OPINION ARTICLE

Is Fluid Dynamics Assessment the New Stage of Cardiovascular Imaging Diagnosis?

¿Es la evaluación de dinámica de fluidos la nueva etapa del diagnóstico por imágenes cardiovascular?

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Echocardiography, as well as the different cardiac imaging techniques, has significantly evolved in the last decades.

Ultrasound machines and software continue to amaze us both in the medical setting as in biomedical engineering.

For a long time we dedicated our attention to the study of the cardiac structure and its impact on velocities, pressures and gradients. We were able to assess myocardial deformation and early predict the involvement of the left ventricular pump function, and numerous scientific studies were published correlating anatomo-functional disorders with clinical scenarios.

At present, we have the immense possibility of evaluating the inverse relationship. That is, what happens to our heart when fluid dynamics are altered and the energy this generates. Although this type of evaluations can be performed with 3D resonance imaging, this is not always available for routine practice. On the other hand, there are similar methods of intracardiac fluid analysis, but they require the use of contrast material, are dependent on the angle or can only be used with transesophageal echocardiography. (1)

Until recently, the evaluation of fluid dynamics with conventional ultrasound machines was done with spectral and color Doppler tools. However, these methods present the limitation of velocity analysis only parallel to the direction of the ultrasound beam, and the rest of the components of the complex intracavitary flow analysis could not be evaluated through this modality. (1)

In order to understand this technology, it is useful to perform a review of some concepts related to fluid dynamics, and vector and scalar fields.

Upon making a closer evaluation of intracardiac flows by echocardiographic assessment with transthoracic transducer, we can incorporate a blood flow vector map and observe that within the cardiac chamber it runs in more than one direction.

As can be seen in Figure 1, the blood that passes through the mitral valve to enter the left ventricle generates a ring of vortices which, if selected and analyzed in the bidimensional plane, show that some rotate in a clockwise and others in a counterclockwise direction. (1)

In the case described, vortices rotate in a counterclockwise direction in the space between the posterior leaflet of the mitral valve and the left ventricular posterior wall. On the other hand, at the left ventricular outflow tract higher magnitude vortices rotate in a clockwise direction.

To understand this phenomenon, we believe it is adequate to define some central concepts

Vortices: physical magnitude used in fluid mechanics to quantify rotation, given by a rotational vector. (2)

Direction of rotation and angular velocity: If an object is rotating in two dimensions, it is possible to completely describe the rotation with angular velocity. A positive angular velocity indicates that the rotation is counterclockwise, whereas a negative value indicates that the rotation is clockwise. (2)

However, the situation is somewhat more complex for intracardiac flow. It is necessary to represent both the angular velocity as the three-dimensional space direction in which the cardiac flow is rotating. To achieve this, the rotation in three dimensions is normally described using a rotational vector where both the vortex magnitude and direction are represented. To evaluate the vortex direction in a simple way, the "right-hand rule" is used. What does it consist of? The right-hand fingers are curled in the direction of the rotation and the thumb is extended. The vector that represents this rotation in three dimensions is, by definition, oriented in the direction of this finger. (2)

Another important point to consider is how a velocity vector map is generated. This technique is derived from the use of two modes, which have been very useful in echocardiographic assessment in the last years: color Doppler and left ventricular deformation assessment by speckle tracking. As previously mentioned, color Doppler only provides the velocity parallel to the ultrasound axes and, on the other hand, it is possible to obtain the transverse velocities of the left ventricular myocardium by speckle tracking. (3)

This means that blood velocity and trajectory within the left ventricle can be represented by means of myocardial transverse velocity vectors as blood flow longitudinal velocity through the color mode.

As seen in Figure 2, another point to emphasize is that having the information of the flow velocity vectors, it is also possible to represent through a parametrization map, the magnitude and direction of vortices generated in a cardiac cycle by means of a color map. (4) By convention, in this map, the vortices that rotate in a clockwise direction are represented in blue, and those that rotate in the opposite direction, in red

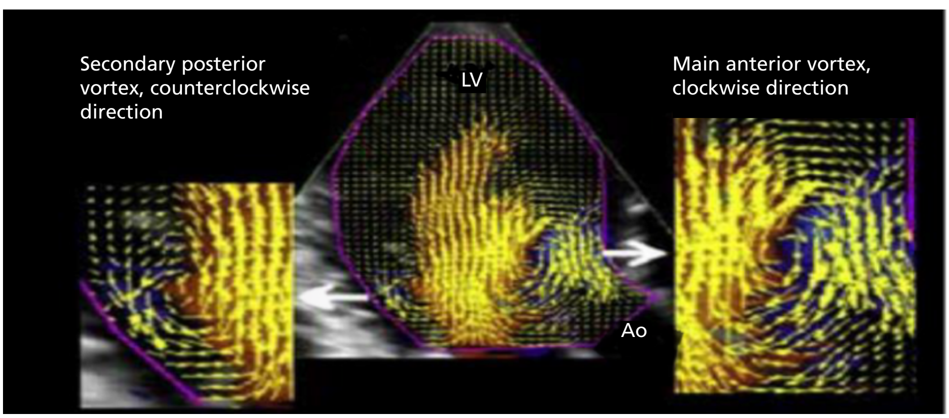
In addition, thanks to fluid velocity vectors and blood density and viscosity values, it is possible to represent a third map of kinetic energy to study the higher levels of energy generated in the left ventricle denoted in red. In a healthy patient, the highest levels of energy directly proportional to velocity variations are in the left ventricular outflow tract. In dilated cardiomyopathy, the kinetic energy analysis shows that the highest levels of energy are far from the left ventricular outflow tract, at the ventricular apical level. Then, by knowing the kinetic energy, it is possible to assess energy dissipation. This variable has been very useful to monitor healthy and ill persons, and it has been shown that patients with dilated cardiomyopathy present lower values of energy loss compared with healthy individuals (Figure 3). (4)

Possibly, the greatest clinical experience with this technique is in left ventricular systolic function impairment.

An interesting work presented by the group of the University of Padua led by Dr. Donato Mele could show the differences present in the dynamics of intracavitary flow among healthy individuals and patients with heart failure. (5) It was seen that the study was feasible and the differences present in the different evaluation parameters of intracavitary flow dynamics were reproducible, therefore providing relevant scientific support to consider it as a highly useful tool.

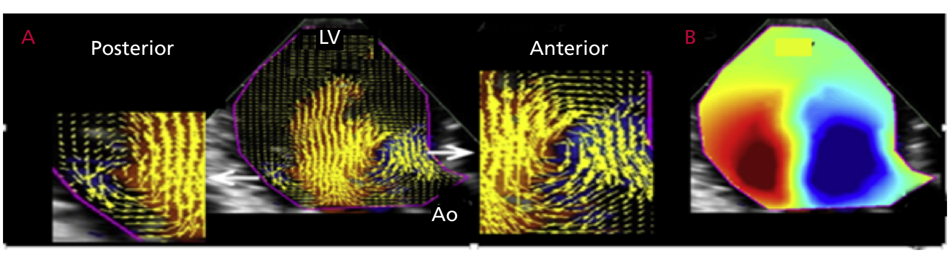
The diverse clinical scenarios in which the anatomical geometry can be affected probably impact on fluid dynamics. An example is supplied by coronary heart disease and transmural acute myocardial infarction: here the extent of infarction and left ventricular systolic function can be considered. Consequently, with this variable, it has been possible to demonstrate the relationship between the extent of the ischemic event, regional dysfunction and left ventricular systolic function with intraventricular turbulence and the fluctuation and dissipation of kinetic energy, a phenomenon that makes a significant difference in the analysis and interpretation of the consequences and implications of these events. (6)

Heart valve disease as well as valve replacement have also been evaluated with this technology, and changes have been shown in the sense of vortex rotation in dual-leaflet mechanical valves. The kinetic energy dissipation parameters are greater in patients with valve replacement compared with healthy ones. (7)



LV: Left ventricle. Ao: Aorta

Fig. 1. Vector mapping illustrating the different rotational behavior of anterior and posterior vortices.



LV: Left ventricle: Ao. Aorta

Fig. 2. To the left (**A**), vortices' vectorial field map generated in the left ventricle. To the right (**B**), vortices' magnitude and direction parametrization map

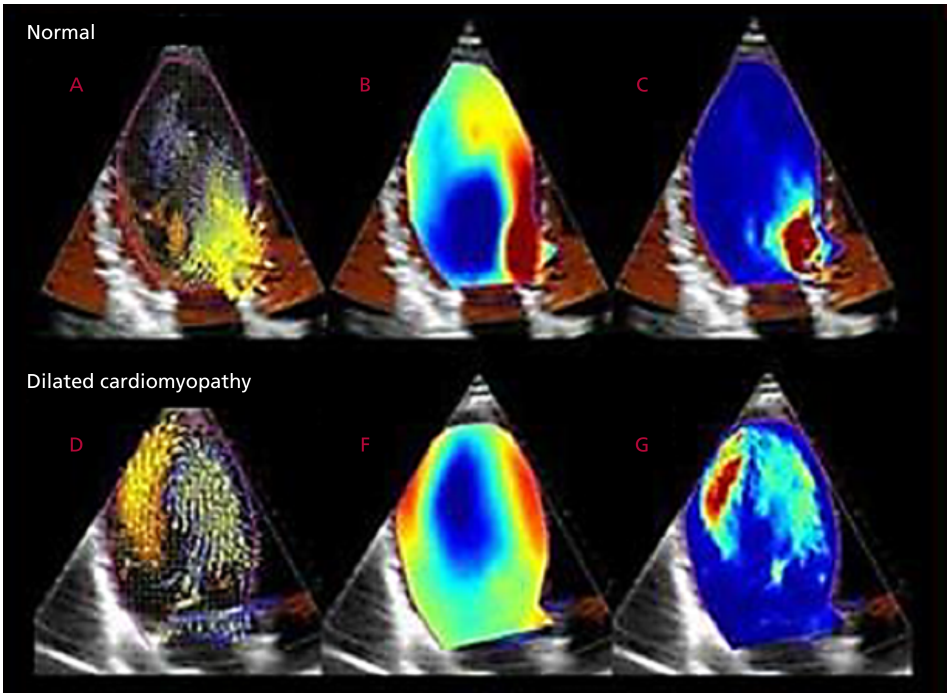


Fig. 3. Panels **A** and **D** exemplify the representation of the flow velocity vector data map, in which a 2D velocity vector field is represented as overlaid vectors in the traditional CFM (Color Flow Mode). Panels **B** and **E** show a circulation parametric map, in which vortices are represented as compact regions colored in blue (clockwise vortex rotation) or red (counterclockwise vortex rotation): Panels **C** and **F** provide representations of kinetic energy maps.

Cardiac resynchronization therapy (8) hypertrophic cardiomyopathy, (9-11) atrial fibrillation (12) and the detection of apical thrombi (6) have also been analyzed with this technology, which offers a novel aspect in the anatomo-physiological explanation of cardiovascular disease.

Once again, the association of technological and cardiology progress demonstrates that joint work defines a course where the goal is the optimization of patient diagnosis.

Conflicts of interest

None declared.

(See authors' conflict of interests forms on the web/Additional material.)

Ethical considerations

Not applicable.

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The chylous vessels. Depart without liver, wayfarer!

Los vasos quilíferos. ¡Vete de aquí, sin hígado, caminante!

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In ancient times, there was some reference to chylous vessels by Herophilus of Chalcedon and Erasistratus of Ceos, both belonging to the school of Alexandria in the 3rd century BC. It was only until the Renaissance that the topic was mentioned. Gabriele Falloppio (also Gabrielle Fallopia) (Modena, 1523-1562) and Bartolomeo Eustacchio (also Eustachio) (Rome, 1520-1574) were the first to introduce a vague reference on the topic. Eustacchio, a staunch supporter of Greek medicine, described the thoracic duct in his work "*De vena azygos*". He also described the valve at the junction of the inferior vena cava and the right atrium, which was named after him.

Notwithstanding this background, the presentation of chylous vessels as a system is due to Gaspare Aselli (also Asello) (Cremona, 1581-circa 1626). On July 23, 1662, Aselli discovered the chylous vessels in a dog. The finding was purely incidental. In the vivisection of a recently-fed dog, while observing the recurrent nerves —together with his friends A. Tadino and S. Settala—, Aselli found some white cords, which he immediately assumed to be a novel finding. However, when the experiment was repeated on a fasting animal the following day, the presence of chylous vessels was not confirmed. Aselli immediately realized that the finding was associated with the postprandial period. Therefore, by reproducing the first experience he confirmed his assumption, and called them "*lacteals*". Aselli, who was a professor at the University of Pavia, left a manuscript on the subject, "*Lectiones de Venis Lacteis*", in which he also described the venous valves of the chylous vessels, which he called "*quartun vasorum genus*"; this research study, "*De lactibus, sive lactis venis, quarto vasorum mesaraicorum genere novo invento*", was published posthumously by his friends A. Tadino and S. Settala in Milan in 1627, and included the first illustrations published in color.

However, Aselli, in line with Galen's theory, thought that the outflow of chylous vessels occurred in the liver, which is essential for blood formation. This work, launched a year before the stunning publication of William Harvey's "*De Motu Cordis*", was criticized by Harvey (did the brilliant Englishman consider his theory of blood circulation threatened?) and by Gaspar Hoffmann, a great connoisseur of Galen, and author of "*Comment in Galen de Usu Partium*" (1625).

Later on, Jean Riolano (1577-1657) confirmed the description of chylous vessels, but also in animals. The discovery in human beings was made by an anatomy enthusiast, Fabrice de Peiresc (French, 1580-1637) around 1634. In that same year, Johann Vesling (1598-1649), a famous professor in Padua, confirmed the previous experience, but still repeating Galen's errors regarding the central role of the liver. Nicolaes Pietersz Tulp (Dutch, 1593-1678) was also one of the first to describe the chylous vessels. His figure was immortalized by Rembrandt (Dutch, 1606-1669) in his famous painting "*The Anatomy Lesson of Dr. Nicolaes Tulp*".

Jean Pecquet discovered the thoracic duct; he was born in Dieppe in 1622 and died in Paris in 1674. He wrote "Experimenta nova" in 1651. In 1647, not yet qualified as a physician, while dissecting a dog, Pecquet found by chance the termination of the thoracic duct at the place where it opens into the subclavian vein; by following its course, he described the chyle cistern that would later be named after him. In his own words: "*I had removed the heart of a dog and placed it on a table. I was thinking of nothing but counting the systoles and diastoles which the last efforts of its spirit produced, when I perceived a white substance like milk flowing from the ascending vena cava into the pericardium, at the point already occupied by the right ventricle of the heart. I found that this substance —which, by taste, odor, color and consistency, could be compared to the milk or chyle I had seen flowing out of the lacteal veins— came from the subclavian branches in which I found, a little above the jugular veins, the orifices through which this milky fluid penetrated into the vena cava.*"

Thus, by demonstrating the actual path of the chyle, the liver was dethroned as the essential organ of blood formation, a fact that was hailed by the Danish Thomas Bartholin (1616-1680) with an epitaph that read: "*Stay, wayfarer. Enclosed in this tomb is one who hath entombed very many, the liver, known to the ages, but unknown to nature... So long he digested, until with his bloody tyranny himself, he digested away. Depart without liver, wayfarer! And concede bile to the liver, that without bile will thou wayst digest for thyself. Pray for him.*" The description of the thoracic duct in human beings was carried out by Jan van Horne (Dutch, 1621-1770), which was published with illustrations.

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