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Original Article

What is the role of biomechanics in cardiac surgery?

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CARDIAC SURGERY IS A DISCIPLINE AIMED AT restoring the best cardiac function of diseased hearts. It is often necessary to implant devices, and surgical tools are of great help in achieving faster and safer procedures. Paediatric cardiac surgery is a more recent specialization of cardiac surgery. In paediatric cardiac surgery, the problem is usually related to congenital malformations, consisting in the main of anatomical abnormalities which produce, among other problems, poor oxygenation of the blood, high cardiac afterload, cardiac failure, hemodynamic problems during growth, and so on. The paediatric cardiac surgeon uses his skill and experience to determine the optimal correction in each individual case. In many cases, however, it is not easy to predict the effects of the given surgical procedure that, for success, depends on many different parameters.

Biomechanics is a discipline which studies the mechanical phenomenons that takes place in the biological world. It is very common to suppose that biomechanics is the application of mechanics to biology, thus implying that biological matter is only that part of the physical world in which we observe the biological phenomenons. This approach, however, is dated, and biomechanics is now regarded increasingly frequently as an alternative means of making progress in biology and medicine. One of the most widely acknowledged books on biomechanics was written by Y.C. Fung in 1981, with the subtitle "Mechanical properties of living tissues". What is characteristic and enlightening in this concise definition of biomechanics is the word *living*, which refers to the exclusive feature of the biological matter. "Living" means being able to react, to grow, to modify, to reproduce, and to die. The motion of blood is one of the topics studied in biomechanics. Two different approaches can be used to stud ymotion the motion of the blood: the experimental approach and the mathematical one. The experimental option has the advantage of being very close to the real system under study. An experimental model may be realized by connecting elastic tubes in which a proper fluid may be forced to flow. The major pitfalls of this experimental approach are the high cost of building the modal, the difficulties of measuring the variables in fluid dynamicsand, as a consequence, in being able to make precise measurements, thus rendering it impossible to produce a parametric model. This last pitfall indicates the need to build a model for every anatomic configuration. The mathematical approach, in contrast, and in particular the numerical approach, makes it possible to study three-dimensional models that are not only geometrically complex, but also fully parametric. The main drawbacks of the mathematical approach are found in the high computational costs when the adopted model has a complex geometry, in the difficulty of applying proper boundary conditions, and in the needto simplify the description of the model. Suitable comparisons between the experimental "in vitro" model and the mathematical numerical model, nonetheless, show that the numerical approach, if used properly, offers the better chances of previewing fluid dynamic behaviour in the cardiovascular system.

The mathematical model is a set of mathematical equations that embodies the fundamental concepts

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and assumptions of a theory. It serves to put hypotheses into concise quantitative forms. Once a mathematical model has been defined, it can be used to calculate the effects of changing any parameters by means of simulations. In this respect, it may be important to clarify the main feature of any fluid dynamic system that is to be considered during a simulation. One set of variables is those usually measured in hemodynamics, namely pressure and the rate of flow. These global variables are generally considered nearly constant along a short vessel, thus not being modified in space, but only in time. The other set of variables is local, and includes pressure and velocity. These variables are considered dependent on both time and location. Velocity is a vector, hence having a direction, as well as three space components. The local variables are usually neither measured nor used in the clinical routine. Experimental simulations make it easy to measure global variables, but it is very difficult experimentally to measure local variables. Using numerical simulations, in contrast, it is an easy matter to calculate the local variables, these being the global ones derived by the local conditions.

Computational fluid dynamics is a mathematical approach for determining a numerical solution of the equations governing the flow of fluid,while advancing the solution through space or time to obtain a numerical description of the complete flow in the field of interest. The role of computational fluid dynamics in making engineering predictions has become so strong that, today, it may be viewed as a new third dimension of fluid dynamics, the other two dimensions being the classical ones of pure experiment and pure theory. The development of more powerful computers has furthered the advances being made in the field of computational fluid dynamics. In consequence, computational fluid dynamics is now the preferred means of testing alternative designs in many engineering companies before final experimental testing takes place, or even rendering such experimentation unnecessary.

When seeking to simulate the fluid dynamic behaviour of the cardiovascular system, as when evaluating an anatomical congenital malformation, one should consider some difficulties. The geometry is fully three-dimensional, the motion of blood is pulsatile, the blood is a suspension of particles, lacking Newtonian viscous properties, the walls of the vesselsare deformable, may be displaced and have visco-elastic mechanical properties, and the biological matter, in particular blood, may show biological reactions to the local fluid dynamic behaviour. As examples, we should remember that haemolysis may be caused by stress on the red blood corpuscles, coagulation of the blood may be caused by its stagnations, damage to the arterial wall may be caused by wall shear stress, and the local morphology unequivoically influences the global hemodynamics.

The use of mathematical models in haemodynamics allows us not only to know the values of local quantities, but also to predict them. But the fluid dynamic problem has to be greatly simplified if it is to be approached and solved. At the moment, there is a lack of quantitative knowledge of the biological response to local hemodynamics.

Typical current applications of computational fluid dynamics are found in seeking solutions to those problems in which it is important to evaluate the influence of either the geometry or the boundary conditions, or both. In the field of congenital cardiac malformations requiring surgical correction, an obvious example is the functionally univentricular heart. In this setting, the use of a computational model may help in the prediction of the hemodynamic changes induced by the surgery. This may be of a great importance, because the surgeon very often can choose among solutions which can show only small differences from the surgical point of view, but which can produce significant variations in fluid dynamics. To understand better, one should consider the angle and location of an anastomosis, the length and diameter of a shunt, or the extension of a patch. All of these surgical variables may strongly affect the fluid dynamic surgical outcome, with particular reference to the future growth of the patient, often undergoing treatment as a newborn.

The most complete approach requires several steps. First, it is first important to know the preoperative anatomy of the malformed heart. This may be done using diagnostic images. When these are available in the form of digital images, as is the case with magnetic resonance slices, it becomes possible to reconstruct in a very precise way the anatomy of the heart and the surrounding large vessels. The major drawback of this procedure depends on the cardiac movements that conspire against the provision of reliable anatomic data. After the geometrical reconstruction of the model, nonetheless, it is possible to modify it according to the planned surgical procedure, thus providing a model of the postoperative anatomy. It is important to stress, however, that the anatomic model is only a small part of the whole cardiovascular system. This means that proper boundary conditions, in particular the rate of flow, pressure, and their cyclic modifications, must be applied to the vascular edges of the model. Normally this is not possible, as those data are unknown. To solve the problem, therefore, the remaining parts of the cardiovascular system are simulated using a simpler model, in which it is not possible to predict local fluid dynamic variables, but which is capable of providing the required boundary conditions. Using the electrical analogy, this is the so-called lumped parameter model. The global model that is obtained may then be simulated using computational fluid dynamics software which give the values of blood pressure and velocity in every location within the fluid domain of the three-dimensional model. The interpretation of these results is not always easy, but the appropriate bioengineering and surgical knowledge and experience may help in selecting the best solutions among the different simulations. This is a typical approach, which requires the integration of different expertises, and the capability to link together two different ways of facing the same problem.

In conclusion, if the question is "what is the role of biomechanics in cardiac surgery", the answer may be "to perform predictive simulations to link preoperative data to surgical outcome". This is not the only potential use of biomechanics in cardiac surgery, but is one of the items likely to create the greatest impact. What is important is to remember the critical issues of the approach, which mainly include the difficulty in collecting complete and consistent data sets for specific patients, in defining the acceptable simplifications, in converting numerical results into clinical indications, in providing validation, and in the time to reach the "market". To provide more reliable results, and to introduce these tools in the clinical practice, it is crucial to increase the general knowledge on the role of local hemodynamics, to quantify the morphofunctional relationships, and to solve a greater number of specific problems. It is our hope that the articles published in this supplement will go some way to achieving these goals.