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ORIGINAL ARTICLE

Mixed reality holograms for percutaneous lead extraction of cardiac implantable electronic devices

Mixed reality image-guided interventions

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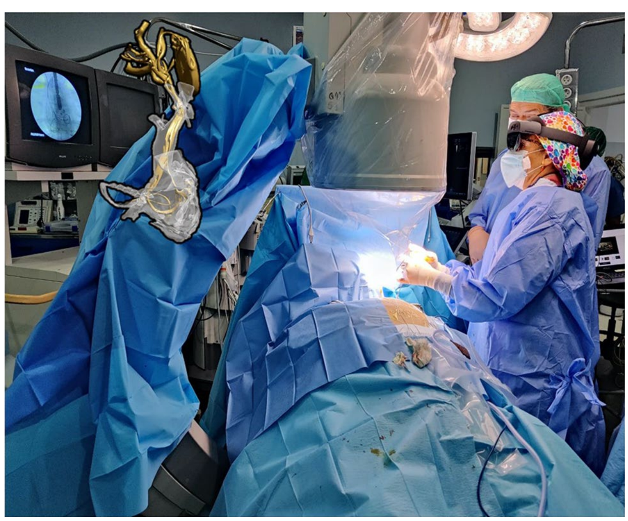
Abstract
To assess the potential of mixed reality holograms (MixR) based on CT images to improve percutaneous lead extraction (PLE) planning and intraoperative assistance. This was a prospective, controlled, single-centre study. Five patients with CIED infection for PLE were included in the study. Conventional imaging (chest radiograph and CT) and MixR holograms were evaluated for preoperative planning to identify common complications such as vascular thrombosis, broken leads, loops, kinking, fibrosis along the wires, and perforation of cardiovascular structures. The degree of difficulty of the procedure was estimated based on potential complications. After the PLE procedure, the level of concordance between conventional imaging and MixR holograms with intraoperative findings was evaluated. The utility of MixR intraoperative guidance was also assessed. MixR holograms demonstrated a very high correlation in predicting the presence of loops, kinking, and fibrosis compared to conventional imaging, which showed a low-to-high correlation. MixR also showed a high correlation in estimating the degree of difficulty of the procedure compared to conventional imaging, which tended to underestimate it. The surgeon who performed the PLE agreed that MixR was helpful during intraoperative assistance. MixR holograms based on CT images are an effective tool for understanding cardiovascular anatomy and detecting potential areas of complications. MixR may be used as a complementary tool for both preoperative planning and intraoperative assistance in PLE procedures.

Graphical abstract
Mixed reality holograms for intraprocedural intervention assistance.



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Keywords Mixed reality · Holograms · Augmented reality · Percutaneous lead extraction

Abbreviations

CIED	Cardiac implantable electronic devices
CT	Computed tomography
ICD	Implantable cardioverter defibrillators
MixR	Mixed reality
PM	Pacemakers
SVC	Superior vena cava
3D	Three dimensional
TLE	Transvenous lead extraction
2D	Two dimensional

1 Introduction

Cardiac implantable electronic devices (CIED), such as pacemakers (PM) and implantable cardioverter defibrillators (ICD), are established treatments for a wide variety of cardiac arrhythmias, heart failure, and other risk factors for sudden cardiac death (Bardy et al. 2005). As implantation rates continue to increase in recent years, so does the incidence of complications that require lead removal (Sohail et al. 2016). CIED removal indications include lead malfunction or fracture, device upgrade, venous occlusion, thromboembolic events, and infections, which are associated with higher incremental costs (Blomstrom-Lundqvist et al. 2020).

Transvenous lead extraction (TLE) of CIED leads is the preferred method of removal due to lower reported morbidity and mortality (Rusanov and Spotnitz 2010; Hindricks et al. 2021). Several TLE tools have been developed to addressing potential complications, including manual traction with blocking stylets, telescoping sheaths, femoral snares, and mechanical-rotating or laser-powered sheaths. However, TLE may result in potentially life-threatening complications, including avulsions of venous or myocardial tissues and vascular tears, particularly in the superior vena cava (SVC) (Wazni et al. 2010; Zucchelli et al. 2019). The procedure can be more challenging in the presence of adhesions between the leads and the vasculature or endocardium, lead perforation, large lead vegetation or thrombus. The range of major complications is between 0.5 and 4.8%, and minor complications range from 3 to 14.7% (Bontempi et al. 2017). Moreover, central venous stenosis or thrombosis can impede vascular access if re-implantation is planned. Risk stratification scores have been proposed to classify patients as low, moderate, or high risk for lead extraction. There is a consensus that difficulty is higher in younger, female patients, leads with a mean indwelling time over 10 years, dual-coil lead ICD, and when three or more leads need extraction (Fu et al. 2015; Bontempi et al. 2017; Sidhu et al. 2020; Sidhu et al. 2021). However, adhesions may unpredictably develop in patients with newer leads, and unexpected complications may arise in any case.

Imaging prior to percutaneous extraction can identify potential areas of difficulty and allow appropriate pre-procedural planning to help avoid complication. Radiographic imaging options, such as radiography and fluoroscopy, can help identify the location and course of leads in the vasculature and cardiac chambers. However, these imaging methods have inherent limitations in assessing vascular lumen and cardiac cavities. During fluoroscopy-guided procedures, identifying whether the tip is crossing fibrosis or anatomical structures can be difficult. Multi-detector CT performed before CIED extraction provides more accurate evaluation of lead tip position and vascular adherence, which is valuable for extraction and subsequent re-implantation of leads (Vatterott et al. 2018; Lewis et al. 2020). However, this technology is not currently implemented for intraoperative assistance.

This study aims to explore the full 3D potential of CT for pre-interventional planning and intraoperative guidance of TLE using mixed reality (MixR).

2 Methods

2.1 Patient selection

This study was a prospective, controlled, single-centre feasibility study that describes the first five patients in whom a novel MixR device was used for pre-procedure planning and intraoperative guidance for TLE. All patients included in the study had CIED infections and were selected according to the current guidelines for CEID lead retrieval during the multidisciplinary meeting (Blomstrom-Lundqvist et al. 2020). The study was approved by the local medical ethics committee, and written informed consent was obtained from all participants who underwent the procedure before inclusion.

2.2 Conventional imaging: chest X-ray and computed tomography

All patients underwent chest radiographs and CT according to the institutional protocol for TLE. Contrast-enhanced CT scans were performed according to local protocol: patients were placed in the supine position and examined on a 16-row multi-slice spiral CT scanner (Aquilon 16; Toshiba Medical Systems, Tokyo, Japan). The scanning parameters were 0.5 mm slice section thickness, 3 mm table feed per rotation, 0.5 s gantry rotation time, a pitch of 0.75, 120 kV, 300 mAs, 512×512 matrix and 25-cm field of view (varying according to patient size).

2.3 3D imaging preparation

The preparation of the three-dimensional model required four sequential stages: importing medical images (CT), imaging segmentation, computer-aided design, and transfer to the MixR device (Supplementary Fig. 1). Image segmentation involved the isolation, from CT medical images, of the CIED and cardiovascular structures of interest, including the generator, leads, innominate vein, superior vein cava, right atrium, right ventricle, and coronary sinus. Segmentation was performed using ITK-SNAP software, version 3.8.0 (University of Pennsylvania, Philadelphia, PA) (Yushkevich et al. 2016), by a consultant cardiologist with more than ten years of expertise in cardiac imaging (Supplementary Fig. 2). A manual thresholding segmentation algorithm was used as described in previous publications (Byrne et al. 2016; Cantinotti et al. 2017; Valverde 2017). The isolation of the generator, leads, veins, and right auricle/ventricle was particularly complex due to metallic and movement artefacts present in the DICOM images. It was necessary to check the radiographs in many locations where the trajectory of the leads was not clear in CT. Segmented geometries were exported as 3D surfaces files in Meshmixer, version 3.3.15 (Autodesk Inc., San Rafael, CA) for computer-aided design. Inaccuracies derived from image artefacts and lack of contrast in some anatomical areas were corrected.

2.4 MixReality development and visualization

An independent local system consisting of three elements was developed: Laptop (server), wifi router (local network), and HoloLens 2® device (client). Detailed information can be found in https://www.microsoft.com/en-us/hololens/hardware#document-experiences and Supplemental material (Supplemental Fig. 1). The system is fully portable and works on any operating room. The Microsoft HoloLens 2 is an autonomous holographic device. It projects holograms (heart and leads) on its transparent front case, which are anchored in the real physical space (operating room). The user (surgeon) can use its own hands, without the need for controls or gadgets, to interact with holograms as if they were real objects. Using a holographic panel, the operator can rotate and dissect the objects and change the colour and opacity of the holograms for preoperative and intraoperative assistance.

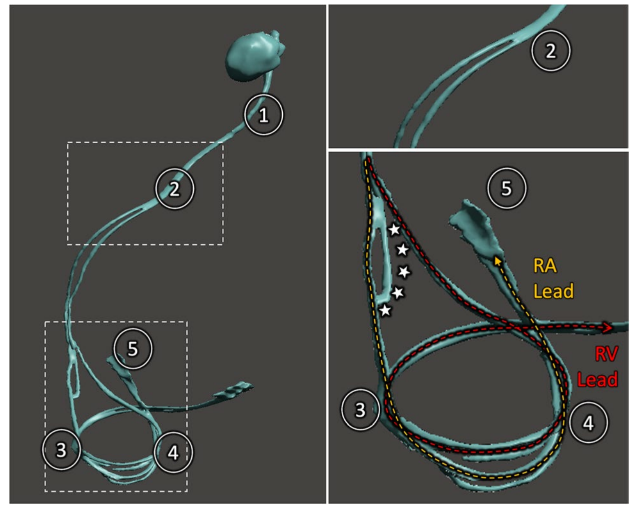

Fig. 1 (Patient 1). The loop in the right atrium was better understood, helping to identify that the ring was actually formed by a combination of the two leads twisting along each other, rather than a true loop. The RV lead created a 360º loop and the RA lead formed just a 180º loop. Up to five areas of potential fibrosis were identified: Innominate vein, SVC, right side of the RA loop, left side of the RA loop and right atrium lead fixation electrode

2.5 Interventional planning: conventional imaging evaluation versus MixR

Each individual case was carefully planned based on conventional imaging and MixR. For conventional imaging, the main surgeon was allowed to review chest radiographs in conjunction with CT images. A questionnaire to exclude potential complications was provided: venous thrombosis, leads loops or kinking, broken leads vascular adherences and lead perforation. For MixR, the surgeon used the Hololens 2 device to evaluate, manipulate and zoom the holograms of the heart and leads (Video 1). A questionnaire to exclude potential complications was provided: venous thrombosis, leads loops or kinking, broken leads vascular adherences, and lead perforation. The same questionnaire was also provided to exclude the same complications.

2.6 TLE procedure guided by MixR

The procedure was performed under general anaesthesia and trans-oroesophageal echocardiogram control in accordance with international guidelines. All cases were planned and performed by the same cardiac surgeon, with over 20 years of experience in TLE.

Generally, lead extraction was performed using locking stylets and mechanical autorotatory sheaths: Shortie RL Controlled-Rotation Dilator Sheath 11F and Evolution Controlled-Rotation Dilator Sheath 13 F (Cook Medical).

All procedures were performed under fluoroscopy guidance and with the aid of MixR.

2.7 Questionnaire design and data analysis

For preoperative planning, the surgeon evaluated a list of six potential complications based on conventional imaging evaluation (chest x-ray and CT) and based on MixR evaluation: vascular thrombosis, broken leads, loops, kinking, fibrosis along the wires, perforation of vascular structures and cardiac chambers). Fibrosis was inferred when wires were joint and there was a significant rectification of cable curvature. The expected level of difficulty was also included. After the surgical procedure, the surgeon confirmed or excluded the presence of the six complications and graded the level of difficulty. The level of concordance between preoperative and intraoperative findings was evaluated using a qualitative 5 scale and plotted using violin box-plot. A subjective questionnaire to evaluate user-friendliness, ease of learning and attitude towards future use of MixR was also included (Supplemental Table 1).

3 Results

The main clinical characteristics of the patients and device types are described in Tables 1 and 2.

3.1 Patient 1

A 67-year-old patient with PM (2 leads) implanted 10 years. Conventional imaging evaluation classified this case as low difficulty, and a lead loop was identified in the right atrium. MixR intervention planning anticipated mild difficulty, as shown in Fig. 1. A complete and successful extraction was performed under MixR assistance. Severe fibrosis along both wires was confirmed after extraction, but there was no vegetation endocarditis at the tip of the lead, as shown in Supplementary Fig. 3.

3.2 Patient 2

A 79-year-old patient with a cardiac resynchronization therapy device (CRTD) (2 leads) implanted 6 years ago. Conventional imaging evaluation classified this intervention as low difficulty. However, MixR classified it as highly difficult due to severe lead fibrosis inferred at several points (Fig. 2). The procedure was highly challenging with severe fibrosis (Supplementary Fig. 4).

3.3 Patient 3

A 70-year-old patient with a PM (2 leads) implanted 11 years ago. Conventional imaging assessment was considered low risk. MixR indicated severe fibrosis between both leads as shown in Fig. 3. The intervention was of medium difficulty, as expected in MixR as illustrated in supplementary Fig. 5.

3.4 Patient 4

A 61-year-old patient with non-ischaemic dilated cardiomyopathy underwent ICD-CRTD implantation (3 leads) three years ago. Conventional imaging ruled out complications, however suggested a lead-related perforation of the coronary sinus. MixR imaging showed severe fibrosis in three regions (Fig. 4) and excluded the potential perforation of the coronary sinus. MixR was found to be much better correlated with intraoperative findings than conventional imaging and accurately predicted the high complexity of the case, see Supplementary Fig. 6.

3.5 Patient 5

80-year-old with PM implantation (2 leads) 11 years ago. Conventional imaging only anticipated low procedural complications. MixR anticipated severe fibrosis and very well evaluated the kinking in the SVC (Fig. 5). Holograms MixR intraoperative assistance was found very useful in this case (Video 2, Video 3).

3.6 Concordance with the intraoperative findings

A summary of the concordance agreement between conventional and MixR planning with intraoperative findings is shown in Table 3 and Fig. 6.

None of the patients had suspected vascular thrombosis or broken leads, neither in conventional imaging, MixR nor during the intraoperative procedure. MixR predicted much better (very high correlation) the presence of loops, kinking, and fibrosis than conventional imaging. Conventional imaging tended to underestimate the severity of lead fibrosis (low correlation) compared to MixR (very high correlation). In summary, MixR predicted the severity of the potential complications much better (high correlation) compared to conventional imaging (low correlation).

The first operator strongly agreed that MixR had a high value for pre-interventional planning and agreed that it helps during intraoperative use (see Supplemental Fig. 8). The surgeon strongly agreed that this technology should be implemented and incorporated as a routine clinical practice, however stated that the user interaction should be better implemented and there is plenty of room for development such as improving user-friendly interaction and resolution.

Table 1 Clinical characteristics of patients

	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Sex	Male	Male	Male	Male	Male
Age (years)	67	79	70	61	79
Comorbidities					
Coronary artery disease	CABP SV-Cx	ACS stent in CX and RCA	2 ACS, 4 stents	No	ACS, 1 stent
Hypertension	Yes	Yes	Yes	Yes	Yes
Diabetes mellitus	No	Yes	Yes	No	Yes
Heart failure	No	No	No	No	Yes
Chronic renal failure	No	No	No	No	No
Atrial fibrillation	Yes	Yes	Yes	Yes	No
Chronic obstructive pulmonary disease	No	Yes	No	Yes	No
Immune suppression/corticosteroid	No	No	Yes	No	No
Malignancy	No	No	Oesophageal cancer	No	No
Use of anticoagulants	Yes	Yes	Yes	Yes	No
Smoking	Yes	Former	Yes	No	No
Other	None	None	Moderate aortic stenosis Hepatic transplant	Dilated cardiomyopathy Dyslipidemia Hemorrhagic stroke	None
Signs/symptoms of local infection					
Purulent drainage	No	Yes	Yes	Yes	No
Erythema	No	No	No	No	No
Pain	No	No	No	No	No
Swelling	No	No	No	Yes	No
Warmth	No	No	No	Yes	No
Skin ulceration	No	Yes (extrusion)	Yes (slinging generator)	Yes	No
Signs/symptoms of systemic infection					
Fever	Yes	No	No	No	Yes
Chills	Yes	No	No	No	Yes
Malaise	Yes	No	No	No	Yes
Signs of sepsis	Yes	No	No	No	Yes
Fatigue	Yes	No	No	No	No
Anorexia	No	No	No	No	No
Nausea	No	No	No	No	No
Other	Confusional state	None	None	None	None
Endocarditis/vegetation					
Presence of vegetation on echocardiography (describe size)	1 cm RV lead	No	No	No	Yes (small, filamentous, 3 mm)
Endocarditis duke criteria positive	Yes	No	No	No	Yes
Indication of lead retrieval[†]	Yes	Yes	Yes	Yes	Yes
Describe	Septicemia (NAPSE class 1) Endocarditis (NAPSE class 1)	Infection or loss of continuity of the generator pouch. Chronic suppuration (NAPSE class 2)	Infection or loss of continuity of the generator pouch. Chronic suppuration (NAPSE class 2)	Infection or loss of continuity of the generator pouch. Chronic suppuration (NAPSE class 2)	Septicemia (NAPSE class 1) Endocarditis (NAPSE class 1)

CABP: Coronary artery bypass surgery; Cx: Circumflex artery; SV: Saphenous vein

[†]Adapted from the Recommendations for the Indication of Pacemaker and Defibrillator Lead Retrieval from the North American Society of Pacing and Electrophysiology (NASPE) (Love et al. 2000)

Table 2 Characteristics of implanted devices

	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Device type	PM	PM-CRT	PM	ICD CRT	PM
Brand–Model	Medtronics	St. Jude	Medtronics	Boston	Medtronics
Dwell-time	10 years	6 years	11 years	3 years	11 years
Indication	Complete AV block	Complete AV block and cardiac insufficiency	Complete AV block	Dilated myocardiopathy	Complete AV block
Location of implanted device:	Left subclavian vein	Left subclavian vein	Left subclavian vein	Left subclavian vein	Left subclavian vein
Number of leads	2	2	2	3	2
Fixation mechanism	Right atrium: active	Right ventricle: active	Right atrium: active (not connected to pacemaker)	Right atrium: active	Right atrium: active
	Right ventricle: active	Coronary sinus: passive	Right ventricle: active	Coronary sinus: passive	Right ventricle: active
				Right ventricle: active	

AF: Atrial fibrillation; AV: atrioventricular; PM: pacemaker; ICD: implantable cardiac defibrillator; CRT: cardiac resynchronization therapy

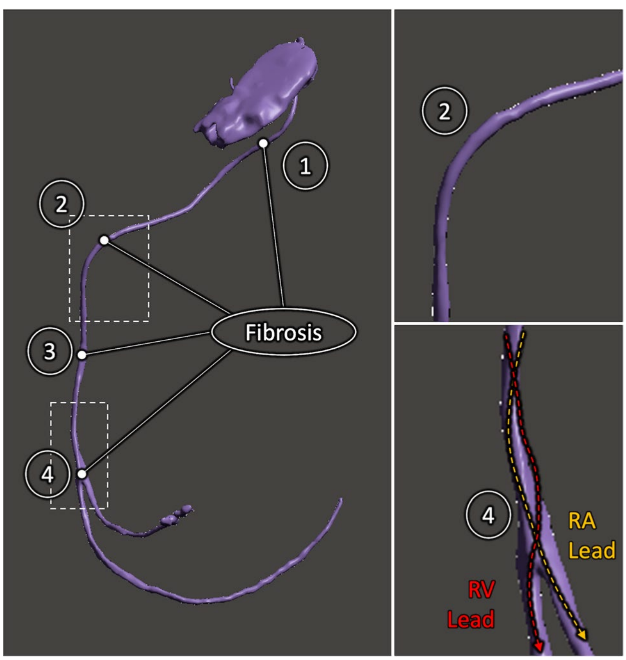

Fig. 2 (Patient 2). MixR clearly identified severe lead fibrosis and thickening all along the innominate vein and SVC. The intervention was anticipated as high difficulty

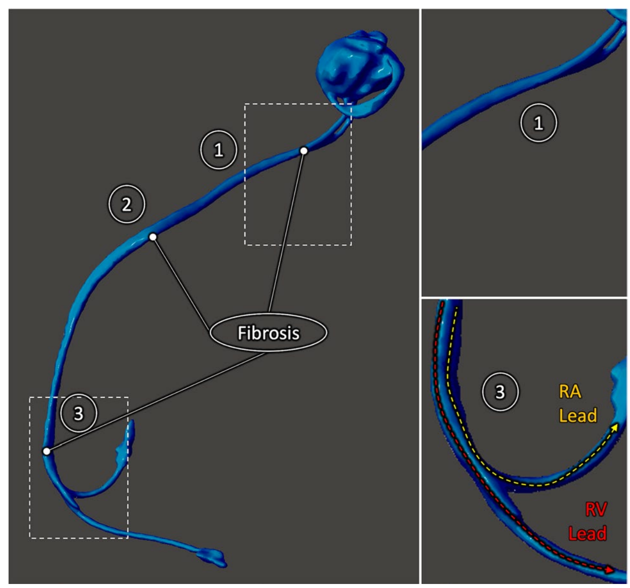

Fig. 3 (Patient 3). MixR showed severe fibrosis in the innominate vein, just after the left subclavian vein (1), which continued all along the SVC (2, 3)

4 Discussion

In this study, we demonstrated that pre-interventional planning is crucial for identifying potential complications during lead extraction procedures. By identifying lead–lead interactions, the surgeon can better anticipate how the removal of one lead can affect others. Our findings indicate that determining the likelihood and location of lead–lead and lead–vessel attachment can help surgeons better prepare for the intervention, potential emergent thoracotomy complications and improve outcomes.

Currently, planning is based on conventional imaging such as chest radiographs and CT. Chest radiography in 2 views may occasionally demonstrate clear evidence of perforations and may suggest lead–lead or lead–vessel interactions, but has demonstrated very poor sensitivity and interobserver agreement compared to CT scanning (Balabanoff

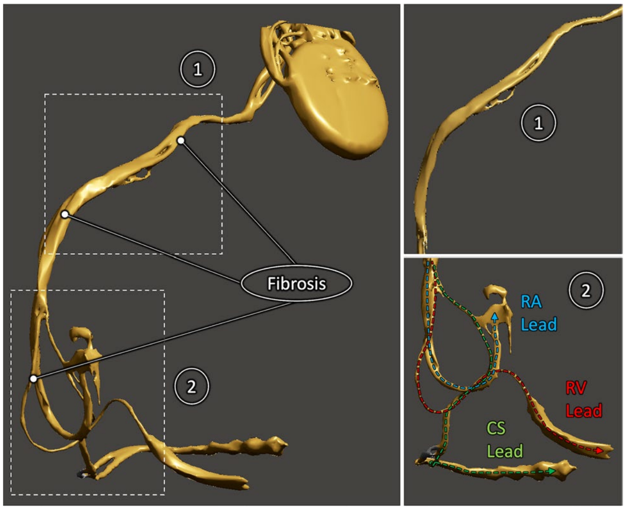

Fig. 4 (Patient 4). MixR demonstrated a much more severe fibrosis and adherences extending all along the subclavian, innominate vein and SVC (1) and at the anchor points in the right atrium and right ventricle (2)

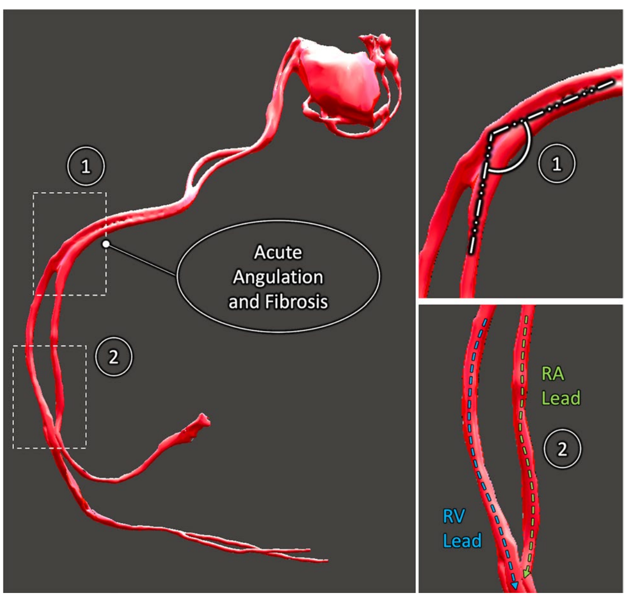

Fig. 5 (Patient 5). MixR anticipate a middle to high complexity procedure due to severe fibrosis and kinking at the SVC entry which prevented sheath progression

et al. 2014). Computed tomography provides excellent high-resolution medical images, necessary to discriminate different tissue properties and anatomical areas. However, CT images are still shown as axial 2D slices and in the best of the cases as volume render reconstruction displayed on a flat screen, loosing essential depth information required for complex cases, and there are limitations in sensitivity and specificity because of metallic streak artefacts. ECG-gated

Table 3 Preoperative concordance with intraoperative findings

	Conventional imaging		MixR	Intraoperative surgical procedure
	Chest Rx	CT scan		
Thrombosis				
Patient 1	–	No	No	No
Patient 2	–	No	No	No
Patient 3	–	No	No	No
Patient 4	–	No	No	No
Patient 5	–	No	No	No
Broken leads				
Patient 1	No	No	No	No
Patient 2	No	No	No	No
Patient 3	No	No	No	No
Patient 4	No	No	No	No
Patient 5	No	No	No	No
Loops				
Patient 1	Yes (?)	Yes (RA)	Yes (RA)	Yes (RA)
Patient 2	No	No	No	No
Patient 3	Yes	Yes	No	No
Patient 4	No	No	No	No
Patient 5	No	No	No	No
Kinking				
Patient 1	No	No	No	No
Patient 2	No	No	No	No
Patient 3	Yes (RA)	Yes (RA)	No	No
Patient 4	No	No	No	No
Patient 5	Yes (SVC)	Yes (SVC)	Yes (SVC)	Yes (SVC)
Fibrosis				
Patient 1	–	+ (InV, SVC)	++ (InV, SVC, RA)	+++ (InV, SVC, RA)
Patient 2	–	+ (SVC)	+++ (InV, SVC)	+++ (InV, SVC)
Patient 3	–	++ (RA)	+++ (InV, SVC)	+++ (InV, SVC)
Patient 4	–	+ (InV)	+++ (ScV, IV, SVC)	+++ (ScV, IV, SVC)
Patient 5	–	+ (SVC)	++ (SVC)	+++ (SVC)
Perforation				
Patient 1	No	No	No	No
Patient 2	No	No	No	No
Patient 3	No	No	No	No
Patient 4	No	Yes (CS)	No	No
Patient 5	No	No	No	No
Level of difficulty				
Patient 1	Low	Low	Medium	High
Patient 2	Low	Low	High	High
Patient 3	Low	Low	Medium	Medium
Patient 4	Medium	Medium	High	High
Patient 5	Low	Low	Medium	High

Concordance between conventional planning (chest Rx and CT) and MixR planning with intraoperative findings. (See Supplemental Material, Definitions of complications for extended descriptions)

ScV: Subclavian vein, InV: innominate vein, SVC: superior vena cava, RA: right atrium

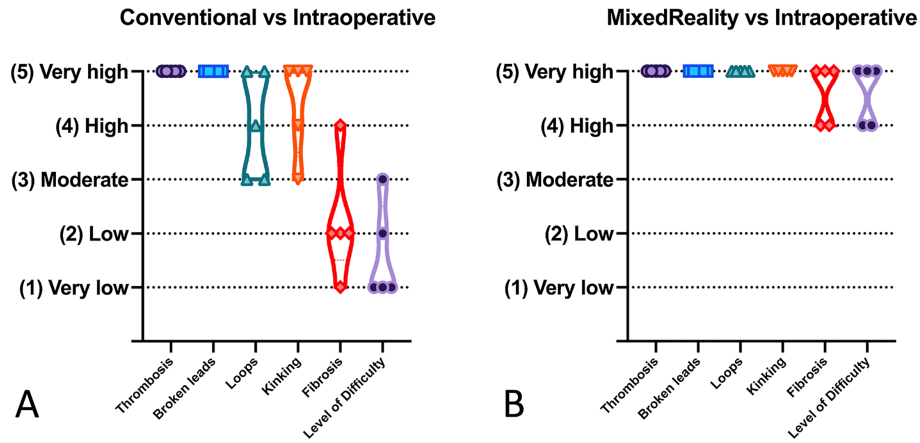

Fig. 6 Conventional Imaging and mixed reality correlation with intraoperative findings. Correlation with intraoperative finding is coded in a numerical scale: 1 (very low correlation), 2 low correlation), 3 (moderate correlation), 4 (high correlation) and 5 (very high correlation)

CT has been proposed for a better accuracy for assessment of cardiac lead perforation (Zhang et al. 2019). Furthermore, Lewis et al. studied 30 patients to determine the feasibility of using CT to determine differences and outcomes between patients with lead adherence to vascular structures and those without (Lewis et al. 2014). That study found significant differences in the laser time and sheath diameter used for extraction, and similar results were confirmed by Patel et al. with procedural and fluoroscopy times (Patel et al. 2019). Ehieli et al. (2017) analysed imaging findings in 100 patients who underwent ECG-gated CT prior to TLE and noted that imaging findings of vascular adherence did not affect extraction success. However, although no further analysis of procedural difficulty was performed, the authors noted that, in a subset of cases where there was suspicion of lead perforation, the procedural approach was changed. Another group used ECG-gated CT preoperatively to assess the course of the leads in the SVC and reported that electrophysiologists could change their approach and technique depending on the findings of the CT scan (Vogler et al. 2018). However, that study did not illustrate how their extraction techniques were affected by the findings of perforation, adherence or calcification seen on CT scan.

Holograms helped better visualize and understand complex and tortuous lead curses and loops and their relationship with the surrounding cardiovascular structures. Similar results regarding lead–lead interactions have been reported recently by Holm et al. (2020).

In this study, despite very complex cases, no complications were reported and all extractions were successful. It may be stated that perhaps the best predictor of procedural success with TLE is the lead age and operator experience (Fu et al. 2015; Bontempi et al. 2017; Sidhu et al. 2020). However, despite years of experience and advancements in TLE procedure, there is still no recommendation on the optimal extraction approach, tools and technique based on the unique risk of each patient. Although the surgeon involved in this study had a significant experience in TLE procedure, it was recognized that MixR helped to identify in advance potential areas of complications, modifying the interventional strategy and therefore reducing the incidence of potential complications. Furthermore, the first operator reflected in the questionnaire that "information and imaging guidance is never enough when performing this procedure". Pre-procedure analysis may be used to impact clinical decisions such as which extraction tools should be used, whether to extract a given lead, or if the patient should be referred to a specialized high-volume lead extraction centre. But more importantly, in those centres in which TLE are routinely performed by electrophysiologists may help to decide which additional resources should be available such as surgical team and pulmonary by pass equipment.

Finally, it should be noted that during the procedure, intraoperative guidance is based on X-ray fluoroscopy which is very limited for vascular navigation. The surgeons have to rely on a previously created 3D model of the patient-specific anatomy and potential areas of interest in their minds, with obvious potential mistakes (Al Janabi et al. 2020). MixR allows merging of the real world (theatre, patient) and interacting with holograms (3D digital representation of the heart, vessels, and CIED) in real time. Surgeons can then perform the TLE procedure in the conventional theatre using the regular material, but with the additional help of MixR. Patient-specific vessels and lead holograms respond to gaze and gestures and are presented alongside the patient, staff, and monitors. The MixR headset allows interaction under sterile conditions. But more importantly, the objects visualized and interacted with in MixR do not prevent the surgeon from following the normal workflow in the operating room. Moreover, a multi-user experience can be implemented where several surgeons can visualize the same virtual model in the same operating room from a different perspective. This would enrich the multidisciplinary meeting discussions and surgical planning and help discuss the intervention in real time.

We consider MixR may offer several advantages compared to virtual reality (Mendez et al. 2019; Tandon et al. 2019). Virtual reality is a fully immersive digital environment, but there is no interaction with the real world. It may help during pre-interventional planning but not during intraoperative guidance that is still guided by fluoroscopy. Soon MixR images may be automatically integrated and co-registered with fluoroscopy system, as it has already been established in electrophysiology laboratories that integrate CTs and magnetic resonance imaging into mapping systems. We are in the early days of this evolving technology and its implementation in the clinical practice. Innovation is the key to improving and providing optimal healthcare by helping professionals carry out tasks.

There are some limitations in our study, in addition to the small number of cases reported. We did not use ECG-gated CT to reduce patient radiation, but it was a significant limitation. Inaccuracies derived from image artefacts had to be corrected by segmentation and 3D reconstructions. Holograms may infer the presence of fibrosis the wires appear to be stuck together or adhered to the vascular wall with significant rectification of leads curvature. However, holograms do not define the complex nature of the scar process. For example, it does not elucidate whether a scar or adhesion is soft or dense. Second, the current device has a restricted projection size, and sometimes the 3D model may cut off at the borders of the screen. Besides, the HoloLens battery life is not designed for long procedures (above 2–3 h). We had to design a belt to store a small external battery (15 × 7 × 2 cm, 358 g, 268,000 mAh), which was connected to the Hololens, preventing battery failure and device switching off.

5 Conclusions

MixR holograms based on CT images improve understanding of cardiovascular anatomy and detection of potential areas of complications. MixR could be used in preoperative surgical planning, teaching and, in the future, as guidance for intraprocedural decisions. We believe that this proof-of-concept research papers play an important role for medical professionals who should seek to identify problems within their workspace to which solutions can be implemented with these novel technologies. It is also the right time to detect MixR limitations that should be implemented according to new procedural applications.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10055-023-00929-2.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests Israel Valverde, Gorka Gomez, Aristides de Alarcon Gonzalez, Antonio Ordoñez, Encarnacion Gutierrez-Carretero have nothing to disclose. Antonio Sierra and Adriano Perez work for the company Sngular, Spain.

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