Mixed reality holograms for heart surgery planning: first user experience in congenital heart disease

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Aims
Proof of concept and feasibility study for preoperative diagnostic use of mixed reality (MR) holograms of individual 3D heart models from standard cardiac computed tomography angiograms (CTA) images. Optimal repair for complex congenital heart disease poses high demands on 3D anatomical imagination. Three-dimensional printed heart models are increasingly used for improved morphological understanding during surgical and interventional planning. Holograms are a dynamic and interactive alternative, probably with wider applications.

Methods and results
A 3D heart model was segmented from CTA images in a patient with double outlet right ventricle and transposition of the great arteries (DORV-TGA). The hologram was visualized in the wearable MR platform HoloLens® for 36 paediatric heart team members who filled out a diagnostic and quality rating questionnaire. Morphological and diagnostic output from the hologram was assessed and the 3D experience was evaluated. Locally developed app tools such as hologram rotation, scaling, and cutting were rated. Anatomy identification and diagnostic output was high as well as rating of 3D experience. Younger and female users rated the app tools higher.

Conclusion
This preliminary study demonstrates that MR holograms as surgical planning tool for congenital heart disease may have a high diagnostic value and contribute to understanding complex morphology. The first users experience of the hologram presentation was found to be very positive, with a preference among the female and the younger users. There is potential for improvement of the hologram manipulation tools.

Keywords
three dimensional • structural heart disease • computed tomography • hologram • mixed reality • 3D printing

Introduction
Three-dimensional image data are increasingly applied as part of standard preoperative evaluation in the treatment of patients with congenital heart disease. Cardiac computed tomography angiograms (CTA), magnetic resonance imaging, rotational angiograms, and 3D ultrasound all provide volume data with the potential to provide real depth perception. However, cardiac 3D images are normally studied on flat (2D) screens, limiting the true depth experience and the possibilities for interaction in 3D space. Two-dimensional visualization of 3D datasets still leaves a lot of the understanding of complex cardiac morphology to individual spatial imagination, often complicating communication between experts. Spatial imagination abilities can be assessed by tests such as the mental rotation test and are unevenly distributed among people. Some spatial functions are found to be better in males than in females and also better in younger than in older subjects.12 True 3D representation of cardiac image datasets has the potential to reduce the importance of these spatial skills and facilitate both the understanding and communication of complex cardiac morphology. This may improve both training, planning and

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conduction of surgical or catheter-based treatment. Segmentation of cardiac image datasets and modelling of 3D objects form the basis for 3D printed heart models. Currently, these are included as part of preoperative work-up for complex congenital defects such as DORV, in many highly specialized congenital heart surgical centres. Similar 3D object files can be visualized as holograms. Holographic visualization technology has been known for decades. Stereoscopic presentation of medical images has been applied in a variety of medical imaging areas but still plays a small role. Stereoscopy is direct extraction of 3D information from 2D images. The most common way to create this is to mimic the layout of our eyes, i.e. two cameras placed horizontally, slightly separated from each other. The relative depth information is obtained by integration of the images from these two cameras with the aid of 3D glasses, as in 3D cinemas. Stereoscopic holograms from 3D echocardiography were described in 1995. However, a cumbersome production process and restricted viewing angle limited the practical application of these early and truly innovative techniques. Recently, Bruckheimer et al. presented initial feasibility data for a new and very promising hologram solution applied in the treatment of structural heart disease. Static and real-time dynamic volumetric rendering based on 3D rotational angiogram and ultrasound data was found to provide detailed anatomic information and excellent image quality, but this platform is not yet commercially available. Various devices capable of virtual or augmented reality (AR) 3D visualization of medical images are available. In virtual reality (VR), the 3D image is created by one image projection per eye, providing good depth sensation. The user is in a make believe world completely separated from the real surroundings. VR started in gaming and is growing into the media industry. In AR, virtual elements are laid on the user’s reality, using a device with a camera and screen to view the virtual elements. The virtual elements are located but not directly part of the user’s reality and cannot interact with physical objects. Pokemon Go is an example of AR. In mixed reality (MR), the virtual elements are blended into the user’s reality and can interact with the physical elements. This is possible by 3D anchoring the virtual elements within the real-world environment. A heart model can thus be anchored and viewed inside the chest of a real patient. Microsoft HoloLens made the MR concept commercially available in 2016. This provides true 3D depth perception integrated in real surroundings, with the potential benefits of high mobility, angle independency, gesture control, and easy sharing of holograms. Applications for areas such as extremity reconstruction, visceral, and neurosurgery have been described but no studies on its use in treatment of congenital heart disease are published.

Methods

Study design and overview

Aims
We aimed at establishing proof of concept and examine the feasibility and initial user experience of a new MR hologram platform for diagnosis and treatment plan in complex congenital heart disease.

Objectives
Segmented cardiac CTA images were viewed as a 3D object in a wearable MR holographic device (HoloLens). The primary objective was registering the recognition of selected major anatomical landmarks and the diagnosis of one specific heart defect as viewed in the hologram. A suggestion for a surgical repair plan was also requested in the questionnaire that was administered individually to clinical team members at different levels of expertise.

The secondary objective was to let first-time hologram users rate their experience of the depth perception, benefit of the hologram for understanding the complex morphology, and the potential benefits of MR and sharing functions. The quality of the interactive tools such as moving, rotating, scaling, and slicing the hologram was also assessed. A rating scale from 1 to 6 was used as shown for the item 3D perception below.

<table>
<thead>
<tr>
<th>Negative</th>
<th>Neutral</th>
<th>Positive</th>
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The first author performed the study and drafted the manuscript. All authors contributed to study design and reviewed the final version.

Hologram visualization system
The Microsoft HoloLens is a MR hologram viewing platform. It provides true 3D holographic representation of 3D objects with full sense of depth. The viewed object is exactly located in the room and can be viewed simultaneously from all angles by a group of viewers...
A 9-year-old boy with double outlet right ventricle and transposition of the great arteries (DORV-TGA) was referred to our centre for corrective surgery. He had a large ventricular septal defect (VSD), distant from, but mostly related to the pulmonary artery and with inlet extension. Bilateral branch pulmonary artery stenosis had prevented pulmonary vascular disease development, allowing for repair at this late stage. In addition, there was anomalous drainage of the left pulmonary artery into the superior vena cava. Surgical plan was based on echocardiography, cardiac CTA, and cardiac catheterization data. The holographic visualization of his CTA based 3D model (Figure 2 and Supplementary data online, Video S1) did not change but confirmed the surgical plan. He was operated with arterial switch and rerouting of the left ventricular outflow to the neo-aorta with a gore-tex patch. Interatrial baffling of the upper right pulmonary vein and patch enlargement of the branch pulmonary arteries were also performed. Immediate post-operative period was uneventful. He was transferred after 7 days to the local hospital but was readmitted for drainage of pleural and pericardial fluid 2 days later. Residual branch pulmonary artery stenosis stenting was performed 2 months post-operatively, reducing RV pressure to an acceptable level. However, restenosis of the pulmonary arteries occurred and at his last follow up 6 months after surgery, the VSD patch had detached in the area close to His bundle. He is fully saturated and doing well but is scheduled for further stent dilatation and evaluation for closure of his residual VSD.

Images and processing
A standard clinical contrast enhanced CTA of the whole heart was made in effort to achieve optimal contrast in the regions of interest (ventricles, VSD and outlets). Imaging was performed on a third generation dual-source computed tomography system (Siemens SOMATOM Force, Erlangen, Germany) using the high pitch mode. In total, 26 mL contrast medium (Omnipaque 350 mg I/mL, GE healthcare, USA) was injected in the right antecubital vein with a flow of 2 mL/s, employing a three-phase injection protocol: 20 mL contrast bolus followed by 20 mL mixed bolus of 30% contrast media and 70% saline, followed by 20 mL saline. Using bolus tracking in the ascending aorta the scan was acquired 19 s after the initiation of the contrast injection. Scan parameters were: detector collimation $2 \times 192 \times 0.6$ mm, gantry rotation time 250 ms, pitch 3.2, and automatic dose modulation (CAREDose 4D and CAREkV) set with 350 reference mAS, 80 reference kV, and slider position 11. The total DLP including topograms and bolus tracking was 37 mGy cm. Phantom size was 32 cm, the CTDvol 1.17 mGy, DLP 33.3 mGy.

Standard cross-sectional Dicom CTA images were segmented and processed to a 3D mesh, using ITKsnap 3X (www.itksnap.org) and 3Matic (Materialise, Leuven, Belgium) software. A two-layer, hollowed heart model was created as a 2 mm extrusion from the segmented blood volume in a similar fashion as performed for 3D printing. This model was exported as a .ply file to the Microsoft HoloLens for holographic visualization.

The diagnostic correctness was assessed, and the benefits of the user tools were rated as described above. We analysed the differences between user groups based on collected data including sex, age, medical subspecialty, and level of expertise (junior/fellow vs. senior/expert).

Results
In this first evaluation study of HoloLens® MR hologram as surgical planning tool in congenital heart disease, we assessed the diagnostic output of the hologram as single modality. The 3D depth experience and the user evaluation of the locally developed hologram tools was registered.

Participant characteristics
Of the 36 congenital heart disease professionals who tested the hologram application, 12 were female. Six were junior staff members. The age range was from 34 to 76 years (median 52 years).

Identification of anatomical structures and diagnosis
All professionals, independently of the level of expertise, were able to identify correctly the aorta, the main pulmonary artery and the
VSD. All but one (junior fellow with short experience) correctly identified the DORV diagnosis and all but two (both junior level) correctly identified the transposition of the great arteries.

### Surgical plan

The three oldest participants and one radiologist suggested Rastelli repair. Two out of five radiologists and two junior cardiologists did not suggest repair method. The remaining participants suggested arterial switch and rerouting as the treatment of choice for the patient. This was the operation that was selected for the patient.

### Rating of the hologram experience

The overall rating of the hologram experience resulted in mean (standard deviation) scores from 5.32 (0.7) to 5.46 (0.6) for all variables. See Table 1 for details on the specific subtopics.

### Hologram tools ratings

The locally developed tools for handling the hologram were given a somewhat lower rating than the visual experience (Table 2) but still closer to maximum positive score (6) than neutral (3, 5). The method of simply moving oneself through the hologram (mean rating 5.30) reached a higher score than the locally developed slicing tool (mean rating 4.78) for studying the inside of the heart.

The basic hologram tools and the slice heart tool were rated significantly higher by women (Table 3). There were no differences identified between men and women with respect to the MR experience, 3D depth perception or morphology understanding. A cut-off of 52 years and above was set for the division of the participants into two equally sized age groups. The functionality of the basic HoloLens tools was rated higher by the younger half of the group (Table 3). There were no age differences for the other variables tested. The Mann–Whitney U test revealed no significant differences in the HoloLens evaluation between the different medical subspecialties or between expert level groups.

### Discussion

We present early experience with the use of a wearable MR platform as diagnostic and planning tool for complex congenital heart surgery. All hologram evaluators were trained in congenital heart disease at various skill levels, but still, DORV-TGA can be a challenging diagnosis to make, even for the expert. This proof of concept study demonstrates that the cardiac CTA-based hologram in this patient case with DORV-TGA, yielded a very high diagnostic and morphological recognition output across all subspecialties, thus allowing for planning of surgery and possibly making this planning easier to comprehend. The junior fellows who were unable to diagnose or plan correctly had never diagnosed DORV-TGA before the trial. The surgical solution suggested by the vast majority of participants was equal to the operation that was performed successfully, albeit with some residual defects. The Rastelli operation suggested by the oldest participants would have required a longer rerouting patch, increasing the risk for complications and possibly interfering with tricuspid valve function. The choice of a CTA based dataset was made due to its superior contrast between the bloodpool and endocardium in this patient. High contrast is crucial for optimal segmentation. Unfortunately, 3D echocardiography datasets do not yet provide full heart volumes with acceptable signal to noise ratio for whole heart segmentation.

We found that the 3D experience of the heart model in the HoloLens platform was rated highly positive by all subgroups of first-time users. This may partly be due to the excitement with new and fancy visualization technology but could also be related to the positive experience of intuitively solving a complex task. There seemed to be a potential for improvement of the locally developed hologram manipulation tools. This may partly be ascribed to unfamiliarity with the gesture control of the hologram. The tools have already been further developed in a later version of the application.

Few studies are published analysing the use of holograms for the visualization of 3D heart models in congenital heart disease. Bruckheimer et al. published for the first time in 2016 proof of concept and feasibility data with a hologram platform that provides exact 3D image representation to guide the treatment of congenital heart disease. A comparably high level of anatomic recognition and image quality was found in their study that included four users. Their system has advantages in its real-time capability, which is not yet developed for the present HoloLens applications. However, some limitations may come with the use of a large projector-based system that may have limitations at present due to the limited field of holographic view, posing the hologram, e.g. into an open chest during surgery. There may be less mobile and thus limit the positioning of the hologram. Wearable holographic devices such as the Hololens®, which was applied in the present study, have strengths in mobility both of the small wearable device itself, and thus the hologram. No external light sources or screens are needed. The MR concept allows for superimposing the hologram, e.g. into an open chest during surgery. There are limitations at present due to the limited field of holographic view.

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**Table 1** User rating of 3D experience

<table>
<thead>
<tr>
<th>Mean rating (SD)</th>
<th>Median rating (1–6)</th>
<th>No. of responders</th>
</tr>
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<tbody>
<tr>
<td>Depth perception</td>
<td>5.46 (0.6)</td>
<td>5</td>
</tr>
<tr>
<td>Morphology understanding</td>
<td>5.32 (0.7)</td>
<td>5</td>
</tr>
<tr>
<td>Sharing</td>
<td>5.41 (0.6)</td>
<td>5</td>
</tr>
<tr>
<td>Mixed reality</td>
<td>5.33 (0.7)</td>
<td>5</td>
</tr>
</tbody>
</table>

Mean (SD) rating scores of the hologram experience, on a scale of 1–6, 6 being the most positive.

**Table 2** Rating the hologram tools

<table>
<thead>
<tr>
<th>Mean rating (SD)</th>
<th>Median rating (1–6)</th>
<th>No. of responders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic hologram tools</td>
<td>4.46 (1.2)</td>
<td>5</td>
</tr>
<tr>
<td>Slice heart tool</td>
<td>4.78 (1.2)</td>
<td>5</td>
</tr>
<tr>
<td>Moving through model</td>
<td>5.30 (0.7)</td>
<td>5</td>
</tr>
</tbody>
</table>

Mean (SD) rating scores of the different hologram tools. See above for rating scale interpretation.
Mixed reality holograms for heart surgery planning

but this is expected to be improved in the next version of the lens. Further, integration with other head-worn devices used by heart surgeons such as headlamps and magnifying glasses needs to be addressed. Thus far, navigational use of wearable hologram devices may be more feasible in a catheter intervention or minimally invasive surgery setting, where fluoroscopy is the main navigation tool. The sharing function of the platform was not fully explored in this study, but the project leader-participant interaction experience is promising for case discussions in surgical conferences. The same hologram can be shared by several users that all can interact simultaneously, using the manipulation tools. Viewing from equal or different angles can be selected. The MR shared hologram preserves both verbal and non-verbal communication between the viewers, facilitating discussions on surgical solution. The higher rating of the tool functionalities by younger professionals was expected, from the familiarity with learning new technologies and devices by younger people in general. However, participants of all ages rated the holographic experience highly positive. Older fist-time users could perhaps have profited from having more time to learn both the gesture control and tools. The higher rating of the hologram tool quality by female participants is interesting. In neuropsychology literature, women are found to have somewhat lower spatial abilities than men. Hologram manipulation could be more positively received by female users, due to a larger potential for enhancement of the 3D perception in women than men. However, the rating of the 3D experience per se did not differ between the genders, which makes this less likely. Lower rating by males could indicate that they are less comfortable when learning new tools. The study was not designed to answer these questions and no conclusions can be drawn with respect to the gender differences. Quite a few participants expressed that the hologram provided a deeper morphological understanding of this complex defect. A typical comment was: ‘for the first time I really understand this morphology’. It is our belief that in accordance with the experiences from 3D printed models, a deeper understanding of complex cardiac morphology via holograms may aid surgical decision making for patients with complex heart defects. The role as educational tool also needs to be explored further.

Importantly, the cardiac defect was further complicated by extensive branch pulmonary artery stenosis. This could not be fully addressed at surgery followed by stenting. The elevated right ventricular pressure and residual VSD are targets for further treatment. Foreseeing these complications would not have changed main treatment strategy apart from perhaps being even more aggressive with early branch pulmonary artery stenting and re-dilatation. The post-operative complications highlight the importance of multimodality imaging and treatment in such complex cases, wherein holographic visualization may be especially relevant for the planning of intracardiac repair.

### Holograms vs. 3D printed heart models

When compared with 3D prints, holographic models allow for much quicker amendments as guided by the original images and by data from echocardiographic examinations. This makes the hologram a more dynamic visualization tool than 3D prints, which often take 12 h to complete. When a physical model is not necessary, a hologram can be a good alternative. When compared with a commercially produced 3D printed heart model (approximate price 7500 Euros) a hologram is a low budget alternative, once the platform is purchased and developed. The HoloLens platform opens for app sharing in a community similar to mobile phone apps, thus making it a potential tool also in developing countries. Three-dimensional prints are normally made in a 1:1 scale, continuously reminding the user of the difficulties related to operating on small hearts. A hologram may be sized up to a very large scale model, losing the small size warning effect on the surgeon. However, this may be compensated by always resetting the model to normal scale. Studies comparing the benefits of 3D prints with holograms would be highly warranted.

### Limitations

As with most segmented and 3D printed heart models, the holograms presented in this study thus far provide no representation of valve leaflets. The marking tool applied on the valve annulus and the segmentation of papillary muscles partially compensates for this, leaving the leaflets for imagination. Future development plans include fusion of 3D echocardiographic valve data into the models to make them more complete. We have at present no measurement tools for use directly in the hologram, making size and distance validation a planned development only. Our solution is till now limited to static images. Segmentation tools for whole heart cycle models may open for dynamic holograms together with increased computational strength in the next version of the applied viewing lens.

This is an open evaluation study of one patient case only. We have continued to use the solution for another few cases as part of a larger study.

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**Table 3: Hologram tools—group differences**

<table>
<thead>
<tr>
<th></th>
<th>Age &lt;52 years</th>
<th>Age ≥52 years</th>
<th>P-value (Mann–Whitney U test)</th>
<th>Female</th>
<th>Male</th>
<th>P-value (Mann–Whitney U test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic tools</td>
<td>5.0 (0.7)</td>
<td>3.9 (1.4)</td>
<td>0.04</td>
<td>5.1 (0.7)</td>
<td>3.9 (1.4)</td>
<td>0.01</td>
</tr>
<tr>
<td>Slice heart</td>
<td>5.3 (0.8)</td>
<td>4.4 (1.4)</td>
<td>Not Significant</td>
<td>5.3 (0.6)</td>
<td>4.4 (1.5)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Comparison of the mean (SD) rating of the hologram tools, split on age group and sex, with significance levels (Mann–Whitney U test).
Conclusions

In this first evaluation study of HoloLens® MR hologram as surgical planning tool in congenital heart disease we found that:

(1) The hologram was overall easy to interpret and diagnose exactly by almost all participating professionals.
(2) The overall rating of the depth sensation, morphology understanding, and sharing experience was highly positive.
(3) The tools for manipulation of the hologram achieved acceptable ratings and were rated higher by younger professionals and by women.

Future perspectives

Three-dimensional segmented heart models are working their way into treatment programs for congenital heart disease, first of all in the form of 3D printed models. We present limited data on our early experience with one holographic MR visualization application, which seems suitable for clinical use. Further automation and standardization of model creation is needed. Future studies should include the validation of holograms for the measurement of critical structures and subsequently clinical evaluation of their usefulness and impact on decision making. Identification of relevant outcomes for clinical studies needs special attention. An increasing population of adults with repaired congenital heart disease is an interesting target for patient-specific heart models.

Supplementary data

Supplementary data are available at European Heart Journal - Cardiovascular Imaging online.

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Conflict of interest: none declared.

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