Abstract

Purpose To evaluate manual and automatic registration times and registration accuracies on HoloLens 2 for aligning a 3D CT phantom model onto a CT grid, a crucial step for intuitive 3D navigation during CT-guided interventions; to compare registration times between HoloLens 1 and 2.

Methods Eighteen participants in various stages of clinical training across two academic centers performed registration of a 3D CT phantom model onto a CT grid using HoloLens 2. Registration times and accuracies were compared among different registration methods, clinical experience levels, and consecutive attempts. Registration times were also compared retrospectively to prior HoloLens 1 data.

Results Mean aggregate manual registration times were 27.7 s, 24.3 s, and 72.8 s for one-handed gesture, two-handed gesture, and Xbox controller, respectively; mean automatic registration time was 5.3 s (ANOVA $p < 0.0001$). No significant difference in registration times was found among attendings, residents and fellows, and medical students ($p > 0.05$). Significant improvements in registration times were detected across consecutive attempts using hand gestures ($p < 0.01$). Compared to prior HoloLens 1 data, hand gesture registration was 81.7% faster with HoloLens 2 ($p < 0.05$). Registration accuracies were not significantly different across manual registration methods, measuring at 5.9 mm, 9.5 mm, and 8.6 mm with one-handed gesture, two-handed gesture, and Xbox controller, respectively ($p > 0.05$).

Conclusions Manual registration times decreased significantly on HoloLens 2, approaching those of automatic registration and outperforming Xbox controller registration. Fast, adaptive, and accurate registration of holographic models of cross-sectional imaging is paramount for the implementation of augmented reality-assisted 3D navigation during CT-guided interventions.

Keywords Augmented reality · Mixed reality · Interventional radiology · HoloLens · Registration · 3D visualization · CT-guided intervention

Introduction

Augmented reality (AR) technology has advanced significantly in recent years. Its ability to display 3-dimensional (3D) datasets, such as computed tomography (CT) and magnetic resonance images (MRI), in a true 3D space rather than on flattened 2D screens has been shown to improve anatomical learning [1, 2], 3D spatial interpretation [3], and pre-operative planning [4–9]. The added benefit of overlaying such 3D information directly onto patients or real-world environments for procedural guidance and navigation has further pushed its expansion in clinical practice, leading to pilot implementations intra-procedurally across multiple specialties [4–7, 10–13].

Recent studies highlighted the clinical value of AR using HoloLens 1 (Microsoft, Redmond, WA), a first-generation commercially available optical see-through head-mounted display. Its use improved spatial understanding and anatomical definition, decreased procedural duration, and reduced
fluoroscopy times and radiation exposure [14–17]. Manual registration methods, such as hand gesture and gaming controller-mediated maneuvers, can be implemented for 3D spatial registration of holographic models onto physical objects [18]. The registration accuracy of spatial information onto the real-world environment is near or within one centimeter for surgical applications [19–24]. However, manual registration methods can be cumbersome and inefficient [18], viewing angle dependent [25], and inaccurate [26]. Automatic registration using computer vision recognition of a CT grid can outperform manual registration methods [18] but can be inflexible and may require manual finetuning [18, 21, 23]. Despite its conferred preclinical benefits, first-generation HoloLens systems have not been widely adopted in clinical practice. One major hindrance was the limited processing power of the headset device, which restricted the full potential of computer vision and other software on the system. Other limitations included small field of view, low display resolution, and unnatural manual manipulations of holographic objects. User experiences were jarring and suboptimal.

The second-generation HoloLens (Microsoft, Redmond, WA), compared to its predecessor, is a more ergonomic headset with larger field of view, higher processing power, and articulated gesture tracking with greater degrees of freedom (Table 1) [27–32]. The improved gesture tracking capabilities on HoloLens 2 allow for more intuitive and natural ways of interacting with 3D models not previously possible [33]. Specifically, HoloLens 2 tracking allows for simultaneous translation and rotation. This new capability eliminates the need to toggle between translational and rotational interactions, as often required on HoloLens 1 [18]. (Supplemental Video 1). However, direct comparisons of registration times between the first- and the second-generation HoloLens using similar registration methods were lacking.

This study aimed to evaluate manual and automatic registration times as well as registration accuracies during alignment of a holographic 3D model onto the real-world environment using HoloLens 2 at two tertiary academic hospital centers. Registration times between the two generations of HoloLens headsets were compared to showcase HoloLens 2’s increased suitability for potential clinical integration.

Methods

Registration methods

A similar workflow previously deployed on HoloLens 1 was implemented for HoloLens 2 [18]. A 3D holographic model of an abdominal CT phantom (CIRS 071B) with an overlying CT grid (Beekley Medical Grid 117) was segmented using ITK-SNAP and projected using HoloLens 2 [34]. Custom code was developed in Unity (Unity Technologies, San Francisco, CA) with Microsoft’s Mixed Reality Toolkit (MRTK) SDK and C#/.NET framework for model registration. Three different manual registration methods were devised using: 1) one-handed gestures, 2) two-handed gestures, and 3) Xbox wireless gaming controller (Microsoft, Redmond, WA) interfaced with HoloLens via Bluetooth (Supplemental Fig. 1). Automatic registration was performed with computer vision and automated image detection using Vuforia SDK and its proprietary feature detection algorithms (PTC Technology, Needham, MA) [14, 18]. Code was distributed and deployed across two tertiary academic hospital centers.

Table 1  HoloLens 1 and HoloLens 2 relevant technical specification comparisons [27–32]

| Specifications                  | HoloLens 1                              | HoloLens 2                              |
|--------------------------------|-----------------------------------------|-----------------------------------------|
| Processor                      | Intel 32-bit (1 GHz)                    | Qualcomm Snapdragon 850 (3 GHz)        |
| Field of view (Horizontal)     | 30°                                     | 43°                                     |
| Field of view (Vertical)       | 17.5°                                   | 29°                                     |
| Resolution (Pixels)            | 1440 x 1440                            | 2048 x 1080                            |
| Refresh rate                   | 90 Hz                                   | 120–240 Hz                              |
| Battery life                   | 2.5 Hours                               | 3 Hours                                 |
| Cost                           | $3,000                                  | $3,500                                  |
| Release year                   | 2016                                    | 2019                                    |
| Hand tracking                  | Thumb and index finger recognition.     | Two-handed fully articulated gesture    |
|                                | Limited preset gesture recognition.     | tracking allowing up to 25 points of   |
|                                | Two-handed manipulation later           | articulation per side including the    |
|                                | introduced in 2018                      | wrist and fingers                       |
| 3D Model manipulation          | Air tap and select                      | Direct manipulation, including        |
|                                |                                        | resizing, scaling, grabbing,          |
|                                |                                        | pinching, dragging and holding         |
| Tracking degrees of freedom    | 6                                       | 6                                       |
| Interaction range              | Far-field interactions only             | Near- and far-field interactions       |
| Eye tracking                   | No                                      | Yes                                     |

© Springer
Participants

This study was institutional review board exempt at the [Blank] and at the [Blank]. Trainees and faculties in various stages of clinical practice or training were recruited at two different academic centers on a volunteer basis. Eighteen participants enrolled, including three Interventional Radiology attendings, three Interventional Radiology trainees (residents and fellows), and three medical students rotating on the Interventional Radiology service at each center.

Registration protocol

Each participant was given a hands-on tutorial for HoloLens 2 basic controls and 3D object manipulation. The participant was allowed upwards of 10 min for practice. Before initiating a specific timed registration trial, the participant was told to manipulate the 3D model outside of the field of view superior and lateral to the intended real-world target. Laterality was based on participant’s handedness (to the right side for right-handedness). Registration times were measured until alignment of the 3D model to the CT grid was within 1 cm in each of the $x$-, $y$-, and $z$-planes. With the participant’s vocal confirmation of registration success, a single mixed reality image (with virtual CT grid superimposed on actual CT grid; 3904 x 2196 pixels, sRGB) was captured directly from HoloLens 2 after each registration attempt. This was done either with the HoloLens 2’s built-in voice command or with manual image capture from the live camera feed on the HoloLens 2 web portal interface. Each participant attempted each registration method three consecutive times.

Registration accuracy

Real-world dimensions of the CT grid (10.4 x 7.6 cm) were used for measurement calibration. Precision was determined based on three repeated measurements of the CT grid dimensions over all obtained mixed reality images. For each registration attempt, a visual inspection of all of the CT grid markers was first performed to determine the CT grid marker with the largest visual deviation from its corresponding phantom grid marker in the captured image’s 2D plane. Registration accuracy was then determined as the distance between this CT grid marker and its corresponding phantom counterpart, center to center (Fig. 1), averaged across three different measurements.

![Fig. 1](https://example.com/image.png) Example image capture displaying measurement of the registration error based on the imaged 2D plane
Lighting conditions

Given potential effects of lighting conditions on registration times and accuracies, the level of illumination was measured at each of the testing center environment using Lux Light Meter Pro (Version 2.1.1 [Mobile iOS app. Developer: Marina Polyanskaya) to ensure transparency and data reproducibility. Five different measurements were taken at each location. Levels of illumination were also measured in the Interventional Radiology procedural suite under regular and dimmed lighting conditions for comparison and to serve as relevant points of reference.

Statistical analysis

Data were presented as mean ± standard error of the mean (SEM). One-way ANOVAs with Tukey’s post-hoc multiple comparison tests, repeated measures ANOVAs, nonparametric Mann–Whitney tests, and parametric t tests were performed using Prism (GraphPad, San Diego, CA). Two-tailed p value smaller than 0.05 was deemed statistically significant.

Results

Center 1 demonstrated mean manual alignment times of 22.6 ± 3.5 s, 25.2 ± 3.5 s, and 77.2 ± 19.6 s for one-handed gesture, two-handed gesture, and Xbox controller registration methods, respectively, on HoloLens 2. Center 2 demonstrated similar manual alignment times of 32.7 ± 4.6 s, 23.4 ± 2.5 s, and 68.5 ± 7.2 s, respectively (all two-tailed p > 0.05 when compared to Center 1). Center 1 reported mean automatic registration time of 7.2 ± 0.6 s versus Center 2 with 3.4 ± 0.3 s, representing a 52.8% difference (p < 0.001). Center 1’s testing environment had an average level of illumination of 107.8 ± 12.7 Lux, which was similar to an Interventional Radiology procedural suite dimmed for ultrasound and/or fluoroscopy image viewing of 123.2 ± 7.4 Lux (p > 0.05). Center 2’s testing environment had a level of illumination of 249.6 ± 7.7 Lux, which was significantly different from Center 1’s level of illumination (p < 0.0001).

Center 2’s testing environment’s level of illumination was comparable to an Interventional Radiology procedural suite under regular lighting conditions of 245.4 ± 8.3 Lux (p > 0.05).

Manual and automatic registration times from the two centers were combined for HoloLens 2 (Fig. 2). One-way ANOVA demonstrated significant differences among the different registration methods (p < 0.0001) except for the difference between one-handed and two-handed gestures. Post-hoc multiple comparisons tests showed Xbox controller registration as the slowest (72.8 ± 10.2 s; p < 0.01, p < 0.001, and p < 0.0001 compared to one-handed gesture (27.7 ± 3.1 s), two-handed gesture (24.3 ± 2.1 s), and automatic registration (5.3 ± 0.6 s), respectively). Automatic registration was the fastest (p < 0.0001 compared to the other three manual registration methods).

Further analysis was performed based on level of clinical experience. There were no significant differences in registration times among attendings, residents and fellows, and medical students with any of the registration methods (p > 0.05, Supplemental Fig. 2). Significant improvements in registration times were detected across consecutive attempts using hand gestures (one-handed and two-handed combined, 31.7 ± 3.6 s, 25.4 ± 2.0 s, 20.8 ± 1.5 s over the three consecutive attempts, p < 0.01, Fig. 3a). However, this difference was not seen with Xbox controller (78.1 ± 11.1 s, 75.0 ± 12.1 s, and 65.4 ± 14.4 s over the three attempts, p > 0.05, Fig. 3b) or automatic registration methods (6.4 ± 0.9 s, 4.4 ± 0.4 s, and 5.1 ± 0.8 s over the three attempts, p > 0.05, Fig. 3c). Notably, during the third attempt, mean hand gesture registration time was 20.8 s with the fastest registration time of 7.4 s on HoloLens 2.

The HoloLens 2 dataset was combined from both centers and compared to HoloLens 1. In total, mean aggregate hand gesture registration was faster with HoloLens 2 (26.0 ± 1.8 s) compared to HoloLens 1 (141.9 ± 10.0 s, p < 0.0001), representing an 81.7% reduction (Fig. 4a. Supplemental Videos 2 and 3). There was no significant difference with manual registration using an Xbox controller (72.8 ± 10.2 s with HoloLens 2 versus 53.7 ± 6.5 s with HoloLens 1, p > 0.05, Fig. 4b) as these interactions remained the same on HoloLens 1 and HoloLens 2. Automatic registration was also similar across HoloLens 1 and HoloLens 2 (5.3 ± 0.6 s with...
HoloLens 2 versus $5.8 \pm 0.7$ s with HoloLens 1, $p > 0.05$, Fig. 4c). Example manual and automatic registration cases on HoloLens 2 are shown in Fig. 5 and Supplemental Videos 2–3, with comparisons to those on HoloLens 1. Note the slight offsets of the virtual 3D model with regards to its real-world counterpart on the HoloLens 1 images and on the automatic registration captured images were due to technical differences between the capture camera’s perspective and the users’ line of sight, making direct measurements and comparisons of registration accuracies unfeasible.

The average manual measurement precision over 80 different line segments, each with three individual measurements, was 4.3 pixels. This was calibrated and translated to an average measurement precision of 0.8 mm. Registration accuracy was not significantly different across manual registration methods, with one-handed gesture at $5.9 \pm 0.4$ mm, two-handed gesture at $9.5 \pm 2.3$ mm, and Xbox controller registration at $8.6 \pm 2.0$ mm ($p > 0.05$, Fig. 6a). Attendings, trainees, and medical students demonstrated similar registration accuracies ($6.9 \pm 0.6$ mm, $8.9 \pm 1.6$ mm, and $7.0 \pm 0.9$ mm, respectively, $p > 0.05$; Fig. 6b). A trend of improving registration accuracies across the three attempts was suggested but not statistically significant ($8.8 \pm 1.3$ mm, $8.0 \pm 1.0$ mm, and $5.3 \pm 0.4$ mm for first, second, and third attempts, respectively, $p = 0.05$; Fig. 6c).

**Discussion**

In this study, manual registration times for aligning a 3D holographic model onto a CT grid using HoloLens 2 were found to be consistent between academic centers and significantly improved compared to manual registration times using HoloLens 1.

Significant reductions in hand gesture-mediated registration times were demonstrated with HoloLens 2 compared to those of HoloLens 1. This was likely due to HoloLens 2’s improved capability of recognizing comprehensive hand and wrist movements compared to HoloLens 1. Natural hand manipulation gestures for object manipulation in the real world, such as pinching and grabbing, was transferrable to 3D model manipulation in the virtual environment. Moreover, freeform spatial manipulation allowed seamless integration of translational and rotational movements, eliminating
the need to toggle between modes of maneuver [18]. As a result, mean aggregate hand gesture manual registration time decreased by more than 80% and was significantly shorter than Xbox controller-mediated registration. Users also demonstrated significant improvements over the three consecutive attempts. For several participants, hand gesture-mediated registration times during the third attempt were less than 10 s and on par with the automatic registration

![Fig. 5 Example manual and automatic registration cases on HoloLens 2 versus HoloLens 1.](image)

(a) One-handed gesture manual registration to align the 3D object in the virtual environment to its counterpart in the real world on the HoloLens 2 system. (b) One-handed gesture manual registration on HoloLens 1. (c) Automatic registration on HoloLens 2 captured via a separate single monocular camera on the device. The centralized camera cannot be accessed while Vuforia-based automatic image detection is active. (d) Automatic registration on HoloLens 1 captured via a phone camera held up to the HoloLens 1 lens. The centralized camera cannot be accessed while Vuforia-based automatic image detection is in use. The slight offsets of the virtual 3D model with regards to its real-world counterpart on the HoloLens 1 images and on the automatic registration captured images were due to the differences between the capture camera’s perspective and the users’ line of sight, making direct measurements and comparisons of registration accuracies unfeasible

![Fig. 6 HoloLens 2 registration accuracy.](image)

(a) Registration accuracy by registration methods ($p > 0.05$). (b) Registration accuracy by training level ($p > 0.05$). (c) Registration accuracy by number of attempts ($p = 0.05$)
times. These results carry significant implications for clinical integration with HoloLens 2 as image-guided interventionalists could benefit from its more intuitive adaptation, ease of use and improvement over time, and ability for rapid manual adjustments in the midst of an intervention.

Manual registration accuracies were similar and averaged within 10 mm across the three manual registration methods and clinical experience using HoloLens 2. The accuracies on HoloLens 2 are congruent to previously substantiated subcentimeter accuracies reported with HoloLens 1 [19–24]. A trend of improving registration accuracies over consecutive attempts was suggested but not statistically significant. Of note, the accuracies reported were measured based on a 2D image and do not represent true 3D accuracies. Currently, a standard for measuring 3D accuracy for AR headset devices does not exist. Further work will involve the use of a surgical-grade optical tracking system (Polaris Vega, NDI, Waterloo, Canada) to assess true 3D accuracies. In addition, automatic registration accuracies were unable to be captured using HoloLens’s built-in camera as the camera was actively being used for automated image detection and unavailable for image capture. Nevertheless, studies that have attempted to measure HoloLens accuracies in meaningful ways have shown accuracies and tracking improved with computer vision augmentation [19, 25, 26, 35].

Registration data obtained at each academic center were analyzed individually. Registration times were similar for different methods of manual registration but not for automatic registration. Center 1’s automatic registration times were more than twice of those obtained from Center 2. Examination of experiment protocols revealed that all testing at Center 1 were completed in dimly lit rooms, similar in lighting conditions compared to an Interventional Radiology procedural suite when fluoroscopy or ultrasound is in use. All testing at Center 2 were completed in brightly lit rooms, similar to that of a procedural suite when fluoroscopy or ultrasound is not activated. Previous work had demonstrated the effects of brightness on depth perception and accurate depth presentation [36]. Dim environments during automatic registration may have resulted in multiple re-aligning attempts by the participants. In addition, better contrast between the registration target and the background in brightly lit environments likely contributed to faster computer vision recognition. Furthermore, a HoloLens-based vascular localization system demonstrated larger precision errors when used without a surgical lamp compared with usage in the same operating room background brightness with the addition of a surgical lamp [37]. These effects should be considered for future AR implementation in different clinical settings. For example, in CT-guided and fluoroscopy-guided procedural suites, the operators could expect longer automatic registration times and potentially decreased registration accuracies given the low light environments.

Operating rooms or outpatient office settings, the automatic registration times may be shorter and registration accuracies better.

There are limitations associated with this study. First, evaluation of HoloLens 2, similar to its previous generation, was performed on stationary objects with a fixated CT grid as the registration target. Registration time and accuracy on actual human patients, accounting for patient movement, respiratory motion, soft tissue deformation, and potential interference from procedural manipulation, were not assessed. Further testing on more realistic procedural settings, with developing technologies in motion compensation and deformable modeling, are needed. Second, the accuracy assessment was performed on a 2D plane rather than in the 3D space. Depth deviation could not be reliably assessed. Future testing with separate images taken from each monocular view may be obtained to calculate true registration alignment errors. Third, a direct comparison of registration accuracies between the two versions of HoloLens was not feasible. HoloLens 1 captures images from a single monocular perspective, despite its stereotactic experience; the captured image does not accurately reflect what the user sees or experiences. HoloLens 2, in contrast, captures images from a centralized camera which aligns better with the user’s line of sight. Given this difference in camera image capture, a direct comparison was not made. Finally, AR technologies have non-trivial associated economic costs. However, with average reduction in procedural duration ranging from 5 to 11.7 min based on prior reports [15, 17, 38] and an average procedural room cost per minute at $62 [39], utilization of a 3D AR visualization system could provide a cost reduction equivalent to $85,250 to $398,970 per room per year based on an estimated schedule of 1–2 CT-related procedures per room per day, offsetting the initial investment costs of a HoloLens or other AR system. More detailed cost analyses incorporating other factors are needed to fully explore the economic impact of AR integration into clinical care.

**Conclusion**

Multicenter assessment of HoloLens 2 for registering a 3D holographic model onto a CT grid showed that automatic registration through computer vision remains the optimal method, with performance dependence on background brightness. Manual registration times decreased significantly with updated hand gesture manipulation on HoloLens 2 versus HoloLens 1, with improvements over consecutive attempts approaching the registration times of automatic registration. Manual registration also significantly outperformed external controller-mediated registration. Accurate and fast
registration will be crucial for the implementation of AR for 3D navigation during CT-guided interventions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11547-022-01515-3.

Authors contributions All authors contributed to study design. B.J.P. developed the AR system. N.L. and J.W. completed data collection. N.L. and J.W. performed statistical analyses. N.L., J.W., and B.J.P. wrote the main manuscript. N.L., prepared the figures. N.L. and B.J.P. prepared the supplemental videos. All authors reviewed the manuscript.

Funding B.J.P. reports grants from NIH, SIR, RSNA, and NVIDIA, during the conduct of the study.

Availability of data and material Data are presented in a comprehensive fashion throughout the manuscript. The data generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request. Devices and material utilized within this study were obtained through open market with the assistance of above disclosed funding resources.

Code availability Code utilized in this study is available from the corresponding author upon reasonable request and will be reviewed on a case-by-case basis.

Declarations

Conflicts of interest B.J.P. discloses his position as a clinical advisor for Medivis, outside the submitted work. S.J.H. discloses his position as a consultant and speaker for Boston Scientific, outside the submitted work. B.J.P. discloses his position as a clinical advisor for Medivis, outside the submitted work. S.J.H. discloses his position as a clinical advisor for Medivis, outside the submitted work.

Ethical Approval This study involves human participants and is institutional review board exempt. This article does not contain any animal studies performed by any of the authors.

References

1. Uppot RN, Laguna B, McCarthy CJ et al (2019) Implementing virtual and augmented reality tools for radiology education and training, communication, and Clinical care. Radiology 291:570–580. https://doi.org/10.1148/radiol.2019182210
2. Weeks JK, Pakpoor J, Park BJ et al (2020) Harnessing augmented reality and CT to teach first-year medical students head and neck anatomy. Acad Radiol. https://doi.org/10.1016/j.acra.2020.07.008
3. Elsayed M, Kadom N, Ghabadi C et al (2020) Virtual and augmented reality: potential applications in radiology. Acta radiol 61:1258–1265. https://doi.org/10.1177/0284185119897362
4. Inccekar F, Smits M, Dirven C, Vincent A (2018) Clinical feasibility of a wearable mixed-reality device in neurosurgery. World Neurosurg 118:e422–e427. https://doi.org/10.1016/j.wneu.2018.06.208
5. Linxweiler M, Pillong L, Kopanja D et al (2020) Augmented reality-enhanced navigation in endoscopic sinus surgery: a prospective, randomized, controlled clinical trial. Laryngoscope Investig Otolaryngol 5:621–629. https://doi.org/10.1002/ino.2.436
6. Perkins SL, Lin MA, Srinivasan S, et al (2017) A Mixed-reality system for breast surgical planning. In: Adjunct proceedings of the 2017 IEEE international symposium on mixed and augmented reality, ISMAR-Adjunct 2017, IEEE, pp 269–274
7. Perkins SL, Krajancich B, Yang CFJ et al (2020) Patient-specific mixed-reality visualization tool for thoracic surgical planning. Ann Thorac Surg 110:290–295. https://doi.org/10.1016/j.athoracsur.2020.01.060
8. Yoshiida S, Sugimoto M, Fukuda S et al (2019) Mixed reality computed tomography-based surgical planning for partial nephrectomy using a head-mounted holographic computer. Int J Urol 26:681–682. https://doi.org/10.1111/iju.13954
9. Kiarostami P, Dennler C, Roner S et al (2020) Augmented reality-guided percutaneous bone biopsy—proof of concept. J Orthop Surg Res 15:540. https://doi.org/10.1186/s13018-020-02066-x
10. Rahman R, Wood ME, Qian L et al (2020) Head-mounted display use in surgery: a systematic review. Surg Innov 27:88–100. https://doi.org/10.1177/1553530619871787
11. Pratt P, Ives M, Lawton G et al (2018) Through the HoloLenses™ looking glass: augmented reality for extremity reconstruction surgery using 3D vascular models with perforating vessels. Eur Radiol Exp 2:2. https://doi.org/10.1186/s41747-017-0033-2
12. Tagaytayan R, Kelemen A, Sik-Lanyi C (2018) Augmented reality in neurosurgery. Arch Med Sci 14:572–578. https://doi.org/10.5114/aoms.2016.58690
13. Auloge P, Cazzato RL, Ramamurthy N et al (2020) Augmented reality and artificial intelligence-based navigation during percutaneous vertebroplasty: a pilot randomised clinical trial. Eur Spine J 29:1580–1589. https://doi.org/10.1007/s00586-019-06054-6
14. Park BJ, Hunt SJ, Nadolski GJ, Gade TP (2020) Augmented reality improves procedural efficiency and reduces radiation dose for CT-guided lesion targeting: a phantom study using HoloLens 2. Sci Rep 10:18620. https://doi.org/10.1038/s41598-020-75676-4
15. Si W, Liao X, Qian Y, Wang Q (2018) Mixed reality guided radiofrequency needle placement: a pilot study. IEEE Access 6:31493–31502. https://doi.org/10.1109/ACCESS.2018.2843378
16. Al-Nimer S, Hanlon A, Cho K et al (2020) 3D Holographic guidance and navigation for percutaneous ablation of solid tumor. J Vasc Interv Radiol 31:526–528. https://doi.org/10.1016/j.jvir.2019.09.027
17. Park BJ, Perkins NR, Prolka E et al (2020) Three-dimensional augmented reality visualization informs locoregional therapy in a translational Model of hepatocellular carcinoma. J Vasc Interv Radiol 31:1612–1618.e1. https://doi.org/10.1016/j.jvir.2020.01.028
18. Park BJ, Hunt S, Nadolski GJ, Gade TP (2019) Registration methods to enable augmented reality-assisted 3D image-guided interventions. In: Matej S, Metzler SD (eds) 15th International meeting on fully three-dimensional image reconstruction in radiology and nuclear medicine. SPIE, Washington USA, p 11
19. Frantz T, Jansen B, Duerinck J, Vandemeulebroucke J (2018) Augmenting Microsoft’s HoloLens with Vuforia tracking for neuronavigation. Healthc Technol Lett 5:221–225. https://doi.org/10.1049/htl.2018.5079
20. Rae E, Lasso A, Holden MS et al (2018) Neurosurgical burr hole placement using the microsoft HoloLens. In: Webster RJ, Fei B (eds) Medical imaging 2018: image-guided procedures, robotic interventions, and modeling. SPIE, Washington USA, p 20
21. Gibby JT, Swenson SA, Cvetko S et al (2019) Head-mounted display augmented reality to guide pedicle screw placement utilizing computed tomography. Int J Comput Assist Radiol Surg 14:525–535. https://doi.org/10.1007/s11548-018-1814-7
22. Liu Y, Hong H, Zhang L, El Saddik A (2018) Technical evaluation of HoloLens for multimedia: a first look, IEEE Multimed 25:8–18. https://doi.org/10.1109/MMUL.2018.2875473
23. Meulstee JW, Nijsink J, Schreurs R et al (2019) Toward holographic-guided surgery. Surg Innov 26:86–94. https://doi.org/10.1177/1553530618799552
24. Perkins SL, Lin MA, Srinivasan S, et al (2017) A Mixed-reality system for breast surgical planning. In: Adjunct proceedings of
the 2017 IEEE international symposium on mixed and augmented reality, ISMAR-Adjunct 2017, Institute of Electrical and Electronics Engineers Inc, pp 269–274

25. Van Doormaal TPC, Van Doormaal JAM, Mensink T (2019) Clinical accuracy of holographic navigation using point-based registration on augmented-reality glasses. Oper Neurosurg 17:588–593. https://doi.org/10.1093/ons/opz094

26. Condino S, Carbone M, Piazza R et al (2019) Perceptual limits of optical see-through visors for augmented reality guidance of manual tasks. IEEE Trans Biomed Eng. https://doi.org/10.1109/TBME.2019.2914517

27. Microsoft Corp (2019) Instinctual interactions-mixed reality. In: Microsoft docs. https://docs.microsoft.com/en-us/windows/mixed-reality/design/interaction-fundamentals. Accessed from 9 Nov 2020

28. Microsoft Corp (2018) Manipulation handler. In: Mix. real. Toolkit doc. https://github.com/MixedRealityToolkit-Unity/Documentation/README_ManipulationHandler.html. Accessed from 9 Nov 2020

29. Microsoft Corp (2019) Gaze and commit-Mixed Reality. In: Microsoft Docs. https://docs.microsoft.com/en-us/windows/mixed-reality/design/gaze-and-commit. Accessed from 9 Nov 2020

30. Pagani M (2018) Two-hand manipulation with the new mixed reality toolkit - microsoft tech community. In: Microsoft tech community. https://techcommunity.microsoft.com/t5/windows-dev-appconsol/two-hand-manipulation-with-the-new-mixed-reality-toolkit/ba-p/317174. Accessed from 9 Nov 2020

31. Kosciesza J (2020) HoloLens 2 vs HoloLens 1: what’s new? 4Experience’s AR/VR Blog. In: 4experience.co. https://4experience.co/hololens-2-vs-hololens-1-whats-new/. Accessed from 9 Nov 2020

32. Microsoft Corp (2019) HoloLens 2—Overview, features, and specs. In: Microsoft HoloLens. https://www.microsoft.com/en-us/hololens/hardware. Accessed from 9 Nov 2020

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.