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Holo-Stroke: Assessing for Immersive Stroke Care Through Stroke Hologram Teleportation

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Abstract

Background: *Augmented reality enables the wearer to see both their physical environment and virtual objects. Holograms could allow 3D video of providers to be transmitted to distant sites, allowing patients to interact with virtual providers as if they are in the same physical space. Our aim was to determine if Tele-Stroke augmented with Holo-Stroke, compared with Tele-Stroke alone, could improve satisfaction and perception of immersion for the patient.*

Methods: *Kinect cameras positioned at 90-degree intervals around the hub practitioner were used. Cameras streamed real-time optical video to a unity point-cloud program where the data were stitched together in a 360-degree view. The resultant hologram was positioned in 3D space and was visible through the head-mounted display by the patient. Radiology images were shared in Tele-Stroke and via hologram. Likert satisfaction questions were administered. Wilcoxon signed-rank testing was used.*

Results: *Each of the 30 neurology clinic participants scored both Tele-Stroke and Holo-Stroke. Out of these, 29 patients completed the assessments (1 failure owing to computer reboot). Average age was 52 years, with 53.3% of the patients being female, 70.0% being White, and 13.3% being Hispanic. Likert scale score median "Overall" was 32 Tele-Stroke versus 48 Holo-Stroke ($p < 0.00001$), "Immersion" was 5 versus 10 ($p < 0.00001$), "Beneficial Technique" was 6 versus 10 ($p < 0.00001$), and "Ability to See Images" was 5 versus 10 ($p < 0.00001$).*

Discussion: *Holo-Stroke 3D holographic Tele-Stroke exams resulted in feasibility, satisfaction, and high perception of immersion for the patient. Patients were enthusiastic for the more immersive, personal discussion with their provider and a robust way to experience radiology images. Though further assessments are needed, Holo-Stroke can help the provider "be there, not just see there!"*

Keywords: *Tele-Stroke, hologram, augmented reality, satisfaction, immersion, telemedicine*

Introduction

Tele-Stroke is reliable and results in excellent decision-making efficacy.[1,2] Though enhancements such as wireless internet, improved bandwidth, and increased resolution have made Tele-Stroke more usable, the technology still amounts to visualizing the patient "through a camera and monitor." Pan/tilt/zoom capabilities help providers, but patients still strain to see the provider on a small monitor near the foot of the bed, or see small, shared images of their CT scans. Though a main goal of Tele-Stroke is to provide immersive care, technology has not yet allowed optimal immersive interactions between patients, family, and remote practitioners.

Although virtual reality (VR) allows for an immersive experience, it detaches the wearer from the physical space. An augmented reality (AR) device is worn on a head-mounted display (HMD) enabling the wearer not only to be tethered to their usual environment (through the transparent lens) but also to see virtual objects placed into their field of vision.[3] Different types of 3D holograms can be projected on that display allowing the wearer to interact with these objects to some degree as if they were actually in the room. Microsoft HoloLens 2 has been increasingly used for surgical assistance, radiographical guidance, and education.[4–12]

Holoportation may seemingly "teleport" the provider, allowing high-quality 3D provider models to be transmitted to a distant site in real time as a hologram and enabling interaction as if the provider was present in the same physical space as the patient.[13] This technology has significant potential value, with some limited validation experiences in the literature.[14] Potential benefits include providing an immersive experience for the patient, allowing them to more fully interact with their provider and medical images. On the patient's side, surrogates or families can see what the patient can see by either wearing the visor or by viewing monitors/tablets showing 2D versions of what the patient sees. Patients can also see radiology images and virtual illustrations pinned to their environment, enriching the 3D holographic experience even further.

Numerous technologies exist that produce hologram-like images for patients.[9,15] Our engineering team has extensive experience with AR/VR applications, including the use of AR in the medical arena[16] such as creating an immersive AR/VR telementoring infrastructure that allows surgeons to remotely aid less experienced medical professionals in the field.[17] With Holo-Stroke, we hypothesized that an AR-viewable real-time hologram of the hub provider projected to the clinic site would allow the patient to have a higher feeling of satisfaction. Our Holo-Stroke technique has the potential to enable patients and providers to feel far more immersed in Tele-Stroke conversations/evaluations. The overall aim was to determine if Tele-Stroke augmented with AR technology, versus standard Tele-Stroke, would lead to improved patient satisfaction and perception of immersion to improve telepresence.[18] This enhanced technology would eventually be included in standard Tele-Stroke and telemedicine (first nonacute, then perhaps someday more acute) care to enable more immersive patient experiences with telehealth.

Methods

In this IRB-approved study, we assessed multiple measures of satisfaction and immersion, comparing standard telemedicine (Tele-Stroke) with Stroke-Holoportation (Holo-Stroke). Clinicians and engineers partnered to develop an AR-viewable real-time representation of the provider (at the hub) and projected it to the participant location (spoke). For the Tele-Stroke setup, HIPAA-compliant Zoom was used from the provider computer, connecting to the patient side via videoconference. The connection was viewed on a setup using an iPad and telecart. For sharing of MRI scans, illustrations, and video clips, Zoom desktop sharing tools were used. For the Holo-Stroke setup, the hologram was developed using 4× Microsoft Azure-Kinect optical and depth cameras positioned at 90-degree intervals around the practitioner (*Figs. 1* and *5*). Each camera streamed real-time optical video data with depth detection information to a unity hub (2019.4.22f1) point-cloud program on the provider computer where the data was stitched together to form a 360-degree real-time image. Images were optimized using a QR code labeled head crown the provider would wear during 1× calibration to match a 360-degree rendering of the provider. The resultant hologram was positioned in 3D space based on relative coordinates visible through the HoloLens 2 HMD (*Fig. 5*). Positional adjustments (yaw, roll, pitch) and overall location/position were also manually adjustable for ideal placement. Single-time calibration and positional changes were saved for future sessions. Information was transmitted via Ethernet connection to a receiving computer located at the simulated spoke site (a nearby conference room to simplify the enrollment, assessment, and survey process). The receiving computer, also running a similar unity program allowed for wireless transmission of the data to the wireless HMD at the patient location. Video and audio were both >128 bit encrypted. The intrinsic HoloLens 2 speakers were incorporated, but an external microphone audio source based on TeamSpeak3 audio technology was utilized on the patient side and allowed sending/receiving of clear audio. For image sharing (MRI scan and illustrations), objects were included within the unity point-cloud and positioned 90 degrees to the right side of the provider hologram. Desktop sharing, via OpenScreen, allowed placement of a 3-foot virtual desktop screen to the left of the provider hologram (allowing the provider to share any object from the desktop directly into the patient's AR field of vision).

Each patient signed informed consent for this IRB-approved assessment, and then the clinical assessment process (for both Tele-Stroke and Holo-Stroke) began with the patient being seated in a conference room. As it was predominantly focused on a patient–provider discussion and examination, we felt that the patient sitting across a conference room table from the virtual provider would yield an ideal experience. The provider joined the Tele-Stroke call with the patient by connecting to the iPad in the patient room. The patient was asked basic

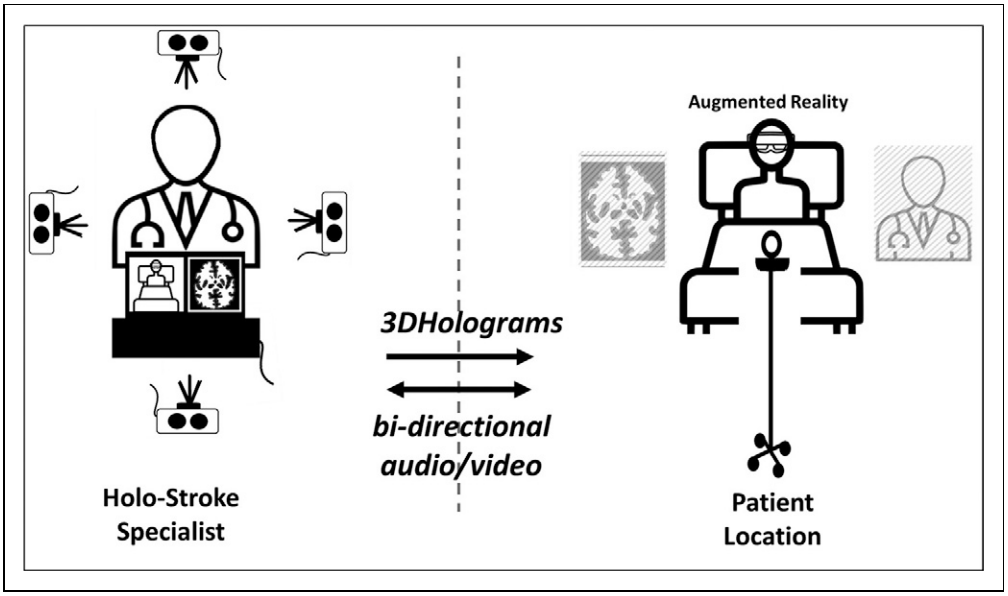

Fig. 1. Holo-Stroke diagram. The figure shows a diagram of the basic Holo-Stroke projection layout. A Holo-Stroke provider views the patient through standard telemedicine setup (HIPAA compliant and encrypted). An array of Microsoft Azure Kinect camera (n = 3–4) connects to a unity player for stitching together a final 3D image and transmitting it to the remote patient site. Provider is seen as a 3D hologram at patient's bedside. Patient wears HoloLens 2 visor to take advantage of AR. HoloLens technique allows the patient to interface with the 3D, full-size, Tele-Stroke provider via Holo-Stroke hologram projection into 3D coordinate pinned space to the bedside/spoke clinical location. For this phase, patient video was projected via standard Tele-Stroke real-time connection so the provider could easily oversee what was happening at the spoke site. Similar technique was used to send the radiology image to the remote patient site as well. Image was pinned in 3D space, allowing the patient to see it next to the bedside at approximately 2–3-foot virtual size. Dashed boxes represent hologram images. AR, augmented reality.

questions and asked to follow straightforward neurological exam commands. Elements included having patient answer questions, state their age, and what month it was, as well as follow commands such as "close your eyes," "smile," "tell me how many fingers I am holding up," and "hold your arms out in front of you like I am doing." Patients followed these commands as examples of real-life questions and commands to assess for neurological deficits over telemedicine.[1] This perception and satisfaction evaluation was not designed to replicate the neurological exam or assess NIHSS reliability. Sample MRI scan, anatomy illustration, and an animation clip showing how a clot migrates in stroke were then shown. Thereafter, the patient was instructed to wear the HoloLens 2 and look across the conference room table at the opposing chair where a full-sized, real-time, 3D hologram video stream of the provider was placed. The HoloLens technique allowed the patient to answer the same questions and follow the same commands when interfacing with the 3D Holo-Stroke provider. A similar technique was used to send the images (sample MRI, illustrations, and video clips) to the remote patient site as well. The image was pinned in 3D space, allowing the patient to see it next to the bedside at 3-foot size.

Although no patient data was disclosed over video and no PHI was collected on case report forms, data files were password protected, encrypted, and stored on a double password protected server. Data such as age, race, sex, ethnicity, Likert scale scores, and any comments/observations were recorded. We prospectively assessed nonconsecutive volunteers (based solely on provider and patient availability), drawn from a neurology clinic, who had a nonacute/nonemergent neurological concern. Patients were excluded if they had an acute condition, could not speak English, or could not consent for themselves. After the Tele-Stroke assessment, a five-question Likert scale (score range 0 for bad and 10 for excellent for each question, total possible score of 50) assessed topics of "Immersion," "Comfort," "Caring," "Benefit," and "Viewing of Images." Participants then participated in the Holo-Stroke portion of the assessment and answered the same five-question Likert scale questions. Patients were prospectively assessed from June 2023 to September 2023. Wilcoxon signed-rank testing was used for nonparametric, matched-pair comparisons.

Results

In total, 30 participants were included, with each participant scoring both the standard telemedicine solution (Tele-Stroke) and the Stroke Hologram solution (Holo-Stroke). Out of these, 29 patients were included in final analysis with 1 tech failure owing to prolonged need for reboot. Average age was 52 years, with 53.3% of the patients being female, 70.0% being White,

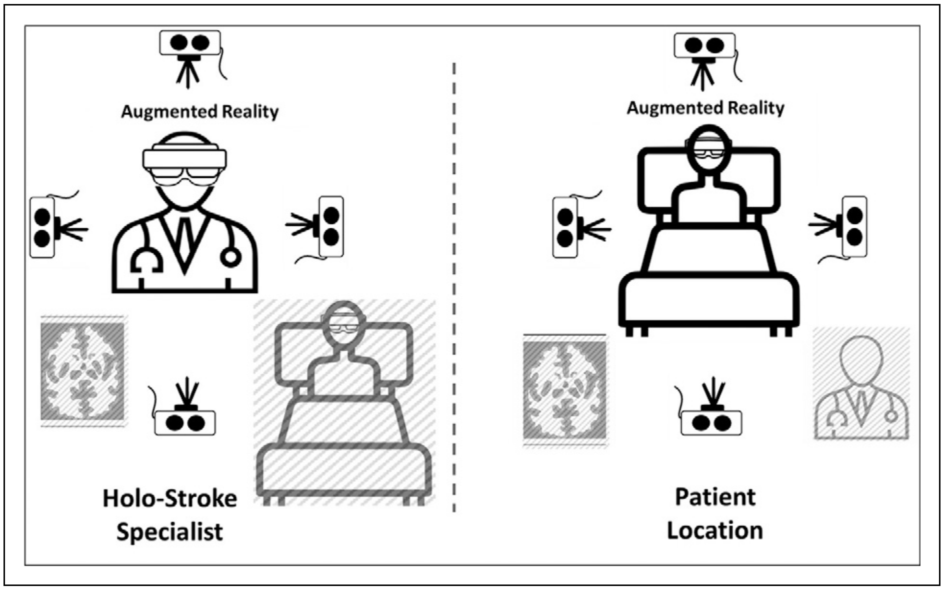

Fig. 2. Holo-Stroke Diagram (2-way). The figure shows a diagram of subsequent phases of Holo-Stroke. As shown in this future state, the same type of setup is used to project the Holo-Stroke specialist to the patient's bedside via HoloLens2 and 3D hologram technology. This same setup, but with deployment of camera array to the spoke site/patient location, could allow transmission of patient and radiographic images to the hub provider side for 3D interaction as if the patient were located at the Holo-Stroke Specialist site. This would require a larger room for the provider to see the full patient (or scaling down patient and radiology images). In this design, both provider and patient take advantage of augmented reality. Standard Tele-Stroke setup would not be necessary. Dashed boxes represent hologram images.

and 13.3% being Hispanic. Likert scale scores for all five questions combined (each participant potential score of 50 points), noting median for all 29 patients, for Tele-Stroke versus Holo-Stroke was 32 (IQR = 17) versus 48 (IQR = 7) ($p < 0.00001$). For the question related to "Immersion," scores were 5 (4) versus 10 (1.5) ($p < 0.00001$). For the question related to "Comfort," scores were 6 (3) versus 10 (1) ($p < 0.00001$). For the question related to "Caring Provider," scores were 8 (4) versus 10 (2) ($p = 0.00194$). For the question related to "Beneficial Technique," scores were 6 (3) versus 10 (1) ($p < 0.00001$). For the question related to "Ability to See Images," scores were 5 (3) versus 10 (1) ($p < 0.00001$). As an overall percentage, all cases of Tele-Stroke scored a 57.07% (827.7/1450) (out of a possible 100% perfect score), whereas Holo-Stroke scored a 92.93% (1347.5/1450). For the question related to "Immersion," Tele-Stroke scored a 45.86%, whereas Holo-Stroke scored a 91.90%. For the question related to "Comfort," Tele-Stroke scored a 60.69%, whereas Holo-Stroke scored a 92.24%. For the question related to "Caring Provider," Tele-Stroke scored a 68.79%, whereas Holo-Stroke scored a 90.52%. For the question related to "Beneficial Technique," Tele-Stroke scored a 64.66%, whereas Holo-Stroke scored a 93.62%. For the question related to "Ability to See Images," Tele-Stroke scored a 45.34%, whereas Holo-Stroke scored a 96.38%. There were two patients who reported mild transient dizziness that did not interfere with their Holo-Stroke participation. Comments regarding the newer technology were overwhelmingly positive (*Table 1*).

Discussion

Even though experts can reliably assess patients using teleneurology and Tele-Stroke, patient engagement with the provider is similar to a "video conference." Although improved resolution, echo cancellation, and pan/tilt/zoom features have improved provider experience, limited patient-side changes may still leave the patient feeling that Tele-Stroke yields a less-than-personal experience. Holo-Stroke set out to assess satisfaction and immersion by transporting the provider to the patient's bedside via hologram.

Our team's experience building functional VR surgical telementoring relationships have helped improve care platforms.[17,19] The 3D hologram technology used in this experience incorporates 4× depth sensing cameras, with data stitched together to have a true representation of the source image instead of computer animation or a scanned replica image with depth morphology. The determination that realism does not necessarily equate with immersion helped guide our current hologram development.[20,21] Patients may prefer glitches or imperfections in a hologram showing a "real" person over a computer-generated imagery avatar even if hyper-realistic. Holograms from sci-fi movies may have conditioned viewers to expect unusual lines, or colors, or even missing elements and still feel it is "the real thing."

Table 1. Patient Comments

VR/AR is the future.
The illustrations and whole experience is far superior.
Turning head to side was uncomfortable. Preferred if images were in front or at most 30 degrees to the side/angle.
(Computer Restarted. Wouldn't connect.)
Mild dizziness.
This is amazing.
Future state: Doc can point finger on actual image rather than mouse. Really liked this and thought it was cool.
Awesome experience!
I like videoconferencing. This is the future. Go forth.
Would be good if we in the future added large text for ASL for deaf patients.
A little dizzy, but it wore off.
Awesome. Totally surprised with how well I felt we could communicate. Images were amazing.
I can actually see your hands on this. I couldn't see them on the regular telemedicine monitor. The X-rays were amazing. I really feel like we can communicate better with this. My mom would LOVE this because she hates the regular video visits.
Mild distraction only with glitchy shaking image/small missing sections. Couldn't see hands or fingers on regular videoconferencing.
Very Cool!
You can see easy. With this you can see everything.
Perfect. Everything was good.
Have to get used to it a little.
VR is the future.
Couldn't see the hands or count fingers because they are out of the regular video box. Didn't happen with Holo-Stroke.
The large 3D brain MRI image and illustrations was far better experience than just screen-sharing.
Thank you so much for letting me see this phenomenal technology that will help people. It put me in a heck of a good mood! Much more personal. Just like being in a movie.

The table shows actual patient comments/observations from the survey study. Patients generally noted robust immersion with Holo-Stroke technique. Many participants noted the inability to count provider fingers or see outstretched arms on the Tele-Stroke monitor, but could easily see this via Holo-Stroke. Similarly, many patients were overwhelmingly pleased with their ability to interact with the example radiology images, illustrations, and video-clips, which were more immersive with Holo-Stroke.

AR, augmented reality; VR, virtual reality.

Our main aims were to assess immersion and satisfaction. HoloLens 2 allowed the wearer to interface with the real environment and see what was actually there (e.g., nurses, IV poles, family). The 3D hologram of the remote provider was added into that environment virtually (Holo-Stroke) allowing the wearer to interact freely, and even, walk around to see the hologram provider from all angles. The added feature of showing hologram images allowed the provider to show large virtual representations of radiology images to the patient directly in their field of view. Vendors are now capitalizing on the ability to pin apps based on coordinates allowing improved interaction with other types of data and expand use cases for VR and AR.[10–12]

A recent evaluation showed that 3D telemedicine was rated higher on satisfaction, presence, and quality showing that patients preferred 3D to 2D telemedicine.[14] Our neurology population yielded similar findings. Our question assessing "Immersion" was scored high for Holo-Stroke (showing the largest comparative difference vs. Tele-Stroke). Patients felt that their provider was more closely "right there" with them. We hypothesize that the full-size holographic version of the provider was better received than the patient having to "squint" to see a provider on a monitor. In Tele-Stroke, patients were not able to see how many fingers the provider was holding up and could not see the provider's outstretched arms because extremities were not visualized on the limited

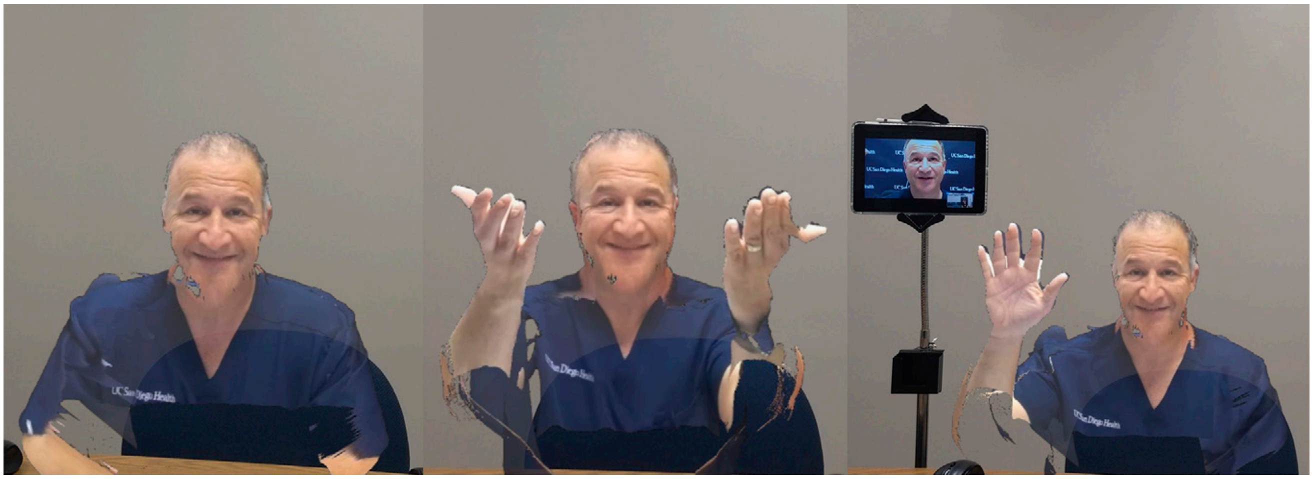

Fig. 3. Hologram image of Holo-Stroke provider. The figure shows multiple panel images of the Holo-Stroke hub provider. First panel shows provider virtually seated at the conference table across from the patient. Provider seems to be "seated in the chair" though actually present from a distance. Second panel shows provider modeling movements for the patient to perform. The 3D hologram is real time and shows full body image, including arms. Third panel shows Holo-Stroke provider virtually seated next to the Tele-Stroke setup. Patient first interacts with the 2D Tele-Stroke videoconferencing device. Thereafter, the patient is then shown the live 3D Holo-Stroke hologram provider. Note that provider's arm is not able to be seen on Tele-Stroke monitor but is easily seen via hologram technique, given multiple camera views.

screen size (*Table 1*, *Fig. 3*). With the Holo-Stroke technique, patients were easily able to perform finger counting or see outstretched arms because of the view of the provider from all four directions. In retrospect, it makes sense that removing the physical boundary of a small computer monitor would improve the perception of the provider being in the room.

Similarly unexpected was the immersion contribution that pinning of radiology images made to overall satisfaction. Experientially, we know that patients cannot see CT scans or MRIs well when screen-shared via Tele-Stroke. By pinning images in 3D space at the bedside (via Holo-Stroke), patients were frequently shocked at how well they could see the images, interface with them, and even read small text on illustrations (*Fig. 4*). The lowest survey score was for patients' ability to "view radiology images" on Tele-Stroke, scoring 45% (whereas this question scored highest for Holo-Stroke at 96%). We conclude that the feeling of immersion is contributed to by the patient seeing both the large 3D hologram of the provider and the radiology images that they otherwise could not see well.

Patients did feel that standard Tele-Stroke was of good quality. Tele-Stroke scored well on the "caring nature of doctor" question (8 [IQR = 4]). With thousands of Tele-Stroke cases performed each year in the United States, there is no question that Tele-Stroke has good quality.[22] For Holo-Stroke, each of the five individual questions and combined totals scored higher than in Tele-Stroke (48 [IQR = 7] vs. 32 [IQR = 17]). The quality-focused question of "How beneficial is the technology?" scored extremely well for Holo-Stroke at 94%. The beneficial effect of seeing radiology images was undoubtedly a sign of a quality experience for the patient. Interestingly, one patient was deaf

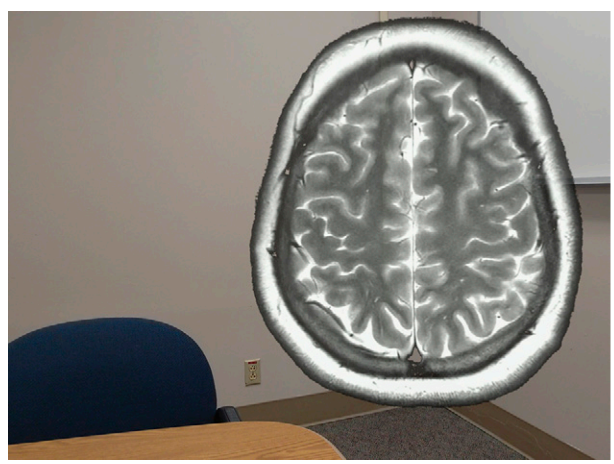

Fig. 4. Hologram of radiology image. The figure shows an image of the Holo-Stroke radiology image. This image is virtually sent to the patient-side (spoke) destination. The large footprint, and ability to virtually designate exact relative coordinates, location, and size of the image, enabled participants to interact with the MRI scan as if it were large-scale and present in the room with them. Other technologies, not shown, were included allowing patients to see illustrations, video-clips, and desktop screen sharing in real time within the virtual environment.

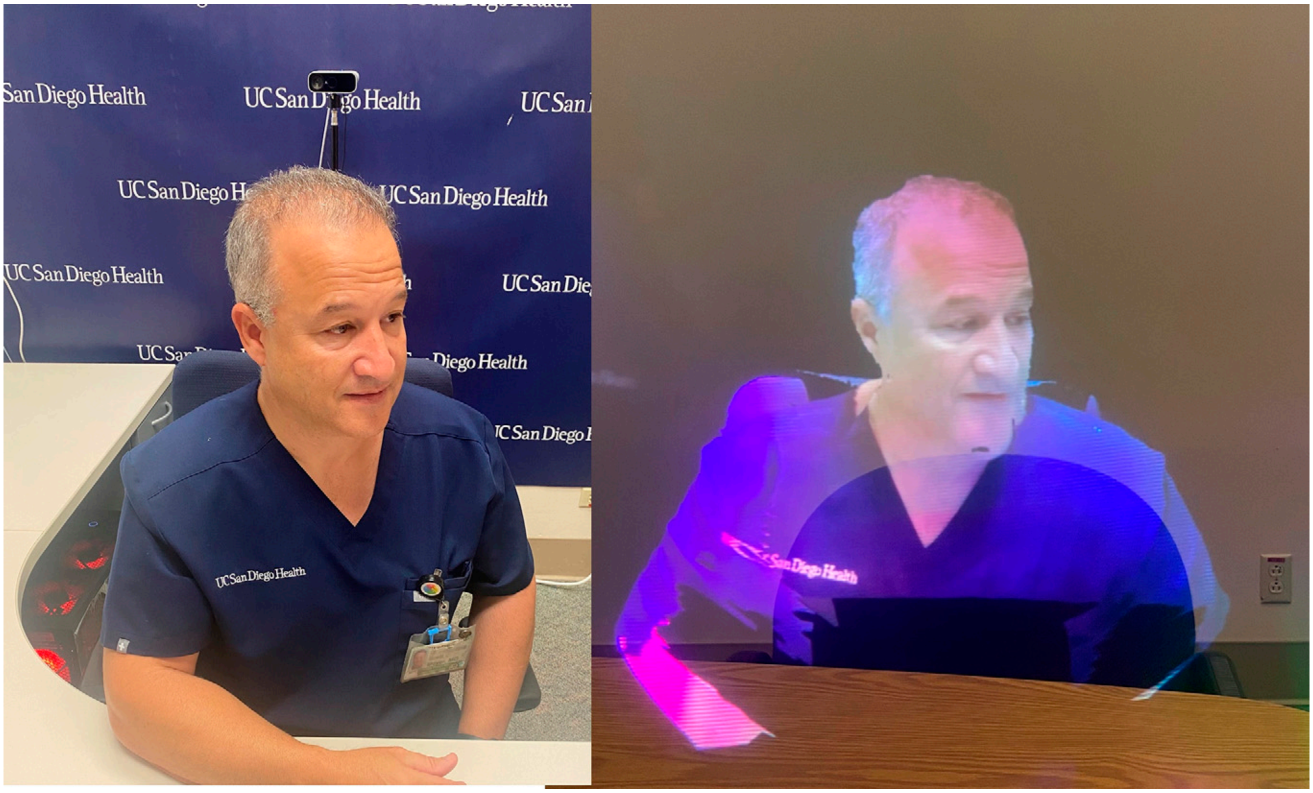

Fig. 5. HoloLens2 View. The figure shows the actual image versus the Holo-Stroke image. Left panel shows the Holo-Stroke provider, in the Hub location. This room, with Kinect cameras positioned at 90 degree increments around the provider (only one camera shown in image) served as the sending location. Right panel shows the actual image, as photographed through the actual HoloLens 2 Head Mounted Display (HMD) visor, at the patient (spoke) location. This device currently allows for large field of view. Patient views their own environment, allowing tethering to the real-world environment. The virtual hologram images are placed at relative coordinates in the HMD's field of vision. Patients can then interact with the 3D Holo-Stroke hologram provider in real-time as if they were actually present in the room. Image was photographed through the lens of the Holo-Lens 2 HMD itself to show the actual brightness, transparency, and positioning of the hologram.

and used lip-reading in conversations. That patient was able to follow the conversation and follow commands well when interacting with the hologram. The technology had sufficient resolution to render quality facial features to allow lip-reading.

This small study has limitations. Although this analysis had 29 patients, significance was noted for all survey questions. Average age was lower than a general stroke population.[23] This was to be expected based on our inclusion criteria that required assessments in a nonacute clinic setting. Our population was drawn from a neurology clinic, but ages did range from 20 to 80 years. Our next assessment will include a stroke population to investigate an older group with more deficits. Though not currently appropriate for a hyperacute Tele-Stroke evaluation, this enhanced technology may soon be included in standard nonacute Tele-Stroke, teleneurology, or other telemedicine care to enable more immersive experiences for patients. Thereafter, with enhancements in the field still needed, this technology could then be used for more acute evaluations/conversations.

This Holo-Stroke experience did not collect deficit severity, but we did include patients with multiple neurological diagnoses and significant deficit (some patients required wheelchair use, walker, or had significant motor or language impairment). Although this technology may also not be useful in every Tele-Stroke case (e.g., depressed level of consciousness, or encephalopathy), even in those cases, the health care surrogates (HCSs) may utilize Holo-Stroke to interact with the provider as their experience is also critical to the patient/HCS–provider interaction.

We presented the standard Tele-Stroke technology and survey first, before presenting them with the Holo-Stroke technology and survey to guard against participants artificially scoring the Tele-Stroke option lower after having seen the new hologram option. Newer technologies could be scored higher than old technologies simply because they are newer.

Establishing the baseline score for Tele-Stroke created a ceiling effect in the possible difference that could then be noted between technologies. Finding a significant improvement in Holo-Stroke even after presenting the good standard technique adds to the confidence in our significant findings. Of course, we cannot fully exclude some anticipatory bias as participants knew they were going to see a standard Tele-Stroke followed by a "new" technique.

Side effects are not uncommon with VR and AR.[24] Neither of the two patients who experienced dizziness found it significant enough to stop the Holo-Stroke experience. With further simplification and improved tethering to the real environment (such as smaller form factors like eyeglasses), future user experiences may be improved and use cases may then be expanded.

Reliability assessments were not required for this experience as we were not examining patients. We also did not send the patient holo-stream to the provider's office as we were assessing patient-side perceptions. We are actively iterating this two-way process (*Fig. 2*). Sending patient holographic video streams in Tele-Stroke will require optimal resolution and reliability assessments as we have done in the past for standard Tele-Stroke.[2] We also note that bringing a full-size patient to a provider hub location via hologram might require a larger room for the provider to interact with a patient hologram. Providers may instead choose to "pinch zoom" and only view specific parts of the patient (such as zooming into facial features), or use hand gestures to swipe away or rotate the entire image (smaller version of patient). How this may be optimally used in the future is still to be determined.

Conclusions

Holo-Stroke was designed to assess if hologram-augmented Tele-Stroke would result in significant improvement in the patient–provider interaction. We found robust improvements in all questions related to both immersion and satisfaction. Results were in line with other recent studies in different populations, adding to the robustness and generalizability of the data. Patients, both young and old, were enthusiastic about the new modality and for the ability to have a more immersive, personal interaction with their provider and radiology images. Holo-Stroke does not replace in-person assessments as the most immersive option, but when providers cannot be there in person, augmented Tele-Stroke in the form of Holo-Stroke results in a more immersive experience than standard Tele-Stroke. Although much more work needs to be done, Holo-Stroke appears to be a strongly viable option to "be there" not just "see there."

Ethical Approval

This project was approved by the University of California San Diego IRB #807864.

Authors' Contributions

N.W.: Conceptualization, methodology, administration, resources, supervision, validation, visualization, review and editing. B.A.: Data curation, methodology, investigation, review and editing. V.R.: Methodology, administration, review and editing. W.L.: Methodology, validation, review and editing. D.M.M.: Investigation, writing—review and editing. T.M.: Investigation, writing—review and editing. E.S.G.: Investigation, writing—review and editing. B.C.M.: Conceptualization, data curation, analysis, investigation, methodology, administration, resources, supervision, validation, visualization, writing—original draft.

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