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Modern tools in congenital heart disease imaging and procedure planning: a European survey

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Aims Congenital heart diseases (CHDs) often show a complex 3D anatomy that must be well understood to assess the pathophysiological consequences and to guide therapy. Three-dimensional imaging technologies have the potential to enhance the physician's comprehension of such spatially complex anatomies. Unfortunately, due to the new introduction in clinical practice, there is no evidence on the current applications. We conducted a survey to examine how 3D technologies are currently used among CHD European centres.

Methods Data were collected using an online self-administered survey via SurveyMonkey. The questionnaire was sent via e-mail and the responses were collected between January and June 2022.

Results Ninety-eight centres correctly completed the survey. Of these, 22 regularly perform 3D rotational angiography, 43 have the availability to print in-silico models, and 22 have the possibility to visualize holographic imaging/virtual reality. The costs were mostly covered by the hospital or the department of financial resources.

Conclusion From our survey, it emerges that these technologies are quite spread across Europe, despite not being part of a routine practice. In addition, there are still not enough data supporting the improvement of clinical management for CHD patients. For this reason, further studies are needed to develop clinical recommendations for the use of 3D imaging technologies in medical practice.

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Introduction

The most commonly used tools in the diagnostic assessment of congenital heart disease (CHD) include computed tomography (CT), MRI, echocardiography and cardiac catheterization. These imaging techniques allow the generation of 2D and 3D visualizations of the anatomy and hemodynamic consequences of CHD. This plays an important role in understanding the complexity of CHD and assisting pre-procedural planning of cardiac procedures.

Despite useful information provided by these imaging modalities, the images remain limited to be viewed on 2D screens, which restricts the 3D volumetric data to a single plane of view, precludes direct interaction with the image and hampers the perception of depth and spatial relationships; therefore, physicians have to 'build' a personal understanding of the 3D anatomy.[1]

In recent years, various 3D imaging techniques for CHD [3D printing, holographic imaging and 3D rotational angiography (3DRA)] have become available. However, it is still not known to what extent these technologies are actually used in European centres, what the reasons are and what financial resources are used to cover the costs.

The aim of this article was to fill this knowledge gap by means of a web-based survey.

Materials and methods

Design, participants and procedure

Data were collected using an online self-administered survey via SurveyMonkey, following the recommendations for conducting web-based surveys. We chose to perform a

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web-based survey because this approach was described as functional to capture responders' perspectives and to facilitate answers, acknowledging the adaptable layout of the web interface developed to fit with the responders' devices such as a tablet or a computer.

The targeted centres were identified among all European centres taking care of patients with CHD, in collaboration with the Adul Congenital Heart Disease working group (ACHD-WG) of the Association for European Pediatric and Congenital Cardiology (AEPC).

The survey

The survey contained 24 items divided into two sections: (the complete list of the Items is reported in Appendix):

(i) the first section aims to characterize the participating centres;
(ii) the second section investigates the use/purpose/costs of the different 3D imaging techniques.

An e-mail, including study rationale, invitation to participate and a link to the online questionnaire, was sent to the respective head of the unit. The estimated completion time was about 10 min. The answers were received anonymously, and the questionnaire was made so that each centre was allowed to answer one time only. Every 2 weeks, the answers were collected, and a reminder was sent to the non-responders. The responses were collected between January and June 2022.

Statistical analysis

The answers (multiple when applicable) were collected on SurveyMonkey, which converted them into an Excel file. The file displays each question of the survey on a single line; then, we proceeded to modify the file, in order to convert every question and answer into a variable that would have been possible to analyse further (data clearing).

Descriptive statistics for categorical variables, done using the χ^2 test (SPSS, Inc., Chicago, Illinois, USA), are reported as frequency and percentage, whereas continuous variables are reported as mean with standard deviations. The results are summarized in tables and/or bar graphs.

Results

Overall, the survey was completed by 98 of 208 centres (47% response rate).

These centres are located in 24 European countries, as shown in the map in Fig. 1. Note: one centre did not specify its location.

Centres overview

Most of the centres that replied are actively involved in research and training activities, in addition to being part of universities (Fig. 2). Most centres follow both paediatric and adult congenital patients (Fig. 3).

In addition, most of the centres have a cardiothoracic unit able to operate on both paediatric and adult patients with CHD (Fig. 4).

The number of surgical procedures performed per year are reported in Figs 5 and 6.

3D imaging

The data set required to make 3D imaging was mostly derived from CT scans (88%). Less frequently, they were provided by cardiac magnetic resonance (CMR) or transthoracic or transesophageal echocardiography.

3D printing

Out of the 98 centres that participated, 43 have the availability to regularly print in-silico models.

Still, some of the centres that declared not having the availability to print 3D in-silico models manage to get them perhaps using an outsourcing provider (Fig. 7).

Furthermore, the models are mainly requested by a surgeon or a cardiologist. In a minority of cases, they are requested by a radiologist or other specialists (Fig. 8).

The main reasons to print an in-silico model are aimed at procedural planning of cardiac surgeries and catheterizations, as shown in Fig. 9.

The 3D facility is mostly shared across the divisions within the hospital; in 26 centres, this facility is only for exclusive use of the paediatric/congenital cardiology divisions. In addition, in 27 centres, the 3D printing facility is based on an outsourced facility, and in 42 centres on an in-house 3D printer.

Finally, centres reported that 3D printing-related costs are mainly covered by the cardiology/surgery service or by the hospital. Only in a few cases, they are covered by the patient or reimbursed by the NHS (Fig. 10).

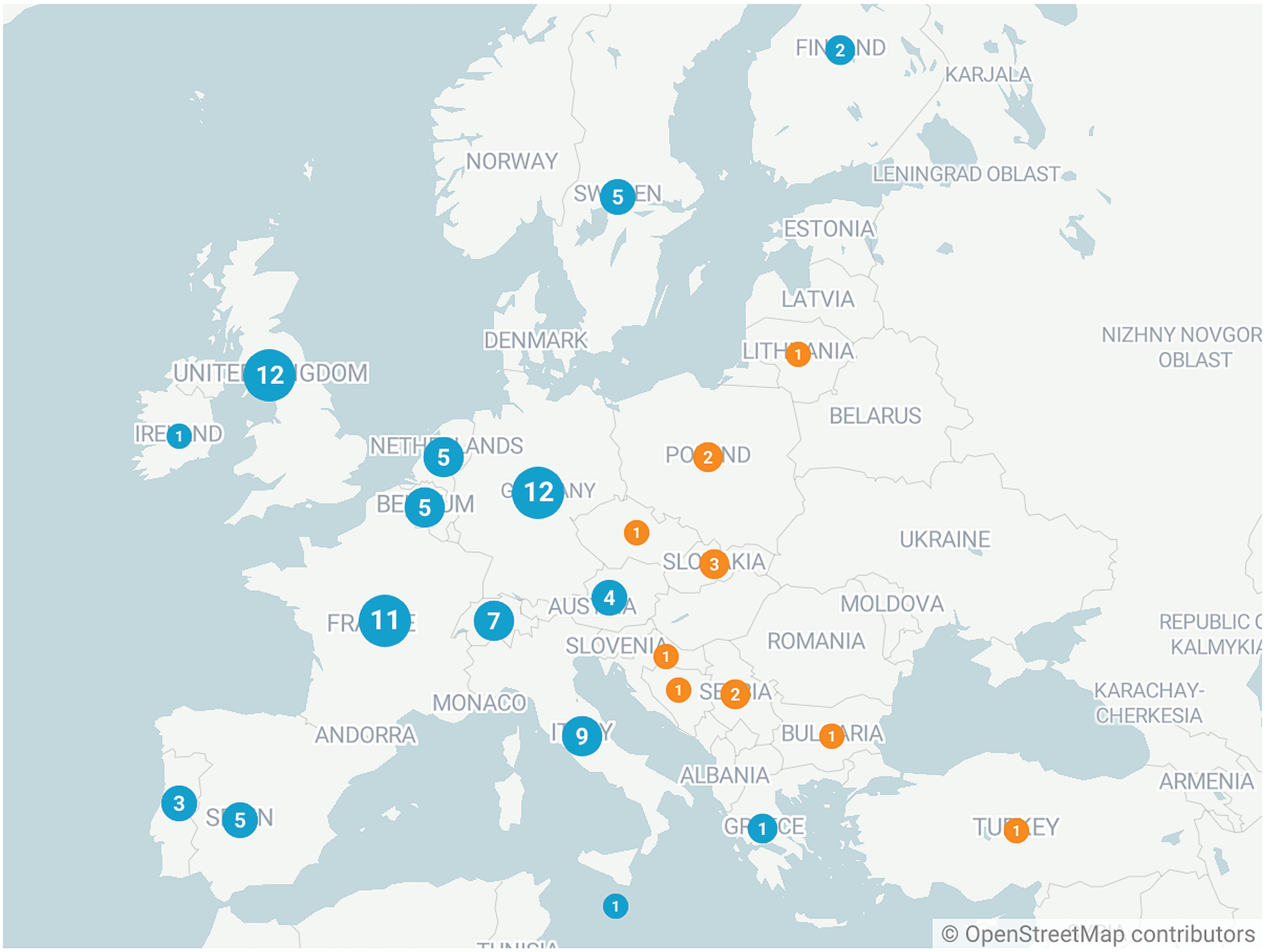
3D rotational angiography

From our data, we found that the number of centres that regularly perform 3DRA is 22. Out of these 22 centres, 16 perform 3DRA on both paediatric and adult CHD patients (16.3% of the total number of centres).

Holographic imaging/virtual reality

Overall, 22 centres have the possibility to visualize holographic imaging/virtual reality (HI/VR); the main reason to

Fig. 1



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Localization of the centres. Centres are localized in 24 European countries. Eighty-four centres are located in Western European countries (blue), 13 centres in Eastern European countries (orange). We considered Turkey as part of Eastern Europe. The size of the dot is proportionate to the number of centres that answered in that country. Note: one centre did not specify the location.

make a hologram was to plan a surgical procedure or to provide a better understanding of the anatomy (Fig. 11).

In 17 centres, the holographic facility is shared across disciplines, while in 21 centres, it is housed within (paediatric/congenital) cardiology and cardiac surgery.

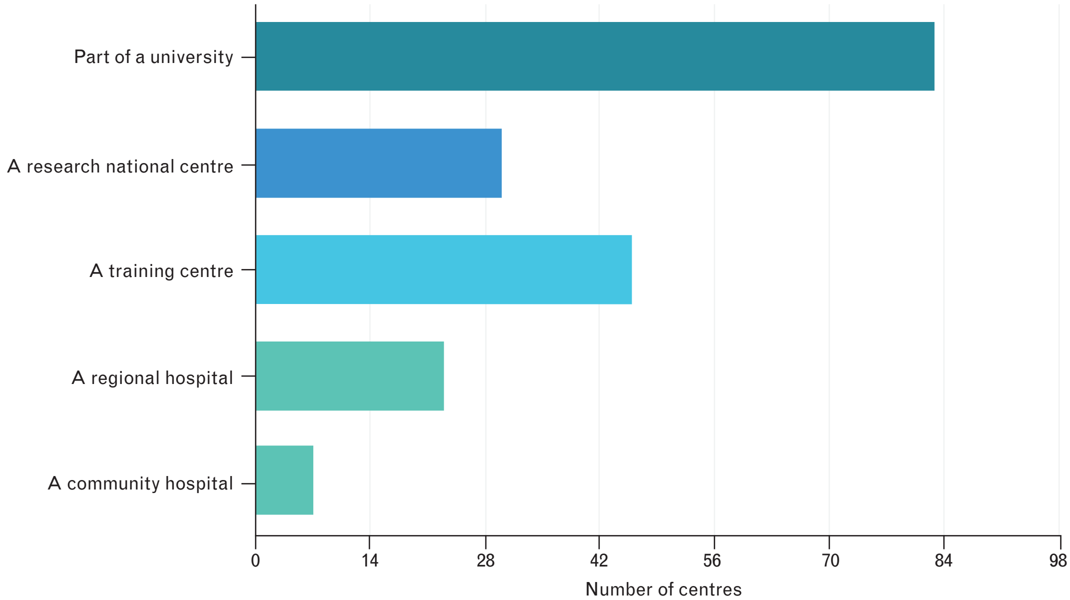
The costs associated with holographic visualization are mostly covered by research funds (Fig. 12).

Differences between low, moderate and high-volume centres

Furthermore, we investigated the association between 3D imaging modalities availability and centre volumes. We classified the centres in low-, moderate- and high-volume centres based on the number of procedures performed per year, to see whether the higher-volume centres have more availability to use 3D imaging modalities. Categorical variables in the three groups were compared using the χ^2 test (SPSS, Inc., Chicago, Illinois, USA). Statistical difference was considered significant at a level of P-value of less than 0.05.

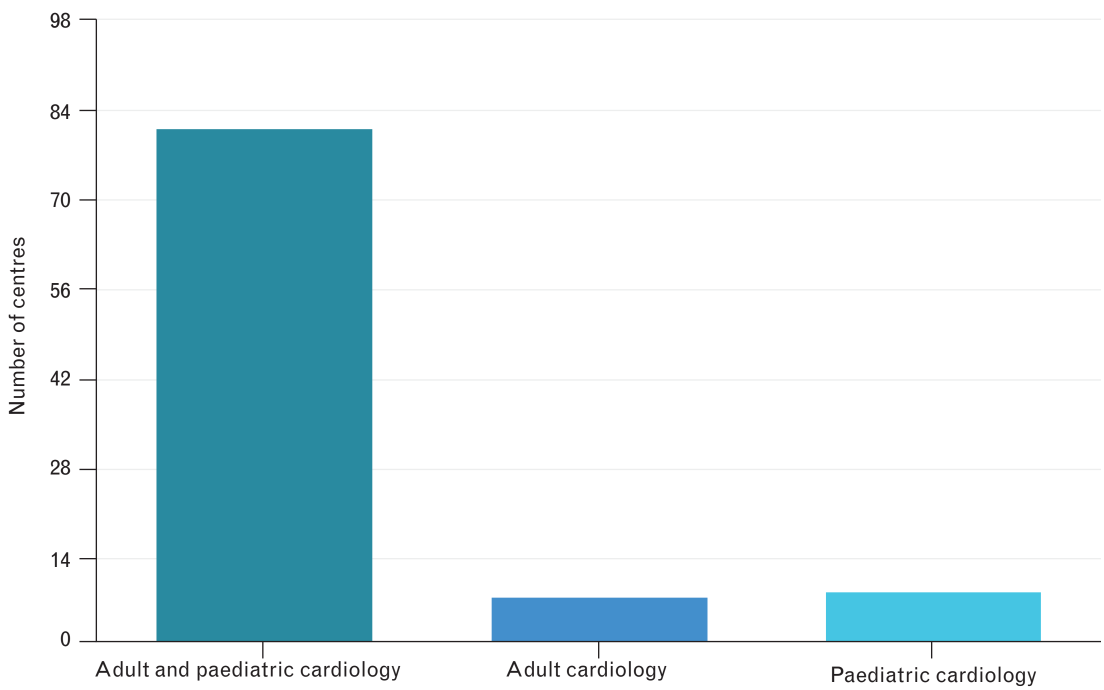
We found that 3DRA is performed in 21% of low-volume centres, 18.2% of moderate-volume centres and 28% of high-volume centres ($P = 0.591$). Concerning the availability to print 3D models, we found that low-, moderate- and high-volume centres have the availability to print 3D models in 21, 39 and 60%, respectively ($P = 0.011$).

Fig. 2



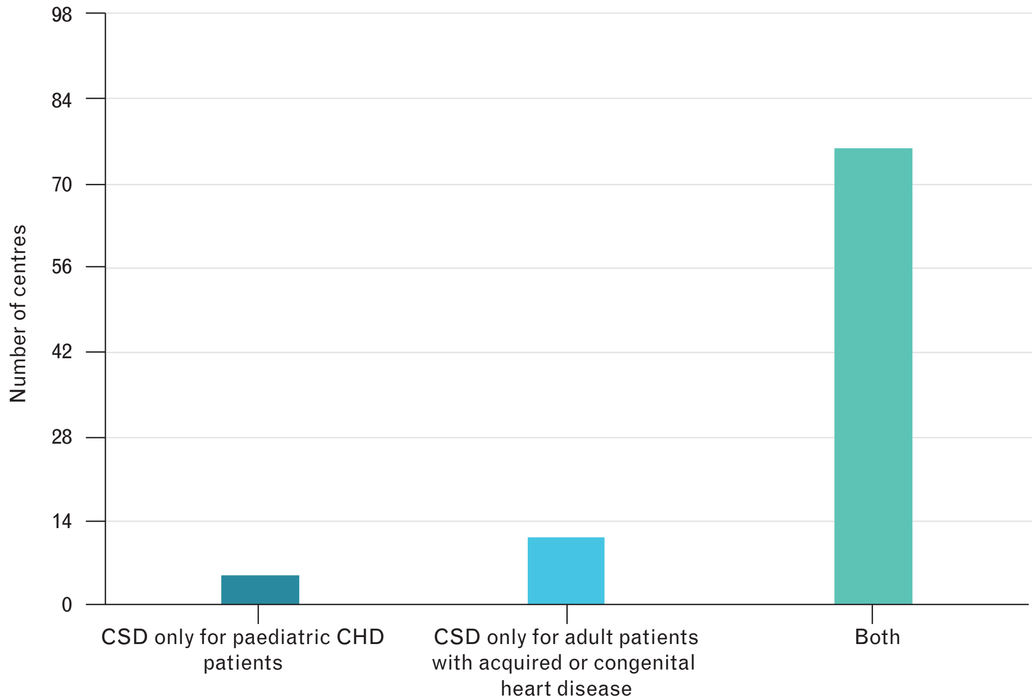
Features of the centres. Eighty-three centres are part of universities, 46 centres are training centres, 30 centres are a research national centre, 23 centres are a regional hospital, 7 centres are a community hospital. Note that multiple answers were allowed.

Fig. 3



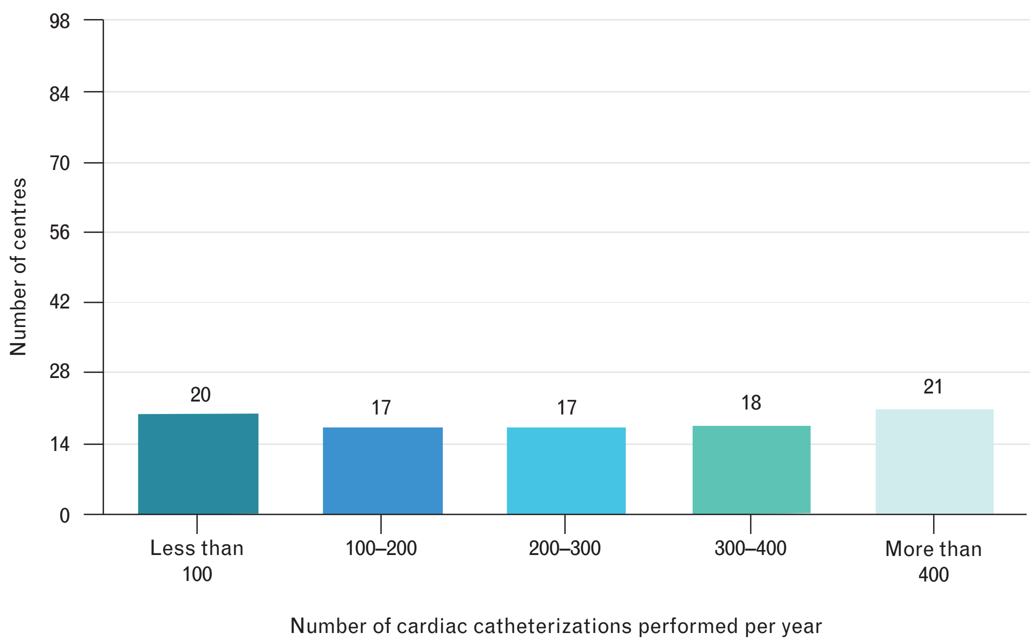
Department affiliations. Among the 98 centres, 81 follow both paediatric and adult cardiology patients, 8 centres only follow adult patients, 9 centres only follow paediatric patients.

Fig. 4



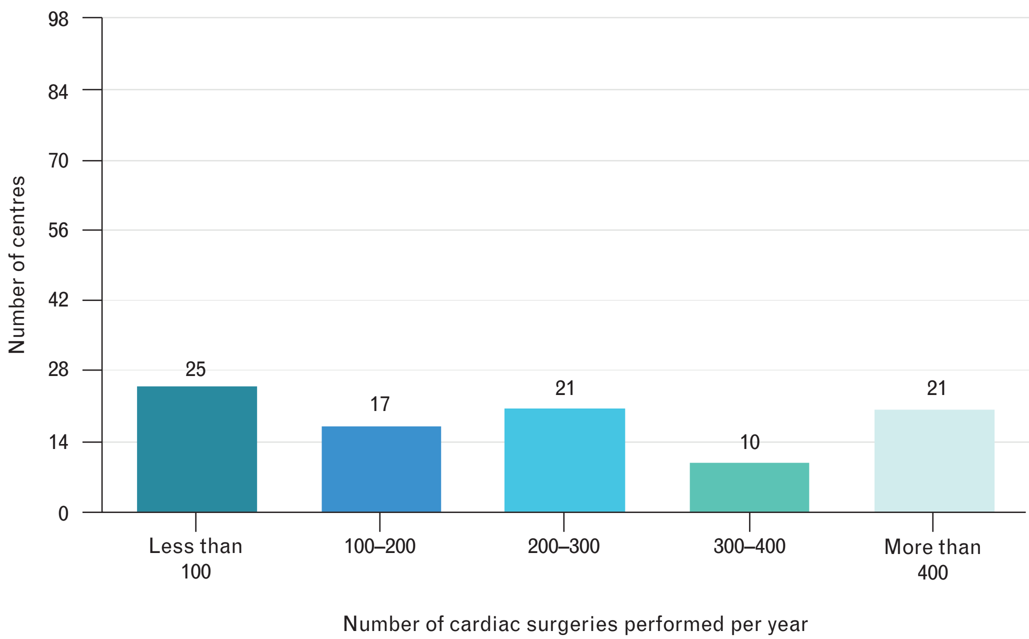
Cardiac surgery departments. Five centres have a CSD for paediatric patients with CHD, 11 centres have a CSD for patients with acquired cardiovascular diseases, 76 centres have a CSD for both. Note: six centres did not answer.

Fig. 5



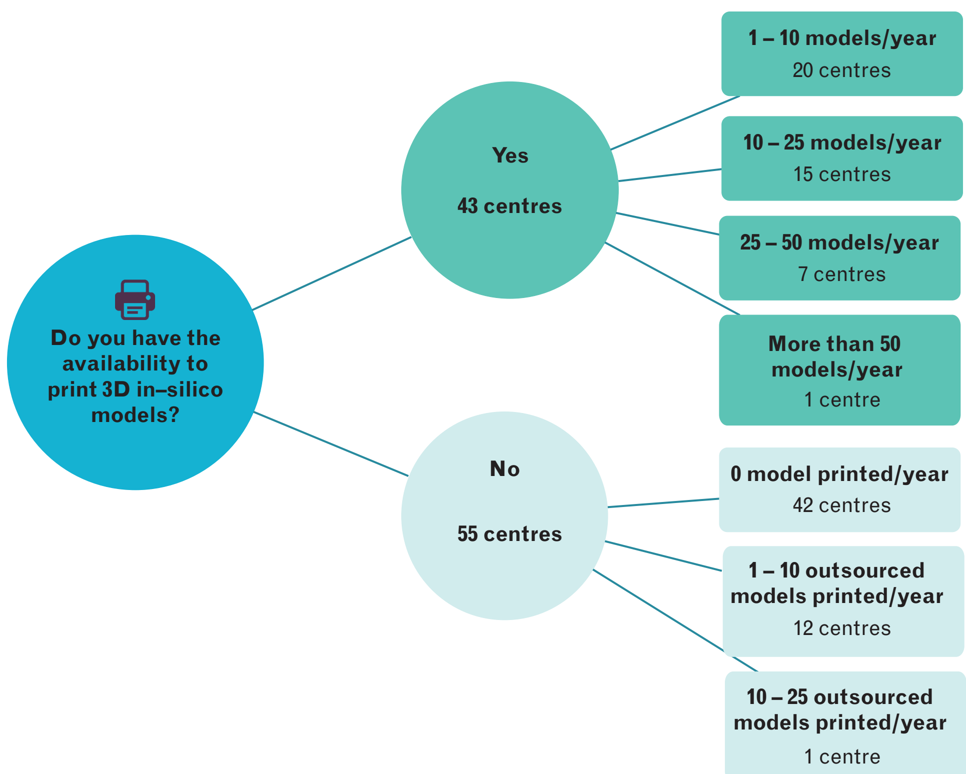
Total number of inpatient cardiac catheterizations procedures performed per year. Twenty centres perform fewer than 100 cardiac catheterisms (cc) per year, 17 centres perform 100–200 cc per year, 17 centres perform 200–300 cc per year, 18 centres perform 300–400 cc per year, 21 centres perform more than 400 cc per year.

Fig. 6



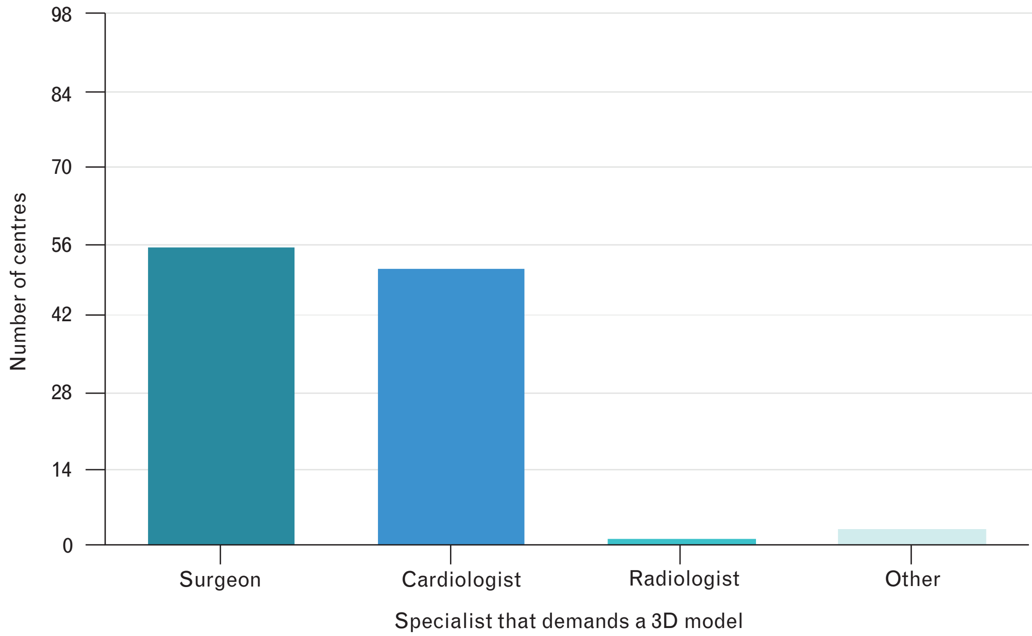
Total number of inpatient cardiac surgeries performed per year. Note: four centres did not answer. Twenty-five centres perform fewer than 100 cardiac surgeries (cs) per year, 17 centres perform 100–200 cs per year, 21 centres perform 200–300 cs per year, 10 centres perform 300–400 cs per year, 21 centres perform more than 400 cs per year.

Fig. 7



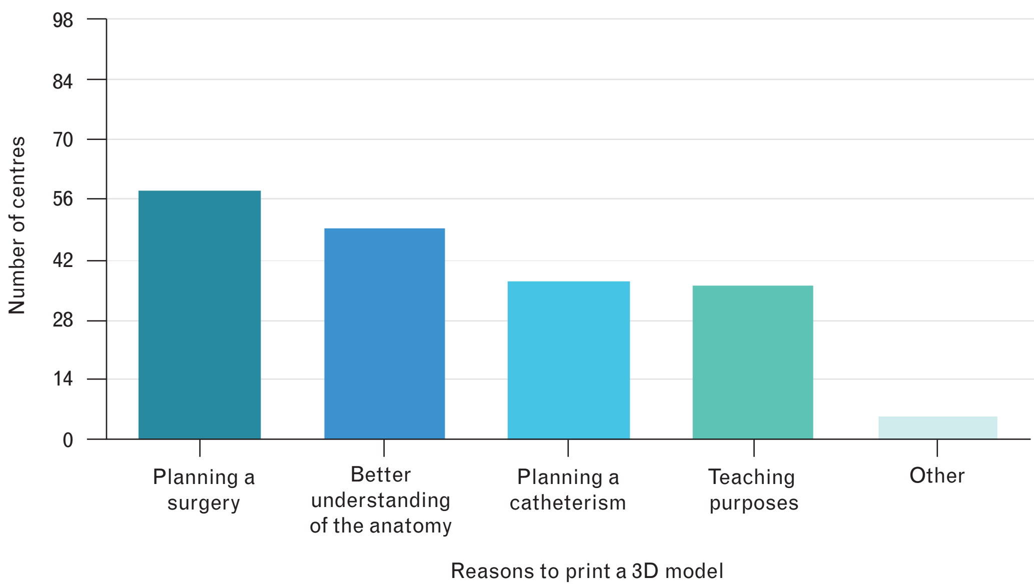
Number of models printed per year. Forty-three centres have the availability to print 3D in-silico models. Twenty centres manage to print 1–10 models per year, 15 centres manage to print 10–25 models per year, 7 centres manage to print 25–50 models per year, only 1 centre manage to print more than 50 models per year.

Fig. 8



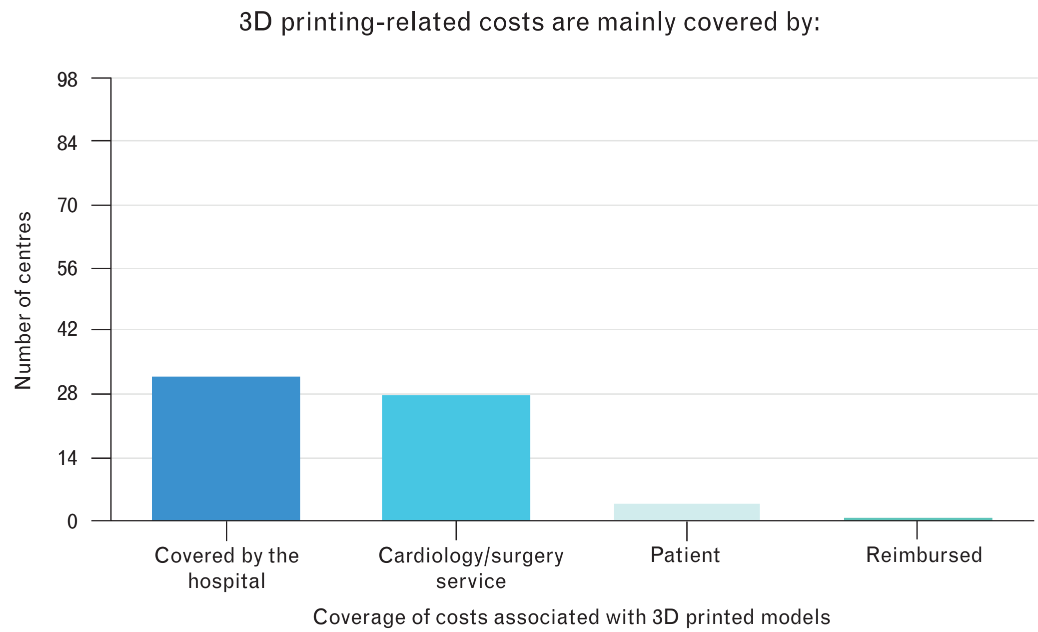
Who typically requests a 3D model. 3D printed models requested by a surgeon (55 centres), a cardiologist (51 centres), a radiologist (1 centre), other specialists (3 centres).

Fig. 9



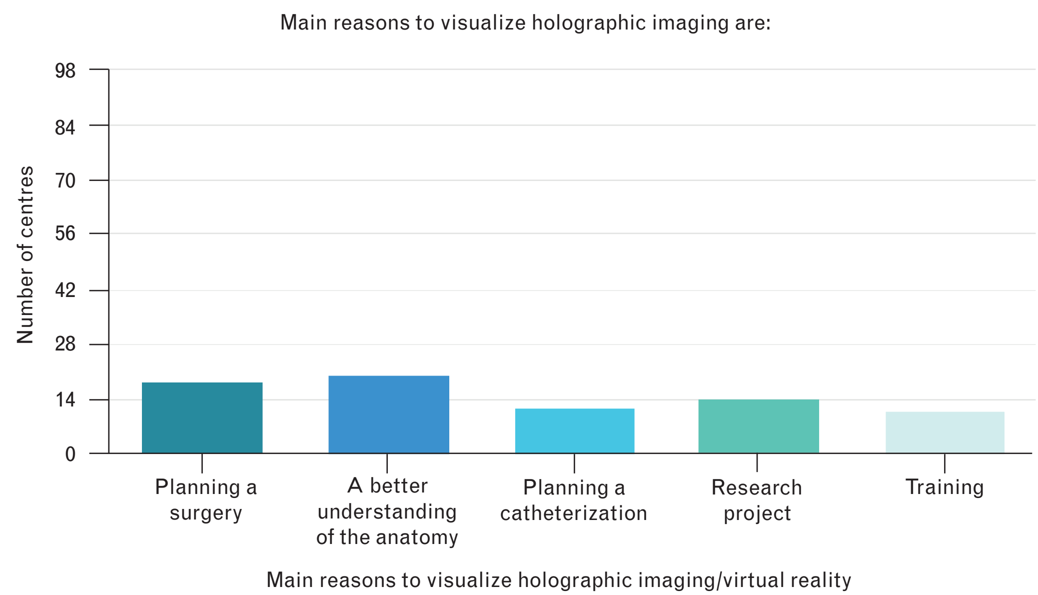
Main reasons to print a 3D model. The main reasons to print a 3D model are planning a surgery (58), a better understanding of the anatomy (49), planning catheterizations (37), teaching purposes (36). Six centres reported printing 3D models for 'other' reasons.

Fig. 10



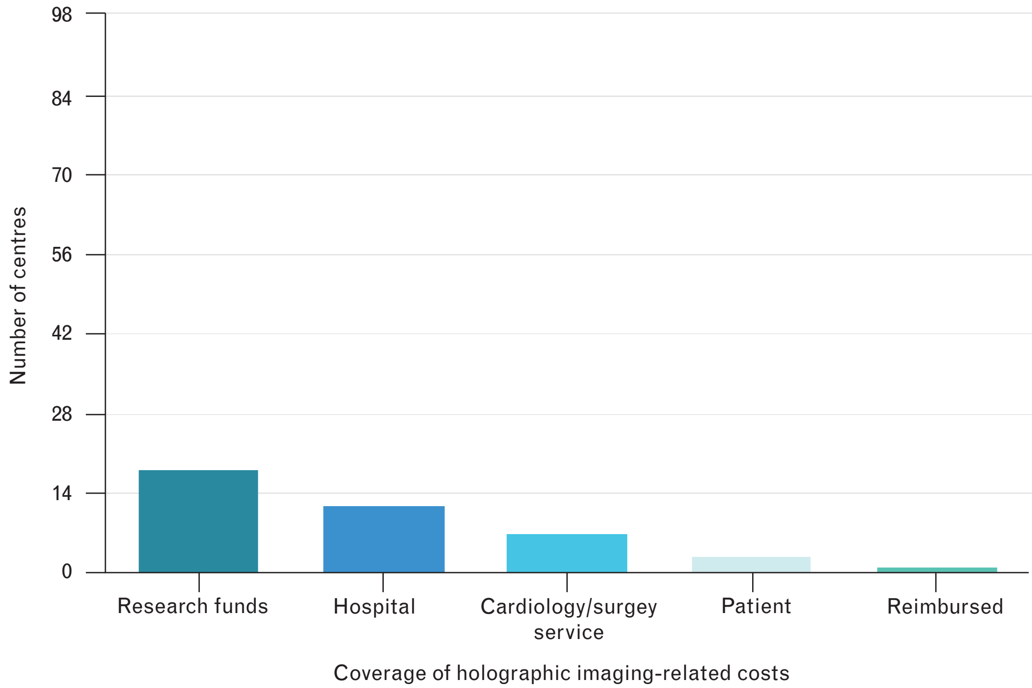
Coverage of costs associated with 3D printing. 3D printing-related costs are covered by the cardiology/surgery service in 32 centres, by the hospital in 28 centres, by the patient in 4 centres, reimbursed in 2 centres.

Fig. 11



Main reasons to visualize holographic imaging/virtual reality. The main reason to visualize holographic imaging is a better understanding of the anatomy (20 centres), planning a surgery (18 centres), research project (14 centres), planning a cath (12 centres) and training (11 centres).

Fig. 12



Coverage of costs associated with holographic imaging/virtual reality. Costs associated with holographic visualization are covered by research founds (18 centres), by the hospital (12 centres), by the cardiology/surgery service (7 centres), by the patient (3 centres) or reimbursed (1 centres).

Finally, HI/VR is available in 16% of low-volume centres, in 21% of moderate-volume centres and in 28% of the high-volume centres ($P = 0.55$).

Discussion

Our results show that 3D printing is the most available 3D imaging support and it is mainly used for procedural planning of cardiac surgeries, transcatheter interventions and for a better understanding of the anatomy. It is mainly requested by surgeons and cardiologists.

These results are consistent with data reported in literature in the field of CHD; that is, 3D printing has a variety of applications in modern clinical practice, ranging from pre-procedural planning to doctor–patient communication and medical teaching.[2]

However, some of the limitations that prevent the penetration of this modality in clinical practice are time, costs of production and insufficient objective evidence of an improvement in clinical management of patients.[3–6]

Valverde *et al.*[7] conducted one of the largest studies that addressed this issue. Specifically, their purpose was to validate the utility of 3D printed models for the planning of complex CHD surgery, judging the effect of using 3D printed models in the course of treatment of congenital heart defects.[7]

They demonstrated the advantage of 3D models over standard imaging on the accuracy of anatomy understanding and management of complex CHD. However, in most cases that had less complex CHD, 3D models supported the surgical decision with no changes in the surgical approach, as the surgeon's experience was enough to overcome the lack of a 3D rendering of the defect. Another factor that limits the utility of this method for daily use is the limited physical properties of printing materials when it comes to simulation of surgical procedures. The materials are not adequate to replicate cardiac valves and tension apparatuses,[8,9] so manipulation of the models is limited and may lead to their destruction.[9]

In addition, the printing process is not instantaneous and currently cannot be performed intra-procedurally in the catheterization laboratory.[9]

As for the costs associated with this technology, it is undeniable that they are currently prohibitively expensive for most users, although the increased efficiency of 3D printers and the introduction of low-cost printers and printing materials have made internalized production more accessible.

We can imagine that in the future, the use of open-source software and hardware, the increase in demand, that is the production of models, could lead to a reduction in costs.

In addition, collaboration between centres and/or single users of 3D printing could reduce costs by enabling the sharing of resources.

Certainly, economic evaluations are not sufficient to fully capture the potential impact of 3D printing in clinical practice, but reimbursement for medical services is and will increasingly become an important issue if 3D-printed heart models will be introduced into routine practice.

Further systematic studies are needed to introduce this tool into routine clinical practice. First, insight from professionals using such technology needs to be obtained to determine whether significant clinical benefit results from its use and whether this benefit justifies the cost.

Second, such studies could establish a data archive to understand in which cases it is more appropriate to create a model.

The introduction of 3DRA has allowed the development of a ‘one-stop’ 3D imaging solution for pre-therapeutic assessment, treatment guidance and post-treatment evaluation of patients with CHD.[10]

3DRA has proven to be an excellent method for 3D evaluation of congenital cardiac lesions and image guided therapy in the catheterization laboratory by improving visualization of complex structures and interactions, guiding interventions, and often decreasing radiation exposure. Initially, due to concerns of excess radiation to obtain 3DRA, its use was limited to complex interventional procedures. Technological changes have made the radiation dose to obtain 3DRA similar to bi-plane cine-angiography[11,12] allowing its routine use in congenital cardiac interventions. Nowadays, the use of 3DRA has become increasingly common among operators performing interventions in children and adults with congenital heart diseases (ACHD).[10,11]

For this reason, it is unexpected that only 22 centres out of 98 perform 3DRA. We assume that one of the main reasons could be the cost of the equipment, which may be prohibitive for some centres. Another aspect reported in the literature was pointed out by Kang *et al.*,[10] who analysed the use of 3DRA in their 10-year single-centre experience. They described a decrease in 3DRA utilization due to the introduction of other noninvasive 3D imaging modalities, for which the formation of native 3D angiographies and subsequent 3D reconstruction are replaced by other pre-interventional 3D-imaging technologies. However, they concluded that 3DRA is still very helpful in unplanned situations during cardiac catheterizations when complex anatomy has to be visualized immediately and accurately as well as in emergencies.

Virtual reality allows the generation of high-quality 3D colour dynamic holograms, in a standard clinical setting with real online patient volumetric data.[13]

Similar to 3DRA, 22 centres reported the possibility of using HI/VR imaging. This is noticeable because, compared with the other imaging modalities, HI/VR was introduced more recently, and its use is mainly limited to a research context. Since its introduction, there has been a rapid expansion to apply this technology to multiple different settings, ranging from surgical cases to outpatient clinic visits.[14–17]

From our survey, it emerges that within the field of CHD, HI/VR has similar use cases to 3D printing, as it is mostly used in pre-procedural planning, followed by research projects. However, Gehrsitz *et al.*[14] reported that holography could improve the depth perception and the representation of the disease when compared with 3D printing, as images can be seen from different planes of view, dimensions, and perspectives. In conclusion, VR is a rapidly growing imaging modality, mainly used in research contexts at present. As for the other 3D imaging modalities, VR has not been introduced in routine clinical practice, as its use is mainly described in single-centre experiences, and there is no evidence of its impact on patient outcomes.

Coverage of costs

It is clear that costs required to make 3D imaging technologies are mainly covered by the hospital/departments’ funds at present.

With the standardization of these new technologies, a cost assessment has become essential to determine its possible integration into patient care. However, despite being one of the main factors that prevents its uptake in clinical practice, this is not a common issue addressed in the literature.

Martelli *et al.*[9] carried out a systematic literature review to assess 3D printing technology economic evaluation and they highlighted the lack of reliable economic data. In the majority of studies, the coverage of costs was often additional data, only briefly evaluated. In addition, the evaluations were too heterogeneous, so the costs varied greatly between them, and no comparison was possible.

Murali *et al.*[18] conducted a survey to evaluate the current use of AR/VR devices, in which they also addressed the issue of costs. Their results show that these devices were predominantly purchased using grants or departmental funding (55%). In addition, nearly half of the respondents (45%) also reported having used some institutional funding and 18% contributed out-of-pocket. An additional 18% of payments were made using industry relationships as well. When ranking the most concerning aspects of AR/VR usage based on six options, reimbursement was among the top concerns. Despite this, it is interesting to see so many physicians continue to use their devices regularly, further emphasizing the value and convenience that these devices provide to physicians.[18] It is predictable that the coverage of costs of 3D imaging modalities may continue to serve as a barrier to entry into clinical practice, so further studies that address this issue are needed to determine their possible integration into patient care.

Low, moderate and high-volume centres

Following our data, higher-volume centres have more availability to use these newer imaging technologies. We hypothesize that the reason may be the higher amount of funds received or that these centres are more likely to need advanced imaging technology given an increased exposure to more complex cases. This could mean that centralization of CHD healthcare in high-volume centres could facilitate providing all the technological tools available; however, this matter should be further addressed in larger studies.

Western/Eastern Europe

Another consideration concerning the number of cardiac catheterizations and surgeries performed is the difference between the centres in Western/Eastern Europe. The percentage of centres that perform more than 300 cardiac catheterizations per year is 44% in Western Europe, while in Eastern Europe, the percentage is 23%.

In addition, the percentage of centres that perform more than 300 cardiac surgeries in Western Europe is 33%, whereas in Eastern Europe, it is 15%. These results are in fact consistent with the study by Margarita Brida *et al.*,[19] in which the author described that important gaps still exist between the countries in the South Eastern European Region and the rest of Europe.

Concerning the use of 3D imaging technologies among Eastern European countries, there is just one centre that performs 3DRA, one centre that has the availability to print 3D in-silico models, and one centre that has the possibility to visualize holographic imaging.

On the contrary, in Western Europe, 20 (23.8%) centres perform 3DRA, 40 centres (50%) have the availability to print 3D models, and 21 centres (25%) have the possibility to visualize holographic imaging.

Conclusion

From our survey, it emerges that these technologies are fairly spread out across Europe, despite not being part of routine practice. Further studies are needed to develop clinical recommendations for the use of 3D imaging technologies routinely in medical practice.

Another issue that has to be addressed is the reimbursement of costs. Again, further studies are needed to demonstrate quantitative proof of improved patient outcomes and cost savings from the use of medical cardiac 3D imaging to expedite the reimbursement process.

The aim of this study is to describe the current state of the art in the use of some different 3D imaging technologies in the management of CHD in Europe, filling an actual gap in the knowledge.

Of course, we are aware that our results are within the surveyed centres, but we hope that this can be a drive for future studies that could lead to implementation in clinical workflow.

Conflicts of interest

There are no conflicts of interest.

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