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EDITORIAL

Multimodal imaging and three-dimensional cardiac computational modelling in the management of congenital heart disease: The secret to getting ahead is to get started

L'imagerie multimodale et la modélisation dans la prise en charge des cardiopathies congénitales : le secret pour être plus performant c'est de s'y préparer

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Augmented reality

MOTS CLÉS
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Réalité augmentée ;
Imagerie multimodale

On 28 December 1895, a crowd milled outside the Grand Café in Paris for a mysterious exhibition. For 1 Franc, promoters promised, the audience would witness the first ''living photographs'' in history. The grainy footage of women emerging from the shadows of a factory is laughably primitive today, but in the Grand Café basement in central Paris that night, the audience gasped, applauded, and laughed. Some simply sat, dumbfounded. At that moment, brothers Auguste and Louis Lumière screened the first moving picture, or movie, in history.

Paris embraced the world's most famous museums and art galleries, alongside a thriving community of artists. Movies — considered as the ''Seventh Art'' — grew up alongside painting and sculpture. Movies were initially scorned, being considered a minor form of art, but opinion has since changed. Today, most people prefer watching movies to viewing sculptures or paintings during their leisure time. Movies are far more realistic in their depiction of life, compared with static two-dimensional (2D) or three-dimensional (3D) representations. Unlike a painting or sculpture, movies also demonstrate motion, making the recording of history possible. Therefore, allow us to play devil's advocate: why is the scientific community still applauding 3D printing from DICOM images? Nowadays, this community faces a technological rupture, with the development of augmented reality and virtual reality. Do we have to wait for another century to pass before we take the plunge?

Congenital heart disease (CHD) encompasses a heterogeneous set of malformations. As children who undergo CHD repair are increasingly likely to survive to adulthood, the population of adults with CHD is swiftly increasing in size and complexity, including for example hybrid repairs [1]. An increasing body of evidence suggests that outcomes can be improved by referral to specialized centres with multidisciplinary teams dedicated to clinical care, training and research in CHD. Nevertheless, in everyday clinical practice, the merger of multidisciplinary skills does not necessarily lead to better understanding, even with access to expertise in CHD surgery, cardiology, ultrasound, interventional cardiology, intensive care, paediatrics, neonatology and anaesthesiology. Each of the experts in these areas forges his or her own view of the complex anatomical

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truth, using the tools he or she relies on, and this can inevitably lead to misunderstandings. Based on each physician's preferred modality, be it computed tomography (CT), 2D/3D ultrasound, magnetic resonance imaging (MRI) or digitalized angiography, individual perceptions of the disease are indeed heterogeneous. Therefore, multidisciplinary discussions on the ''perfect repair procedure'' are fiercely debated. This issue highlights the need for a universally understood language, which represents the anatomical and functional truth of the CHD, regardless of the type or stage of previous repairs [2].

The more complex the CHD, the more ''personalized'' the surgical procedure should be [3]. There is an extreme morbidity and mortality difference between a full repair and a palliative decision [4]. Consider, for example, the family of ''vascular malposition''. The lack of hindsight and legibility on these pathologies limits the biventricular repair and therefore the reconstruction of a ''normal'' heart. Suboptimal repair implies sanctions, and intensive care for CHD validates this idea. No matter how well-trained the attending physician in the intensive care unit, there will always be a poor outcome if the surgical procedure is imperfect. This lack of perfection leads to immediate postoperative complications and poor long-term cardiac function (due to ventricular ejection obstacle, compliance impairment, valve dysfunction, rhythm issues, vascular stenosis, etc.). Proper repair implies a multidisciplinary decision that is often fraught with consequences. What if advanced digital technologies can simulate the surgical result? What if testing several settings and determining the best repair procedure for a complex CHD becomes a reality?

Multimodality imaging is, in essence, the combination of imaging modalities. It may provide a better solution to overcoming the limitations of each separate technique. Multimodality imaging may provide a unified anatomical and functional image of the truth. It merges the best information provided by each modality for a given CHD regardless of the stage of the repair. Using this approach simplifies the insights. For example, digitalized angiography gives vascular 2D image projection but reveals little spatial information, and provides good information about blood flow. In contrast, MRI and CT scans provide a higher spatial resolution (Fig. 1), but with a significantly lower level of dynamics and motion resolution; both MRI and CT suffer from a lack of resolution for valvular imaging. 3D ultrasound provides a very good assessment of dynamics with a medium resolution of the valves and the chordae tendinae. Combining the imaging modalities expands the scope of information available while performing the best trade-off possible. This multimodal approach improves the precision of the information and gives physicians access to a unified truth.

Technically, multimodality imaging leads to a single image file that can be queried. The process starts with each image modality, to which transformations are applied (with respect to quality), to achieve coregistration and temporospatial normalization. Reports in the literature have mentioned processing between morphological imaging (CT and MRI) and ultrasound, because these modalities are widespread [5], or multimodality imaging for interventional cardiology [6]. Whereas research into multimodal imaging has been ongoing for a long time, the technology itself is only just beginning to mature [7]. The entire batch processing relies on 3D + time REALIGNMENT (motion correction: adjust for movement between slices and modality, slice timing and syncing), COREGISTRATION (overlay structural and functional images from modalities), optional NORMALIZATION (warp images to fit to a standard template heart, time warping), SMOOTHING (increase signal-to-noise ratio), and then UNWARPING/SEGMENTATION/MODELLING [8]. In the future, one can expect that these modalities will be merged with coronary angiography, scintigraphy, high-resolution electrocardiography, biomolecular imaging, and so on. Morphological imaging and time resolution, computational power brought by graphic processing units (GPUs), and mathematical processing for modelling are properly attuned to each other.

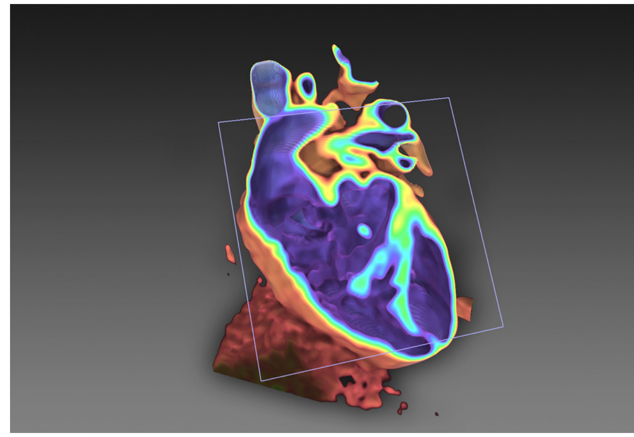

Figure 1. Anatomical modelling of a congenital heart disease (ventricular septal defect) with a perimembranous defect and straddling of the tricuspid valve. Once computing is performed, staff can easily navigate inside the heart and gain access to a unified truth.

Multimodality imaging is the leading approach in terms of excellence in precision/personalized medicine. It is mandatory in the era of big data (and complex analysis), and will also be used in simulation [9]. Through virtual reality, the multidisciplinary staff gain access to 3D navigation/simulations inside the CHD (with cheap stereoscopic glasses) [10]. Surgeons may imagine and test several procedures, and ''virtually'' repair the CHD on a computer-aided design software (Fig. 2), as we have done [11]. Once complete, which may be difficult, it is possible to simulate blood flow inside the model, and compare the quality of these procedures with computational fluid dynamics tools [12]. Taking the turbulence intensity of the blood flow into consideration, one can determine which approach is the most appropriate. This preclinical simulation needs to be compared with the results reported in the literature, but it is very helpful for complex CHDs, where the evidence is lacking. Through virtual reality, surgeons may practice, through simulation, a specific procedure, rather than trying it out first on a living patient [13]. Beside this, cardiovascular imaging is performed in physiological conditions (Fig. 3), whereas the surgeon will carry out the repair on a discharged heart (i.e. on cardiopulmonary bypass). The difference between these two conditions may be a cause of error. The use of augmented reality in the operating room, based on multimodal imaging with real-time GPU processing,