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Augmented and mixed reality: technologies for enhancing the future of IR

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Abstract

Augmented and mixed reality are emerging interactive and display technologies. These technologies are able to merge virtual objects, in either two or three dimensions, with the real world. Image-guidance is the cornerstone of IR. With augmented or mixed reality, medical imaging can be more readily accessible or displayed in actual 3D space during procedures to enhance guidance, at times when this information is most needed. In this review, the current state of these technologies is addressed followed by a fundamental overview of their inner workings and challenges with 3D visualization. Finally, current and potential future applications in IR are highlighted.

I. Introduction

Spatial computing is a new paradigm of computing that uses the immediate, surrounding environment as a medium to interact with technology. Virtual, augmented, and mixed reality are all types of spatial computing. Virtual reality (VR) completely immerses the user in an

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artificial, digitally-created world. Augmented reality (AR) overlays digital content on the real world, enhancing reality with superimposed information. Mixed reality, also known as merged reality, represents the fusion of both virtual and real-world environments, where digital and physical objects co-exist and can interact with each other.

Despite mixed reality devices being an evolution of AR, traditionally, mixed reality represented a continuum with the real-world environment at one end of the spectrum to a completely virtual environment at the opposite end (Fig. 1) [1]. This review will consider mixed reality as synonymous with AR and will focus on AR and its potential impact on IR; VR will not be discussed in detail. Much of the research highlighted has been demonstrated as proof-of-concept or as a feasibility study; more established studies and clinical trials remain to be published.

One of the key benefits of AR over VR is the ability to visualize and interact with digital objects while maintaining views of the natural world. Preserving direct line-of-sight with the surrounding environment permits the use of AR during image-guided interventions, provides relevant depth cues, and reduces virtual reality sickness, also known as cybersickness. Cybersickness is due to discrepancies between the visual and vestibular senses and can still occur with AR but is less frequent and milder compared to VR [2].

AR helps increase situational awareness by reducing shifts in focus [3, 4]. Strategically placed digital content minimizes refocusing between the content and the real world. AR devices can be grouped into multiple distinct subtypes (Fig. 2): head-mounted displays (HMDs), handheld displays, and stationary displays. These classifications can be further categorized into optical see-through (OST) and video see-through (VST). OST displays utilize special transparent lenses that allow direct views of the external environment. VST displays use a video feed to indirectly view the external environment. These categories can be further subdivided into monocular or binocular. Monocular displays provide a single channel for viewing. Binocular displays provide two separate channels to each eye to simulate the perception of depth through stereoscopy.

An OST display has three main components: light engine, optical combiner, and computer (Fig. 3). Special transparent lenses, called optical combiners or holographic waveguides, merge digitally-created images with light from the natural world. The optical combiner acts essentially like a partial mirror, allowing light from the real world to pass through while redirecting light from the projector to generate a hologram. A complete evaluation of OST-HMDs and their applications for surgical interventions is provided by Qian *et al* [5].

In general, there are two conventional methods for rendering 3D volumetric data: 1) surface rendering (SR, Video 1), also known as indirect volume rendering or shaded surface display, and 2) direct volume rendering (DVR, Video 2) [6–9]. SR is a binary process with visualization of surface meshes at tissue interfaces, which are usually preprocessed by segmentation and represent a fraction of the raw volumetric data. DVR is a continuous and much more computationally intensive process involving the entire volume of data but provides the most accurate visual 3D representation medical imaging [9–11]. Both of these methods can be incorporated into AR displays to render medical imaging in actual 3D space [9].

The primary advantage of AR displays is the ability to place and anchor virtual objects anywhere in space. This can be useful for projecting anatomic models or 3D imaging through the surgical drape, flat panel detector, or CT gantry. However, this feature can also unintentionally preclude visualization of important physical objects, such as instruments and the operator's hands (Fig. 4). Therefore, object occlusion, or the way virtual objects project in front of and behind physical objects, will be important for managing virtual content in procedural settings [12].

One of the key limitations of AR displays is the field-of-view (FOV) for augmentation. Naturally, binocular FOV of the human eyes is about 200 degrees in the horizontal plane and 135 degrees in the vertical plane [13]. All commercially available OST-HMDs have less than 90 degrees horizontal or vertical FOVs, with most ranging 30–40 degrees [5]. Additionally, most untethered displays have battery lives of 2–3 hours [14], an important factor to consider during prolonged procedures. In general, early clinical studies will seek to define how and whether AR can potentially offer additional benefits in IR, such as enhancing anatomic understanding, decreasing procedure times, and reducing radiation exposure.

II. 3D Accuracy, Tracking, and Registration

Accurate tracking and registration are needed for any image-guided navigation system [15]. For binocular displays, projectional accuracies are dependent on accurate calibration of the device. Calibration of OST-HMDs is necessary to tailor projections to the user's inter-pupillary distance (IPD) [16]. Inaccurate IPD can result in poor eye-lens alignment, image distortion, and eye strain. Additionally, small errors in the IPD as well as off-centering of the device can propagate to large projectional errors due to off-axis projection [17].

Near-perfect accuracies are needed for AR to be useful during image-guided interventions. Although measuring accuracies of virtual objects in a 2D plane is relatively straightforward, measuring accuracies of virtual 3D objects is more challenging. Accuracy in depth, or the z-plane, is affected by the vergence-accommodation conflict [18]. Human eyes naturally converge and focus on an object at the same distance. However, since most OST-HMDs have fixed focal planes, the eyes may focus and converge at separate distances causing distorted depth perception (Fig. 5). This conflict is also the leading contributor for causing eye fatigue and discomfort, common symptoms from prolonged AR use [19].

Microsoft HoloLens (Redmond, WA), which was released in 2016, has been shown to be systematically superior to comparative OST-HMDs on the market for surgical interventions [5]. Several validation studies have reported HoloLens accuracy to be near or within one centimeter [20–25]. With subcentimeter accuracies, the U.S. Food and Drug Administration approved Novarad Opensight (American Fort, UT) and Medivis SurgicalAR (Brooklyn, NY) software applications in September 2018 and May 2019, respectively, for *preoperative* visualization using HoloLens.

Tracking is the sensing and measuring of spatial properties. Registration involves the matching or alignment of those spatial properties, allowing anatomic imaging to be overlaid directly onto the patient. AR devices contain multiple sensors that continuously map and track its position within the environment, a process known as SLAM [26]. Accurate mapping and tracking are necessary to update spatial relationships of virtual objects. Full tracking requires 6 degrees of freedom: 3 degrees of freedom in position (x-, y-, and z-axes) and 3 degrees of freedom in rotation (pitch, yaw, and roll) (Fig. 6). Because AR involves 3D tracking, accurate registration can be challenging and limited by built-in sensors, known as “inside-out tracking.” However, computer vision algorithms using built-in cameras to detect and track image-based markers can supplement “inside-out tracking” and provide accurate and fast registration [20, 21, 27–29].

Many existing AR-assisted navigation systems integrate an external optical tracking system, or “outside-in tracking,” and bypass internal sensors to further improve accuracies or track additional hardware [30–36]. Another external tracking system commonly employed is electromagnetic tracking [37]. Despite the type of tracking, most external tracking systems provide limited degrees of freedom, balancing tradeoffs between sensing position versus orientation. For integration with external trackers, each coordinate system needs to be calibrated and transformed to be congruent within the same space, or world coordinate system (Fig. 7). Calibration of the AR device and external trackers can be performed using manual, semi-automatic, or automatic methods [32, 38]. Once calibrated, 3D datapoints in virtual space can be registered to known and tracked points in physical space.

The aforementioned registration processes have all been based on rigid transformations. However, multiple practical considerations impede accuracy and rigid registration, such as patient motion, breathing, and organ deformation, which are dynamic processes that may require dynamic and potentially computationally intensive solutions [39, 40]. Respiratory and patient motion continue to remain one of the largest technical and practical hurdles for adoption of many navigation or fusion systems in IR, with many systems opting for simple respiratory gating [41] or a rigid to elastic switch [35].

III. AR in medicine

The enhanced ability of AR to visualize and localize targets may have downstream implications for improving procedural outcomes, complication profiles, and operating time. Thus, AR has been explored to augment a variety of surgical procedures. Recent applications with AR technologies have been demonstrated in neurosurgery [25, 33], otolaryngology [42], vascular surgery [43], hepatobiliary surgery [44], orthopedic surgery [45], plastic surgery [14], and urology [46]. Despite the importance of visualizing and localizing targets in IR, a recent systematic review of wearable heads-up displays in an operating room identified IR as having the fewest number of published studies among ten other procedural specialties [47]. As image-guided experts and proceduralists, more experimentation and developments in IR should be undertaken to evaluate this new visualization technology as other specialties have done.

IV. IR applications

The role for advanced imaging and technologies in image-guided procedures has transformed procedural medicine. The 1996 RSNA New Horizons Lecture emphasized the capability for computers to enhance visibility and navigate through 3D coordinates during IR and minimally invasive procedures [48]. The lecture highlighted the promises of preoperative planning to select optimal approaches, register models onto patients, and display virtual needle paths, all of which continue to be active areas of research and applicable to a variety of IR procedures. Over two decades later, these promises still have yet to be fully realized, but current research endeavors show progress and potential for translation into the IR suite.

A. Endovascular Procedures

The additional spatial information provided by AR can enable the IR to obtain a more intuitive understanding of complex vascular anatomy. Currently, IRs must cognitively associate 2D images on a monitor screen with a mentally reconstructed 3D model. AR permits the ability to easily visualize 3D vascular anatomy from prior cross-sectional imaging for preprocedural planning [49] or use as an intra-procedural reference [50]. This capability can alleviate the continual process of associating and mentally reconstructing 2D images into 3D [51]. Indeed, cognitive reconstruction and registration have been shown to be less accurate than registration with computer assistance for fusion-guided, needle-based interventions [52].

With AR, the IR can look virtually inside of the patient from any viewpoint. Anterior, posterior, and oblique divisions of vessels can be easily differentiated and optimally displayed with the added depth dimension [51]. Prior to the procedure, the IR can simulate ideal fluoroscopic angles and positions that highlight vessel courses and branchpoints. During the procedure, a virtual 3D roadmap can be placed anywhere within the IR suite as a reference to augment vessel selection and catheter positioning. Acquired cone-beam CT, or rotational angiography, can also be projected in 3D to quickly confirm the target of interest, as opposed to scrolling though axial 2D images.

AR utilization may also help achieve radiation dose savings during endovascular procedures in the future. Using AR and external electromagnetic tracking, Kuhlmann *et al* demonstrated the ability to overlay a 3D vascular model on a patient phantom and virtually track and navigate an endovascular catheter through the vascular model, foreseeably eliminating the need for any radiation for real-time endovascular guidance [53].

B. Percutaneous Procedures

Many AR implementations currently exist for navigation during percutaneous needle-based interventions. For example, virtual 3D needle trajectories can be registered to patients to assist in the placement and positioning of ablation probes (Fig. 8); protocol approved by the institutional review board at [*omitted*]. Moreover, AR has been shown to reduce procedure times, number of acquired images, and radiation dose during simulated percutaneous bone interventions [54]. In a similar fashion, fusion navigation with electromagnetic tracking has been proven in a randomized controlled trial to reduce radiation, number of CT scans, indwelling needle time, and the number of needle manipulations in CT-guided liver biopsies [55]. A clinical trial utilizing HoloLens for percutaneous liver ablation is currently underway (Fig. 9) [56]; protocol approved by the institutional review board at [*omitted*].

One of the first AR systems for this application was made by Siemens (Erlangen, Germany) in 2006 and called RAMP, which used a VST-HMD system to project virtual needle trajectories during CT- and MRI-guided interventions [57, 58]. More recent AR-assisted navigation systems have been developed using tablets and OST-HMDs. An AR-assisted needle guidance system using an OST-HMD and external optical tracking demonstrated guidance error between the actual and virtual needle trajectories by less than two degrees in a CT phantom [31]. Another system utilizing a tablet computer and computer vision marker detection achieved sub-5 mm accuracies in a porcine model and cadaver for liver thermal ablation [28], which has been subsequently upgraded with a VST-HMD and commercialized as Bracco Imaging Endosight (Milan, Italy) for CT-based tumor ablations. In contrast to these rigid needle-based navigation systems, HoloLens was used to project and extrapolate bending 3D needle trajectories with a shape sensing needle and reduce targeting error by 26% compared to rigid needle assumptions [32].

AR can provide enhanced volumetric tumor margin visualization and localization, potentially leading to more successful ablation coverage and adequate treatment margins [59]. Higher ablation success rates have been shown in simulated microwave liver ablation following planning in 3D, albeit on a monitor screen, compared to 2D [60]. In a similar fashion, AR my help plan and facilitate optimal probe placement by visualizing theoretical ablation treatment volumes in actual 3D space (Fig. 10 and Video 3). These plans can then be transferred and registered onto the patient for virtual procedural guidance using the planned trajectories. This approach may give more confidence to the IR for approaching and treating targets in challenging locations that were previously unfavorable, such as liver dome lesions requiring nonorthogonal or out-of-plane approaches [15].

AR may be able to help achieve considerable radiation dose savings and resource utilization during percutaneous procedures. The use of an AR capable C-arm system revealed approximately 40–50% radiation dose reduction during needle localization of targets in pigs compared to standard CT fluoroscopy while preserving accuracy [61]. HoloLens and Novarad OpenSight were used to virtually guide spinal needles into a lumbar spine phantom and resulted in sub-5 mm accuracies using preoperative CT alone without the need for any real-time imaging [24].

C. Training & Instruction

Simulations with AR for medical training are becoming increasingly popular for teaching procedural and technical skills [62]. AR can help create immersive scenarios within a real IR suite to improve performance before complex cases or simulate the use of new equipment before actual use [63, 64]. However, current evidence regarding the relative superiority of AR simulations to conventional instruction is lacking. One study found no difference in internal jugular vein cannulation time and total procedure time using AR compared to conventional instruction [65].

In addition to simulations, AR devices enable the ability to share environments for collaborative experiences with other users. Existing interactive platforms allow remote consultants to project live annotations into the AR display of another operator, offering remote real-time instruction or expert assistance [66, 67]. Additionally, procedures performed with AR HMDs can be broadcasted on a larger scale, allowing IRs in rural settings or developing countries to visualize live or recorded procedures performed by experts [68].

D. Ergonomics & Workflow

There are benefits to projecting virtual 2D objects as well as 3D objects in IR. AR headsets are able to deploy virtual 2D monitors that can improve ergonomics, patient monitoring, and workflow. Virtual 2D monitor screens, as many as needed, can be placed anywhere within the IR suite for readily accessible viewing. These virtual screens can be made as large as desired but will fundamentally be constrained by the headset's FOV. Images from the C-arm or ultrasound (US) machine can be streamed to the AR headset in real time with a video capture device [30]. This allows the operator to maintain focus on the task at hand while reducing gazes away from the procedural field. For example, virtual 2D monitors placed within the procedural field during vertebroplasty can allow the IR to have close observation of cement placement without shifting focus [69]. A randomized control trial in breast phantoms showed that AR-assisted needle guidance using a VST-HMD and a virtual screen displaying live 2D US images along the end of the US transducer led to improved biopsy needle accuracy compared to standard US guidance [70].

Finally, AR can have beneficial impacts on all IR staff members. C-arms requiring manual positioning can be cumbersome and require several adjustments until the desired view is obtained. An AR-assisted virtual C-arm positioning guide can aid technologists to quickly establish desired C-arm views, eliminating the need for iterative refinement and thereby reducing radiation [71]. Additionally, AR can be used to project a radiation dose map of the patient onto the IR table as well as help virtually and visually monitor radiation dose to staff members during the procedure in real time [72]. Furthermore, the advent of virtual screens and controls permits the removal of extraneous cables, carts, and mounts to allow staff members to more easily maneuver around the IR suite.

V. Conclusions

Augmented and mixed reality are novel display technologies that are able to provide a new way to visualize images and localize targets during image-guided procedures. Although IR has been somewhat slow to adopt such technologies, these technologies may be appealing to IR and image-guided therapists for readily-accessible image viewing or advanced 3D visualization intra-procedurally. AR-assisted systems should be further developed and evaluated to see if they can improve outcomes in IR with safer, more efficient procedures that require less radiation. Clinical evidence is currently lacking, but as these technologies evolve, AR may become easier to implement and utilize imaging in an actual volumetric fashion to enhance interventions. However, it will be paramount that metrics be established and clearly defined through validated, high-level, evidence-based studies. In doing so, translation and adoption into the IR suite may transform the way future image-guided interventions are undertaken and provide benefits to patients, operators, and staff.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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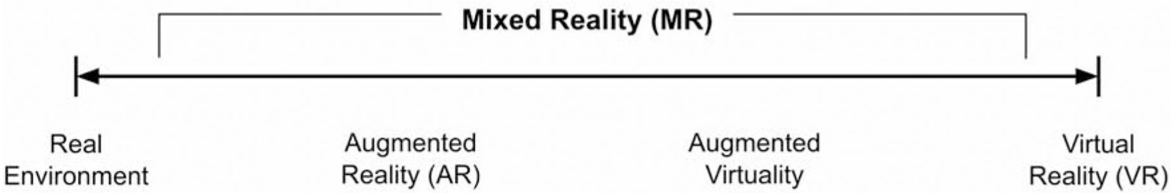


Figure 1.
Reality-Virtuality Continuum proposed by Milgram in 1994 [1].

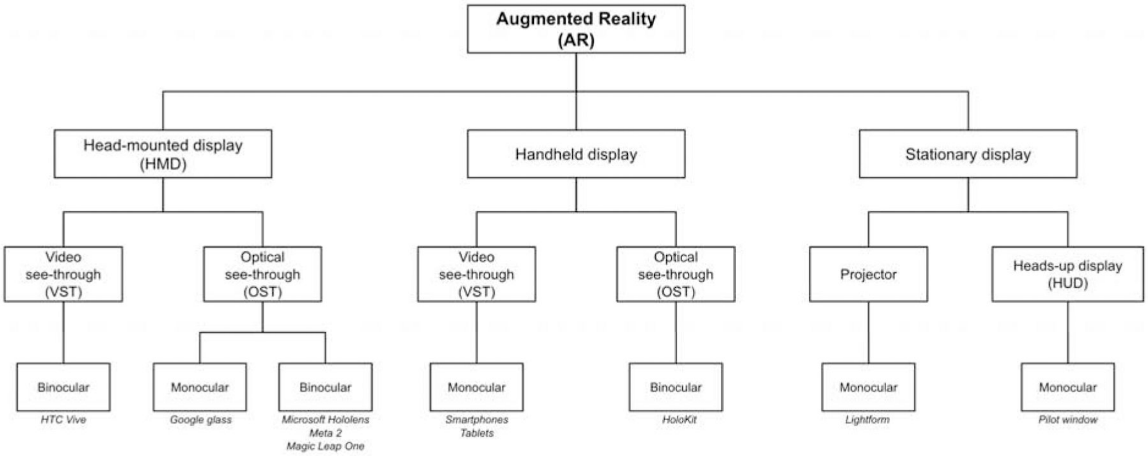


Figure 2.

Organizational chart on types of AR devices. Specific examples are displayed in italics where appropriate.

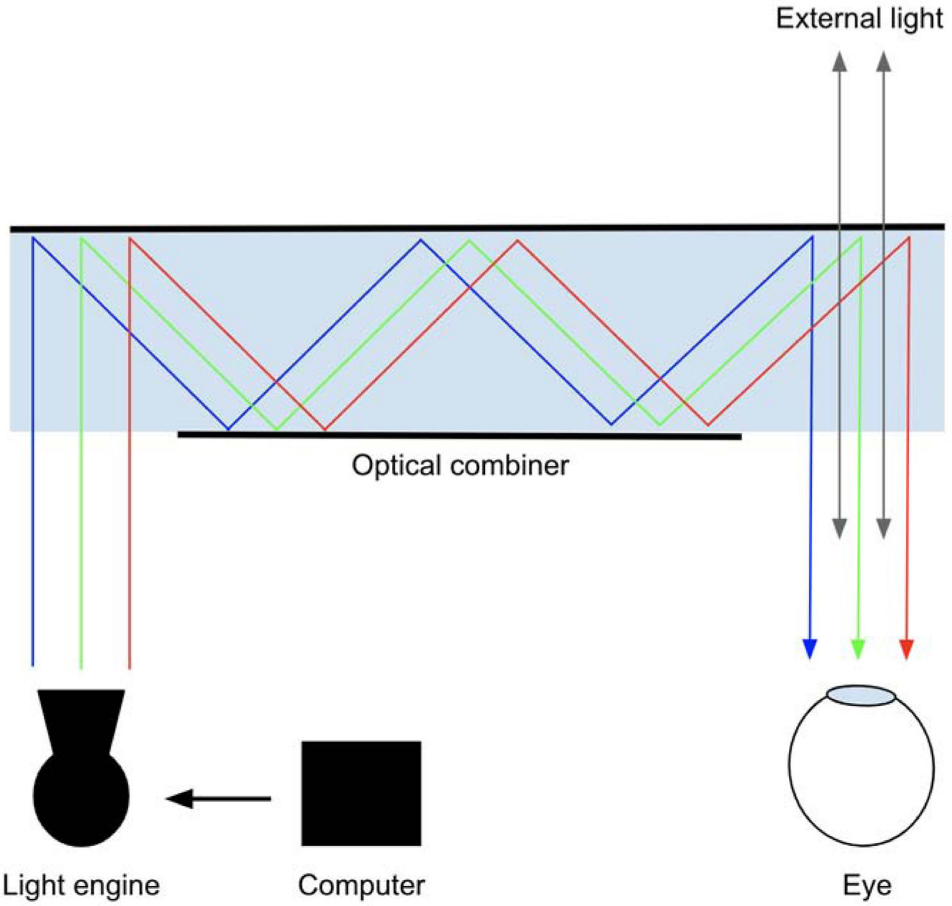


Figure 3.

General schematic of an optical see-through (OST) display. Light from a projector is reflected through a waveguide using total internal reflection and diffraction and is directed at specific angles and wavelengths into the eye to produce a hologram. External light from the natural world also passes through into the eye.

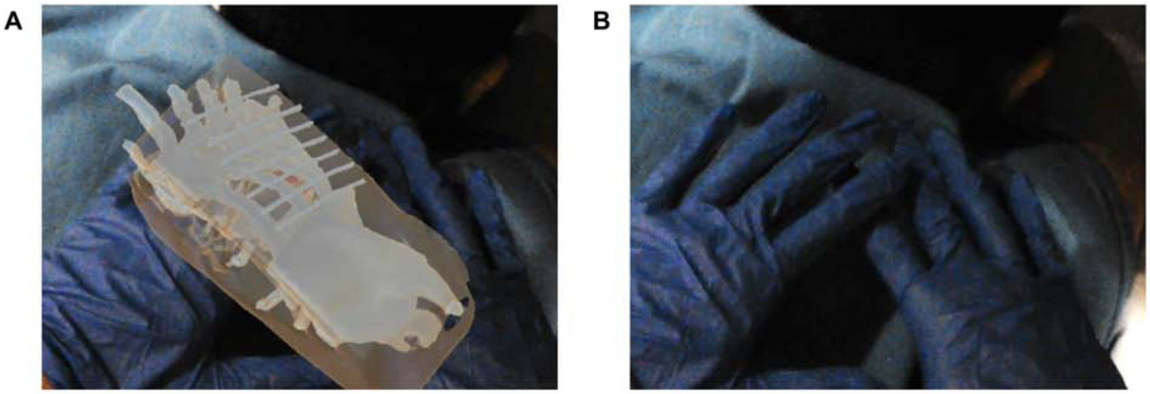


Figure 4.

Object occlusion as a potential unintended consequence of AR. **A.** Virtual model within the patient projecting through the operator's hands, unintentionally occluding visualization of the hands. **B.** Hands are visualized with hologram turned off.

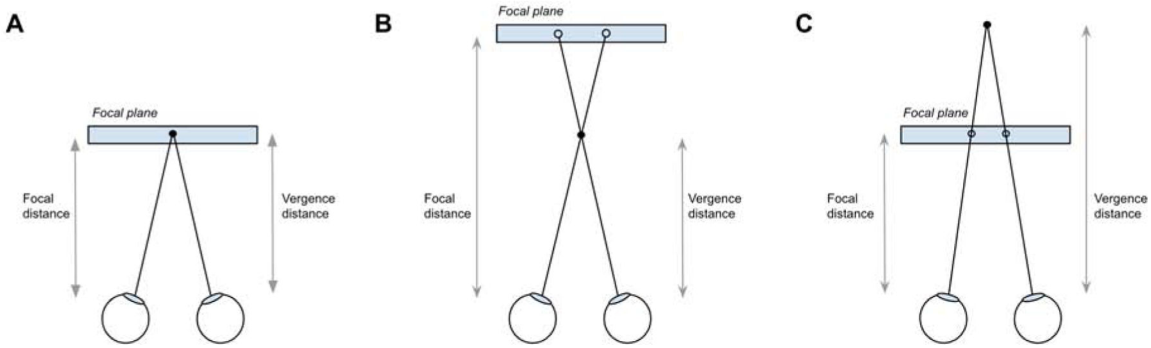


Figure 5.

Various visual perception scenarios affecting vergence and accommodation. **A.** Focal distance and vergence distance are equal, which occurs naturally with human vision. This is the ideal configuration for OST-HMDs. **B.** Vergence-accommodation conflict with focal distance greater than vergence distance when virtual objects are projected close to the display. **C.** Vergence-accommodation conflict with focal distance less than vergence distance when virtual objects are projected far from the display.

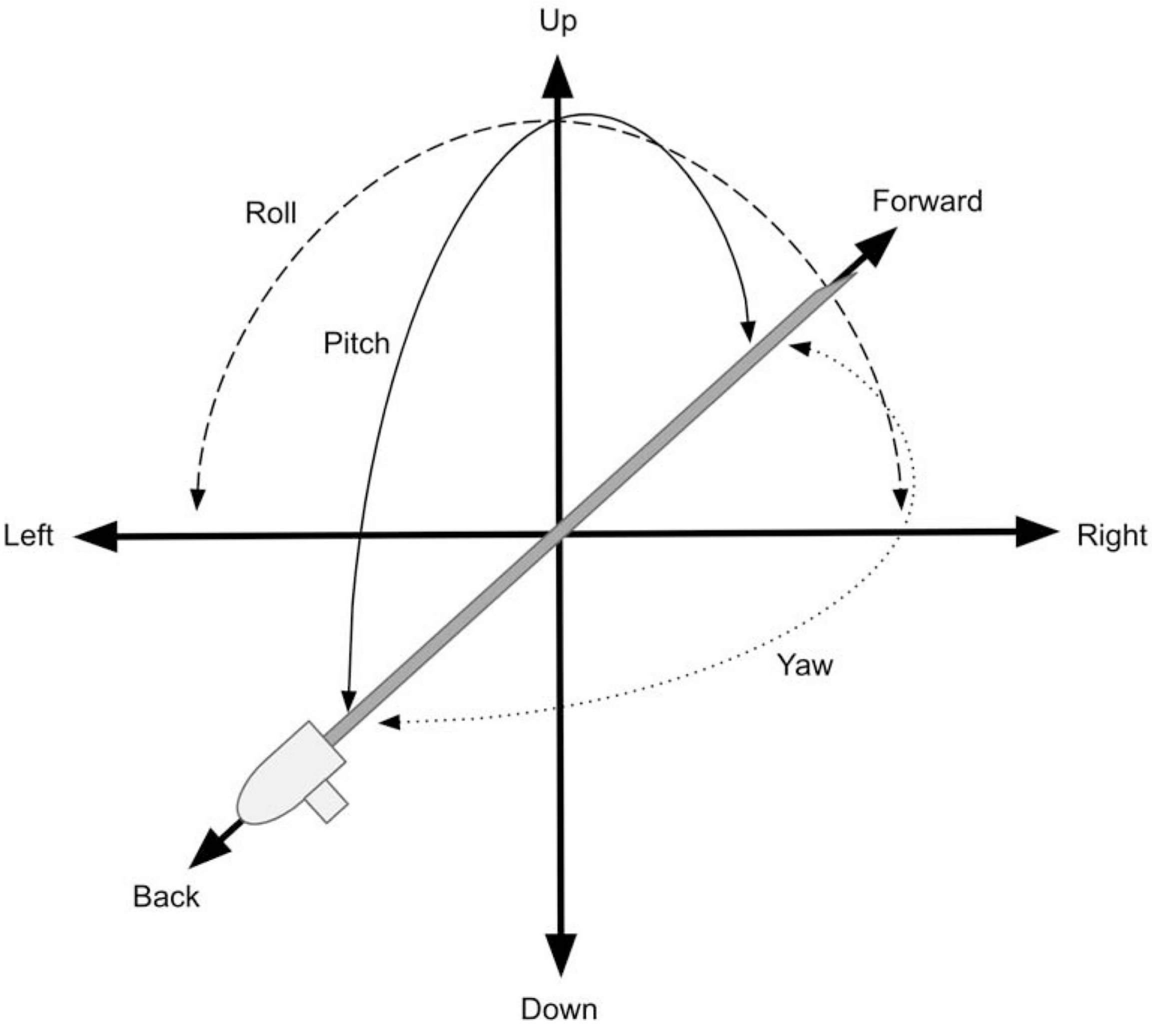


Figure 6.

Six degrees of freedom representing combination of three positions (x-y-z) and three orientations (roll-pitch-yaw).

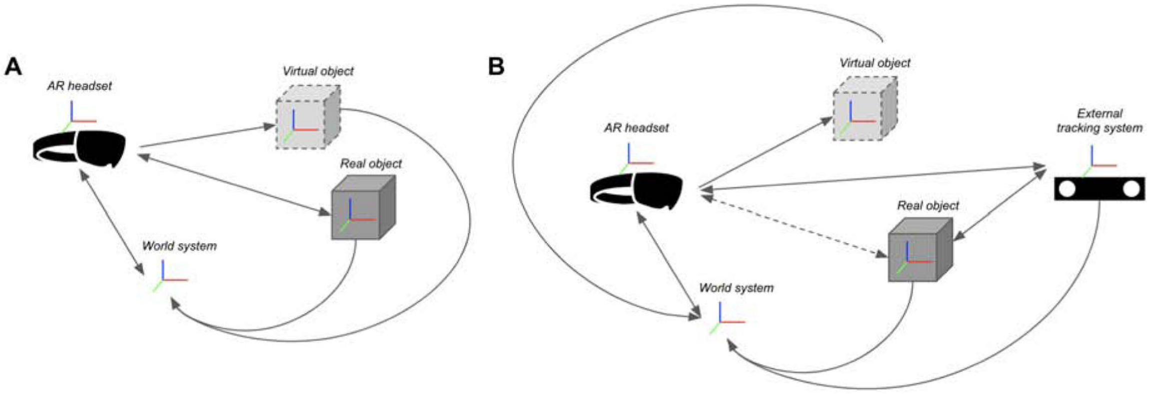
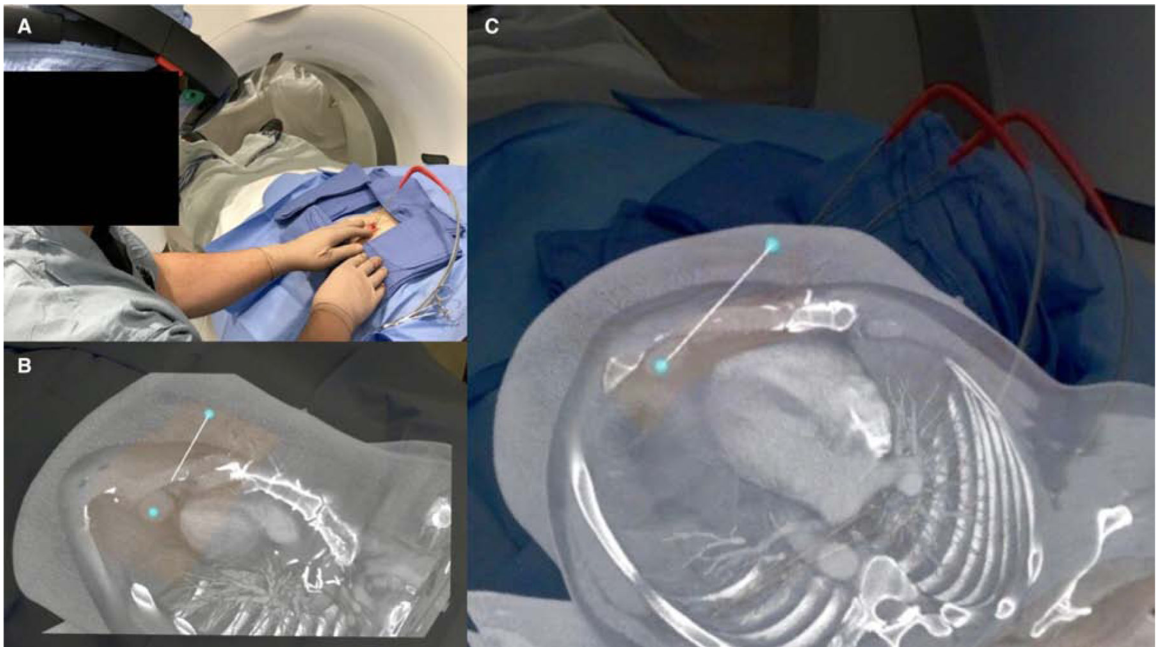


Figure 7.

Various types of tracking with arrows representing transformations needed for virtual and physical objects to be congruent within the same space. Red-green-blue axes represent respective coordinate systems. **A.** “Inside-out tracking” using built-in sensors within the augmented reality headset. **B.** “Outside-in tracking” after integration with an external tracking system. Tracking of real physical objects by the AR headset (dotted line) is replaced by the external tracking system.



[redacted]

Figure 8.

A. Metastatic thymoma for cryoablation of cardiophrenic lymph node using AR-assisted visualization intraoperatively. Preoperative CT was projected using Microsoft HoloLens (Redmond, WA) and Medivis SurgicalAR (Brooklyn, NY). Rendering was performed on a remote workstation and wirelessly streamed to HoloLens in real time. Holographic 3D volume was manually registered to the patient using the patient's nipples as markers. **B and C.** A virtual needle trajectory track can be overlaid during planning and used as a virtual guide during the procedure.

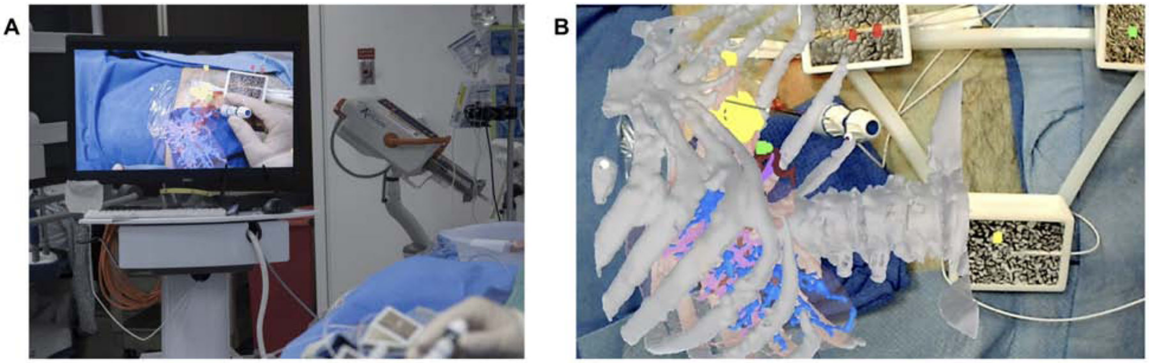


Figure 9.

A. Hepatocellular carcinoma for microwave ablation using intraoperative AR-assisted navigation. The preoperative CT was projected using surface rendering software and navigation system by Medview AR (Cleveland, OH) and Microsoft HoloLens (Redmond, WA). The holographic projection was registered to the patient using an electromagnetic tracking system and image-based markers. **B.** Combined real-time tracking of virtual/actual ablation probe relative to tumor target (yellow).

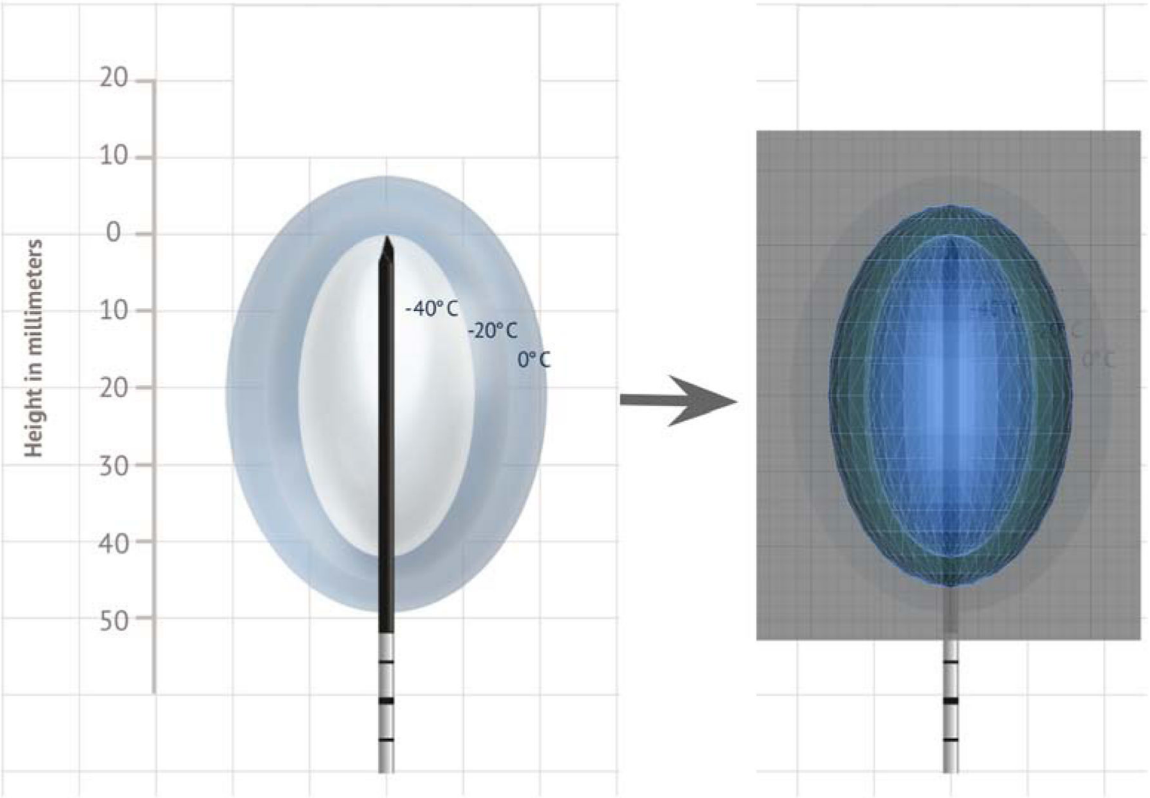


Figure 10.

Planning an ablation with augmented reality. 3D surface-rendered model of −40°C and −20°C isotherm ice balls from manufacturer technical specifications from Galil Medical (Arden Hills, MN).