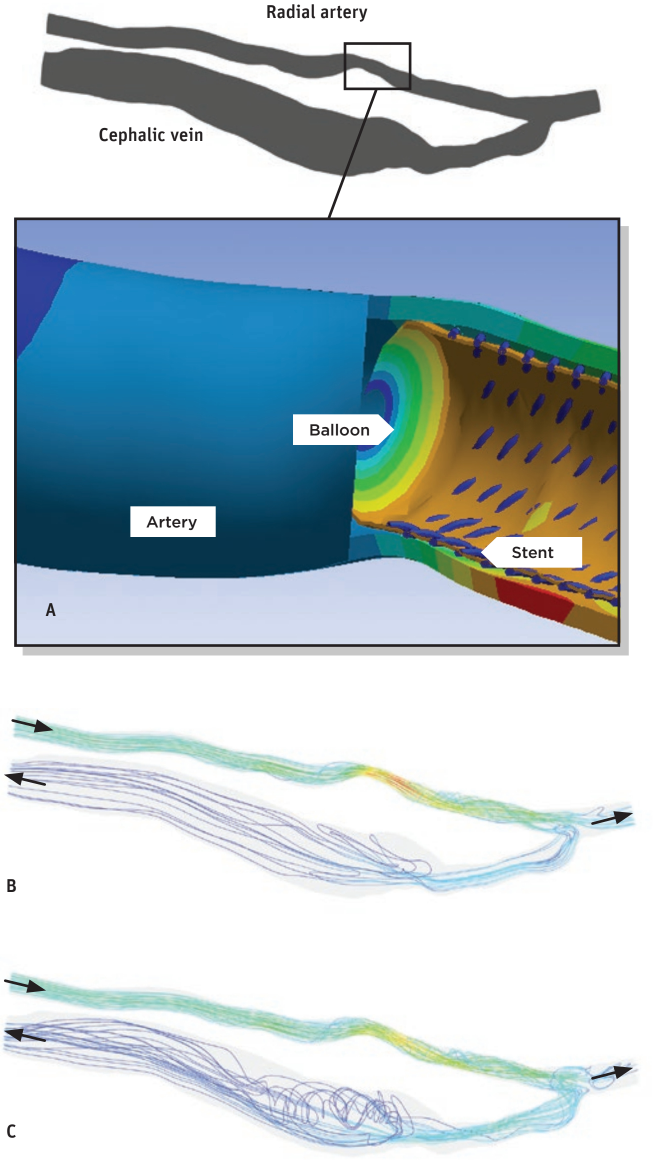
**CFD of altered vascular geometry after stent implantation provides detailed information regarding the flow domain, which is impossible to measure experimentally.**

mechanobiology of stent implantation to be explored in detail. Further studies of the relationship between localization of vascular wall stress, fluid dynamic parameters and in-stent restenosis will provide a deeper understanding of the phenomenon, leading to the identification of new design solutions and helping to guide developments in clinical techniques to unblock arteries.

## ACCESSING THE CIRCULATORY SYSTEM FOR HEMODIALYSIS

Because there is a lack of kidney donors, the majority of end-stage renal disease patients need to be treated with hemodialysis. This treatment uses an external machine to perform some kidney functions by circulating the patient's blood through it; therefore, it requires creating a permanent vascular access, typically obtained by connecting a vein onto an artery to form an arteriovenous fistula (AVF) into which a catheter can be inserted to connect to the hemodialysis machine. The hemodynamics inside the AVF is likely to induce several complications, but clinical tests are unable to determine which sites are more prone to cardiovascular problems. Modeling can help to answer clinical questions about local hemodynamic and structural stresses and their relationship with the onset of complications from AVF formation. The treatment of these complications can also be simulated.

MeDDiCA researchers have employed ANSYS fluid dynamics and structural mechanics software to study fluid–structure interactions within a patient-specific AVF that develops an arterial stenosis. The results highlight the regions of the vasculature that are more prone to complications due to altered hemodynamics and wall mechanics. The team also has numerically simulated treating the stenosis with two therapies: balloon angioplasty, with and without subsequent stenting. Comparing the results of the FSI simulations before and after treatment, the research team identified the influence of the stenosis on blood flow and wall stresses. Both treatments are equally effective in restoring the heart's work load, but stenting may help to prevent restenosis in the months following treatment by preventing contraction of the vessel.




**Geometry of patient-specific arteriovenous fistula; A) magnification shows ANSYS simulation of stent deployment following balloon angioplasty. B) Velocity streamlines at peak systole in stenosed patient-specific case and C) after endovascular treatment by balloon angioplasty. Notice that the treatment locally reduces maximum velocity value at the stenosis, but hardly impacts blood flow distribution farther downstream.** COURTESY UTC-COMPIÈGNE, FRANCE.

## SIMULATION DELIVERS NEW MEDICAL INSIGHT

Modeling and simulation are well-established practices in the aeronautics and car manufacturing industries; the methods are an integral part of the design process. Similarly, these techniques are utilized to guide the design of medical devices, such as stents and artificial heart valves, by simulating their mechanical interaction with the vessel wall and blood flow dynamics. It is, however, more challenging to model the biological interaction of medical devices with the vessel wall, especially as the disease evolves. Researchers should not think of these as merely biological problems, but rather as mechanobiological problems — the mechanical environment plays a governing role for the biology. Mechanical analyses play a vital role in understanding biology and predicting biological processes. State-of-the-art simulation models integrate observations, theories and

**These are not merely biological problems, they are mechanobiological problems — the mechanical environment plays a governing role for the biology.**

predictions across a range of temporal and spatial scales, scientific disciplines and anatomical subsystems. Models that enable the cardiovascular system and its interactions to be investigated in silico can shed new light on phenomena observed in vitro and in vivo, assisting in the formulation and validation of new hypotheses and integration of novel, improved clinical tools to guide diagnosis and optimize personalized treatment. ANSYS software is already playing a vital role in such models and will play an increasingly important role in the future.

### Author's Note

Contributors to this article include: **Paul Watton,** University of Oxford, U.K.; **Justin Penrose,** ANSYS; **Benjamin Bhattacharya Gosh** and **Vanessa Diaz,** University College London, U.K.; **Brandis Keller, Gabriele Dubini** and **Francesco Migliavacca,** Politecnico di Milano, Italy; **Claudia Maria Amatruda, Iwona Zwierzak** and **Andrew Narracott,** University of Sheffield, U.K.; **Iolanda Decorato** and **Anne-Virginie Salsac,** Université de Technologie de Compiègne, France; **Li Yan, Rajeev Kumar Nallamothu** and **Dan Rafiroiu,** Technical University of Cluj-Napoca, Romania; **Guanglei Wang Giuseppe D'Avenio** and **Mauro Grigioni,** Istituto Superiore di Sanità, Italy.

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