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Review Article

Radiology Section

Augmented Reality System Guidance for Computed Tomography-based Needle Insertion: A Narrative Review

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ABSTRACT

The new advancement in percutaneous intervention procedures, which provides more accurate needle placement compared to other modalities, is Augmented Reality (AR). It provides the operator with 3-dimensional (3D) or 2-dimensional (2D) structures of the anatomy along with the target during surgery to get a precise needle placement into the target. The review highlights that using AR systems for needle navigation and placement can become productivity in various interventional procedures. The AR navigation system reduces radiation exposure, procedural time, risk to the patient, and ensures higher accuracy of needle placement than conventional Computed Tomography (CT)-guided percutaneous procedure systems. The AR system can provide precisely guided needle insertion and reduce the risk of complications. As technology and research are increasing, new techniques, such as automatic image-hologram registration, can be brought into the picture. This review compares conventional image-guided procedure systems with the AR system in the interventional radiology field. This review also provides detailed information about AR as a promising tool for optimising needle placement in interventional procedures, paving the way for safer and more effective clinical practices.

Keywords: Bull's eye view mode, HoloLens, Vergence-accommodation conflict

INTRODUCTION

Interventional radiology is a branch of radiology that comprises less invasive procedures, such as angioplasty, ablation, and biopsies, among others. Over the last few decades, the development of imaging modalities and many other devices has increased. Image-guided biopsy and ablation are essential for lymphoma, kidney, liver, lung, and other soft tissues. In such procedures, accurate needle placement should be correct to make the procedure safety and productive. Compared to other modalities, CT is mainly used for percutaneous procedures. Many advancements are developed to perform percutaneous interventions, such as laser systems, gyroscopic tracking, robotics, and Electromagnetic (EM) tracking. However, these techniques increase the precision of needle placement. This kind of advancement has many limitations because of which they are not used clinically [1].

EM field generators and EM sensors, which are parts of EM navigation systems, perform numerous procedures, such as thermal ablations of hepatic tumours, providing less radiation exposure for interventional radiologists and patients. They help track the position of operating components by detecting infrared light using sensors from optical navigation systems or video cameras. Some limitations associated with these advanced techniques include the lack of devices suitable for EM fields, the requirement that the optical path between the camera and instrument layout be unobstructed, the large size of instruments in robotic-assisted systems, and the high cost and set-up time required for laser guidance systems [2].

A new technique called AR has been discovered to overcome the above limitations and achieve more precise needle placement than conventional image-guided systems. It has been used in various fields such as education, entertainment, the military, and medicine [3-5]. AR is a technology that provides an enhanced version of reality by overlaying digital information over the real world using handheld or head-mounted devices [1,4,6-9]. The accuracy will be better in percutaneous needle interventions if the access of the needle's access to the area of interest is closer to the operator's eyesight [10]. Since the mid-1990s, AR has been viewed as a tool that could be used in the future for picturising image data in interventional procedures, leading to continuous technological improvements [11].

Issues such as eye fatigue, heating, calibration, system lag, and user customisation occur due to goggles or head-mounted displays, so smartphones are mostly preferred over other devices in the AR system [1]. When employing other interventional modalities like a fluoroscopy system, the surgery planning for the target area is then shown on a flat-panel screen. This can cause distractions for the surgeon when switching between the screen and the patient, a problem that AR technology addresses [3,12,13]. By overlaying the needle entry site and its route onto the patient's anatomy, needle placement using AR technology can be achieved [1]. Operators can move the smartphone over the phantom to verify if the needle is following the correct planned path and make any necessary adjustments. In the case of smart glasses, the operator has to attach it to the head and carry out the procedures while moving the glasses to different positions above the phantom [10].

At the bedside, interventional radiologists can obtain a simple, easy, and overlapping view of the planned needle pathway using AR technology. It helps to compare the actual and planned needle pathways and provides correct adjustments. By superimposing Magnetic Resonance Imaging (MRI)/CT images and data on patients, AR tools help visualise the internal structures and find the correlations between them by using a wearable camera or smartphone [1,14]. AR technology in CT-guided free-hand needle insertion requires a preprocedural CT scan to mark the needle's entry point and pathway. However, the AR system displays the planned needle pathway information within the procedural environment instead of on a remote monitor. This provides a better appreciation of the anatomy of interest, procedural planning, and performance of the procedure [10,15].

WORKFLOW OF THE AR SYSTEM

Smartphone

The AR applications or apps should be installed on smartphones like Android, tablet hardware, etc. The operator should plan the needle insertion angle, entry point, and pathway on the preprocedural CT images. The smartphone's screen shows real-time video captured by the camera. The three buttons used to start and stop capturing the video and switch between the front and back camera using a camera button are at the bottom of the screen. One need to calibrate a button for registering the smartphone to the CT scanner, a configuration button for setting up a wireless connection between the smartphone and a Personal Computer (PC), and additional control from the PC and a needle button to set the planned needle angle on the smartphone is present at the top of the screen.

Calibration and gyroscope tracking of the smartphone coordinate system in correlation to CT immediately give the correct 3D rise in the smartphone's perspective. In smartphones, the x-axis is from the left to the right of the screen, the y-axis is from the bottom to the top of the screen, and the z-axis points out of the screen [16]. The gravity vector and the second vector, set by touching the CT table with the smartphone's long edge, called one-touch calibration, should be matched in the two coordinates for the correct calibration of the smartphone to CT. After planning, the data is sent to the smartphone with a dropdown menu where one can select the required target. The path angle shown on the smartphone is referenced to CT, and the planned path angle in the CT is then transformed into the smartphone's local reference frame.

When the smartphone is parallel or perpendicular to the planned path, the guidance modes, such as Guideline mode and the Bull's Eye View mode, change automatically. A green line represents the scheduled path angle in guidance modes. The needle's insertion angle is selected by comparing the needle's adjustment with the guideline overlay. Bull's eye view mode shows the needle tract from the top of the needle, providing the correct insertion angle. When the smartphone is perpendicular to the scheduled route, one can see a bull's eye when the needle is seen as a point with the needle hub at the top of the needle tip. The smartphone is perpendicular; the circle and cross from the camera display should overlap [17].

The operator should hold the smartphone correctly; otherwise, getting a Bull's eye view is challenging. To eliminate the smartphone's movement, a passive arm, smart glass, or needle holder can be used so that the operator can focus only on one device during manipulation. Finally, a CT scan is performed to confirm the correct placement of a needle into the target [16]. A sterile, transparent bag should encase the AR smartphone to provide clear operator visualisation of the screen during use, and a 3D reference marker should be replaced by an adhesive skin marker if using them clinically [1]. Most operators found it easier to carry out procedures with smartphones than with smart glasses because the operator's hands obstruct the camera view of the reference marker, causing a lack of image registration and AR display [10].

HoloLens

The HoloLens consists of a visor with a holographic unit covering both eyes and an installed Windows PC [17]. HoloLens works basically on voice commands such as "select," which picks up the needle tool, "scan," which shows the CT scan of the virtual needle location, "next," which guides to the delivery of the following CT slice, and "previous," which shows the last CT slice. The objects in the CT data were coloured to quickly identify biopsy needle placement by the participants. The biopsy needle is then placed in the target's anatomy and aligned along the green line. It is advanced further towards the target until it is correctly placed within it.

Microsoft's HoloLens is a head-mounted display system and a recent development in AR devices that has generated a lot of interest. A headset such as Microsoft's HoloLens permits spatial projection of 3D holograms within the mentioned surroundings with the help of an integrated holographic computer [1,18]. Sterility in the operating room must be maintained as MRI images and open and close the windows of the HoloLens using hand gestures or voice commands without touching them [19,20].

The higher precision of needle placement and acceptable ablation margins have led to more excellent outcomes during ablations of small tumours under the AR guidance system [1]. AR tools only have mobility problems when using a smartphone or smart tablet compared to stationary devices. The actual and digital objects displayed on the smartphone provide images rapidly transmitted to numerous users for feedback and to confirm the needle placement during the procedure, which is not possible with smart glasses. Instead of overlaying on a 2D screen, smart glasses allow for the anchoring of digital 3D objects in physical space, representing a recent development in AR tools [21].

Smart glasses are fastened and accommodate the user's head, and works on voice execution and signals made by hand, thus allowing hands-free use [22]. By using these tools, interventional radiologist gets to alter the patient's anatomical location and attain better recognition of the treatment planning through the undeviating sightline of the patient. Real-time corrections cannot be made for a respiratory expedition in mobile organs as it is based on preprocedural CT imaging, a standard limitation of AR technology and the CT-guided free-hand needle insertion technique. Smart glasses provide a large and direct field of view, stereoscopic vision for depth information, hands-free operability shows a 3D hologram of the digital object in a 3D environment, and require less time than a smartphone. The interventional radiologist performing the procedure holds the smartphone in one hand and uses the other hand for needle placement. Procedural time can be compensated using a smartphone holder or a bedside-attached arm [21].

The head-mounted display HoloLens 2 was discovered in 2019 with more advancements; otherwise, the HoloLens was one of the first AR head-mounted displays. The HoloLens 2 features a wide field of view and a shifted center of gravity, permitting better workplace efficiency. It also has a higher resolution visible light camera than the previous HoloLens, which helps to provide more accurate pattern recognition and tracking. The increase in effectiveness and quality of medical training at a lower cost than usual is achievable while performing a biopsy on a phantom, along with realistic simulation of CT-guided procedures using HoloLens 2. Tactile response can be expected in the future because of the current capabilities of 3D AR head-mounted devices [23]. HoloLens is preferred over all these devices as it can be operated with hand gestures, has good battery life, and can visualise the structures in holograms in a real environment [19]. Vassallo R et al., found that the HoloLens 1 has better stability than any other AR device [24].

DISCUSSION

AR provides the exact tumour location or pathology beneath the patient's skin due to the stereoscopic view. This helps the physician properly plan the needle pathway into the tumour, preventing damage to other vital structures and providing patient comfort and easy access [25,26]. Hecht R et al., compared a smartphone-based AR system with CT-guided freehand navigation on percutaneous procedures using a phantom. The study found that needle placement precision was higher, with a lower mean total error of needle insertion in AR technology than in CT-guided freehand navigation, along with less radiation exposure and procedural time [1]. Similar results were also found by Li M et al., who stated that in conventional CT-guided needle approaches, uncertainty in accuracy increases with the surgeon's experience. They also found that AR users take more time to move about the phantom and rearrange the needle as necessary to compare planned and actual needle routes, but accuracy is better [21].

Faiella E et al., calculated the total error in the needle insertion pathway and placement using lateral and indirection errors in their study to check the accuracy. Indirection error was calculated as the distance from the target's center to the needle's long axis, and lateral error was the distance orthogonal to the long axis of the needle, calculated using Pythagoras theorem. The error was considered zero when the needle tip touched the target [2].

Agten CA et al., explored an agar-embedded phantom study to check the feasibility and accuracy of AR application in lumbar facet joint injections. Most lumbar facet joint injections are performed with higher radiation doses to the patient and operator using fluoroscopy and CT [27]. This study proved that AR-based facet injections are more precise, harmless in needle placement, and are less time-consuming than CT-guided procedures, similar to the aforementioned studies. In recent years, various AR-directed systems have been introduced, which are assessed as effective tools for lung lesion biopsies. Patient comfort is essential to avoid discrepancies between the CT-acquired volume and the real patient's position. The AR navigation system provides excellent patient safety, optimises resource utilisation, has sufficient capacity for primary and secondary bone lesions with diagnostic-therapeutic management, and provides acceptable quantity and quality of biopsy samples for histological and immunohistochemical analysis to know the patient's condition [2]. Also, Badiali G et al., demonstrated that AR head-mounted devices, an advancement in the AR system, can be used for surgical procedures on the facial skeleton [6].

To determine whether needle accuracy is affected by any factors, Hecht R et al., performed two experiments. In the first experiment, they used two different-sized phantoms with targets placed at various locations to assess whether the accuracy of needle insertion changed based on the size and depth of the lesion. However, no changes in accuracy were observed. The second experiment involved a single phantom in which procedural efficiency, the total number of scans, and procedural time were evaluated. A final confirmatory CT scan was conducted to verify the needle insertion track in the target, and lateral error and indirection error were calculated. This literature concluded that the size and depth of the lesion do not affect the needle accuracy when using the AR system [1]. Li M et al., also compared smartphone- and smart glasses-guided AR systems to assess the accuracy and execution of needle placement on an acrylamide-based phantom. The study indicated that image overlay and angular overlay are precise for both AR tools for needle placement guidance. However, the smartphone-guided AR system is preferred over the smart glasses-guided AR system due to issues such as eye fatigue and overheating [21].

Another issue associated with a head-mounted AR system is the movement of the operator's head when wearing a headset, which can cause the hologram to shift. This occurs when the HoloLens fails to form the correct spatial mapping of the object or target, and compels the operator to move their head for accurate alignment and accuracy [27,28]. Xu S et al., published a study demonstrating that smartphones or mobile devices can accurately guide needles in percutaneous interventions with ease of implementation using a phantom [16].

Future studies on head-mounted displays should address and refine registration and movement problems. Recently, the Microsoft HoloLens system was used in an anatomic pathology study for different applications, such as remote supervision of autopsies, annotation of anatomic structures, and telepathology [27]. AR needle guidance systems provide many advantages, such as precise needle tip positioning, accurate needle insertion precision, decrease in needle deviation and passes, decreased radiation exposure and procedural time, fewer needle adjustments, and lower procedural risks [16,29,30].

Amiras D et al., carried out a study on an AR simulator for CT-guided interventions using Microsoft HoloLens on a mock phantom of a torso made of an agar jelly mixture, which showed that simulating a CT-guided procedure with AR can be achieved, which is used as a training tool for future trainees [23]. However, there are some problems related to HoloLens. Firstly, the battery usage lasts only 2-3 hours, which may require replacing the HoloLens with a fully charged one during complex surgeries, which take longer, HoloLens can be replaced with another one by putting the previous HoloLens for charging. Secondly, it needs hardware that can magnify the area of interest, especially for smaller and more complex areas [19].

Fritz J et al., studied cadavers using AR-based MRI-guided arthrography for the shoulder and hip, using the 2D image overlay. The 2D image overlay does not require segmentation and uses cross-sectional images for guidance. However, challenges arise when using 3D holograms, which require density-based segmentation [31]. Medical simulation allows individuals to develop clinical skills through regular practice rather than traditional apprentice learning.

Simulation tools serve as substitutes for real patients, providing risk-free training opportunities as students can practice many times and learn from their mistakes [1,32]. In recent years, the potency of simulation as a training tool has been increasingly recognised. The advancement of AR and VR in simulation is required in practice as interest in experiential learning increases. Some AR simulators are used for percutaneous renal access using ultrasound for beginners, resulting in improved performance. Also, when used to teach trial users in fluoroscopy-guided lumbar puncture, it offers an accurate replication of anatomy and the procedure [1,33].

Identical results to those in the above-mentioned studies were found in the study by Faiella E et al., which aimed to assess the impact of the AR navigation system (SIRIO) on percutaneous procedures compared to a standard CT-guided technique. This retrospective study done using the optical-based navigation system [2]. SIRIO reconstructs a 3-D model from formerly acquired CT images using a semiautomatic algorithm, an intraoperative AR navigation system. It also avoid damage to the risky structures near lesions, such as nerves, by correctly positioning the needle. SIRIO-based procedures are sensitive to patient movement, which is identified after the first CT scan. In such cases, it will discover the changes that have occurred and alerts the operator to consider performing another CT scan before proceeding with the procedure. The unavailability of the SIRIO system in medical centres and the expertise required to perform this procedure avoid its use in daily clinical practice. In percutaneous procedures, SIRIO-based procedures require lower radiation doses, fewer CT scans, and less procedural time compared to non-SIRIO procedures [2].

Surgical navigation systems that combine ultrasound and CT data for pedicle screw placement and needle biopsies in an animal model are performed using AR [27]. Studies by Rosenthal M et al., and others related studies also stated that needle insertion and placement accuracy are improved with AR devices [34-37].

In a study by Racadio JM et al., needle localisation of targets for AR with and without motion compensation was compared to cone-beam CT with real-time fluoroscopy navigation in a pig model. The study evaluated the precision of needle route and radiation exposure. Tracking markers were placed on the patient to reduce motion, enabling real-time registration of cone-beam CT and needle positioning to enhance the accuracy of needle placement in the area of interest. The accuracy of needle placement was determined by measuring the distance between the needle tip and the target center. The dose area product of fluoroscopy and cone-beam CT measured the radiation dose and was recorded for each procedure. The study found no difference in precision between AR with or without motion compensation, and there was also no difference when comparing cone-beam CT fluoroscopy to AR. The radiation dose to patients with AR, with or without motion compensation, was less than with cone-beam CT fluoroscopy [38].

CONCLUSION(S)

The AR system provides the ability to view the patient's anatomy in real-time and reduces the risk to the patient. Advancements from conventional image-guided procedure systems to AR-guided navigation systems led to a reduction in the radiation dose to the patient, procedural time, and increased needle placement accuracy. It can also be used in developing countries as it is less expensive than other advanced techniques, such as robotics.

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