ISSN: 2474-9206

Research Article

Journal of Anesthesia & Pain Medicine

Needle Navigation; a New Era in the Interventional Pain Practice: A Narrative Review

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Submitted: 2023, Mar 14; **Accepted:** 2023, Apr 20; **Published:** 2023, May 10

Citation: Fathi, A., Hosseindoost, S., Inanloo, S. H., Espahbodi, E., Ahmadian, A. et al. (2023). Needle Navigation; a New Era in the Interventional Pain Practice: A Narrative Review. *J Anesth Pain Med, 8*(3), 125-129.

Abstract

Background: *The hazardous effects of x-ray based technologies and shortcomings of other imaging systems like ultrasound have raised attention to create a new guiding system for interventional practice. After the introduction of virtual reality, the next challenge was how to implement it in the medical guiding systems. Medical engineering used registration aligned features of one imaging modality with real anatomical points and merged them into one single hybrid model. This augmented reality made the foundation and provided a level surface for the construction of every other new level. The next level was how to track a device in this augmented reality, which was accomplished with trackers and registration. To overcome the shortcomings of each imaging modality, the solution was fusion imaging, the combination of more than one modality to overcome the limitations of each. Nowadays, this fusion imaging plus needle tracking is the most sophisticated of navigational systems that interventionists work with. Despite clinical improvements in other medical fields like neurosurgery and urology, most of the work in the interventional pain practice has been done on phantom models and human cadavers, and there is still low experience in clinical studies about this new guiding system.*

Methods: *The electronic search for this review included full text English article between 1990-2021 in PubMed and Google Scholar databases. The terms that have been searched are: "virtual reality", "augmented reality", "needle navigation", "needle tracking", and "fusion imaging".*

Results: *The navigation imaging guided system can be a practical, safe, efficient, reproducible, feasible guiding option for interventional pain procedure.*

Conclusions: *The navigation based interventional injection is a new era in the interventional pain practice and can omit X-ray based hazardous.*

Keywords: Virtual Reality, Augmented Reality, Needle Navigation, Needle Tracking, Fusion Imaging.

Abbreviation list: CT: Computed Tomography, MRI: Magnetic Resonance Imaging

1. Introduction

For many years x-ray based imaging systems such as fluoroscopy or computed tomography were and still are the gold standard for imaging guidance the interventions. However, this landscape has changed with the emergence of ultrasound. Since its introduction in the 1960s, ultrasound has offered a good alternative. It requires less expensive equipment, while it is real-time with no ionizing radiation. Nonetheless, the image quality is far from superior in some especial circumstances involving deep structures or bones. It is operator dependent and needs adequate education and training [1].

Mentioned shortcomings necessitated the development of a new era. From the early 1990s, virtual reality concepts started to enter the field of medicine. Till then, dependency on radiation imaging systems as the guidance for interventions posed significant risks to the patients and operators due to ionizing radiation. Virtual reality is the replacement of the user's existing field of view with an entirely new graphical environment. The purpose was to construct a hybrid patient model, which combines what the interventionist observes with what he can observe on medical images. This is called "Augmented reality", and it differs from virtual reality in that it adds graphics to the interventionists existing field of view instead of replacing it with an entirely new environment. This single hybrid model is a coordinate system that matches reality and the model. Because of technical difficulties, this process was challenging. However, the reward was great; real-time imaging, high-quality images, and radiation dose reduction [2,3].

To construct a single hybrid model, we have a "map" of either computed tomography (CT) or Magnetic resonance imaging (MRI) and a "terrain" the patient's anatomy in the operating room, these two should be linked. The goal of this map-to-terrain linkage is to determine, for every point of interest in the anatomy, the unique point in the map that corresponds to it. When this point-to-point correspondence is determined, the map is said to be aligned with the terrain. The point-to-point correspondence is accomplished via a process known as "registration". In registration, a few clearly discernible features of the map, more technically called "Fiducials", are identified and aligned with those same fiducials on the patient. The term "Fiducial" is from the Latin fidere, meaning "to trust". As a general rule, one needs at least 3 fiducials to align or register. These fiducials can be either manufactured markers taped to the body surface or anatomical points detectable by a 3-D localizer.

Electromagnetic fields or sets of optical cameras are used as a 3-D localizer. After the selection of fiducial points, registration involves identifying pairs of corresponding points in image space and in physical space and aligning all pairs as well as possible [4]. Now we have a hybrid patient model based on augmented reality. The next step is to navigate the position of an instrument on the virtual model, which is called "Tracking". We compute the 3-D position of a surgical tool in the coordinate system of a localizer. The localizer is an electromagnetic field or set of optical cameras. We have to estimate the transformation between two systems, for example, a pre-operative MRI image (the virtual model) and the 3-D localizer (the real-time position of the tool). The technical challenge is in estimating the transformation between two systems which is accomplished via registration. To establish a link between two systems, the same fiducials are used to navigate using a tracked surgical tool. In earlier systems, they used three little spheres. They pasted the spheres on the patient's body before the MRI scans and kept them in place till the end of the intervention. These landmarks were detectable by both MRI and 3-D localizer, and their positions were used as reference features. During the intervention, the 3-D localizer quickly computed its position, and the transformation between the two systems was estimated very efficiently. Systems that are more sophisticated only use patients' anatomical structures instead of material landmarks in order to register all the data. In these new systems, instead of position sensors the device itself has a sensor, function. In a very general and practical method, the chosen reference structure is on the surface and visible, and a set of optical detectors is used as the localizer [2-4].

Until this point, only one imaging modality was used as a map for map-to-terrain registration. As everyone knew, each single modality has its own shortcomings. Computed tomography is radiation based and has low quality in showing soft tissue details. MRI is time consuming, and paucities in bony structures were evident. Ultrasound has limitations in depth and soft tissue details. "Fusion" was the solution for this shortcoming, which means the combination of more than one imaging modality to overcome each modality's limitations. For this purpose, all the information, including pre-operative images of CT or MRI, intra-operative images of fluoroscopy and ultrasound, and anatomical models, should be gathered. These are raw data, and they have been obtained from different classes of systems. They need to be processed, computed, and finally merged in one single model [4].

In commercially available navigation systems like CANON Smart Fusion Imaging, the experts have superimposed a recent CT scan or MRI on the ultrasound-created image during the ongoing procedure. The only addition is the electromagnet as a 3-D localizer in proximity to the field and is especially useful when the lesion is not well visualized by ultrasound alone. The fusion technique can be coupled with CANON Smart Navigation/Needle Tracking to follow the needle for any intervention. The needle is visualized using a detecting electromagnetic device. This device is integrated at the base of the needle with sterile precautions. An algorithm installed on the system does the registration process and estimates the transformation between CT or MRI and needle position. This unique technique combines imaging modalities and is accessed by helping needle navigation, a needle tracking technology. The latter permits for some needle paths that are oblique and real-time needle monitoring without exposure to radiation [5].

2. Evidence Acquisition

The electronic search for this review included PubMed and Google Scholar databases. The terms that have been searched are: "virtual reality", "augmented reality", "needle navigation", "needle tracking", and "fusion imaging". We searched for published articles between 1990 and 2020. All papers that were published in these databases were included. We excluded the papers, which were not in English, or their full texts were not available. We manually searched and added additional references like textbooks to the review.

3. Results

In the intervention arena, besides the technical difficulties, preserving the optimum accuracy is another challenge. The final goal is to find a guidance system with no radiation and the same or higher accuracy. In 2009, Moore and colleagues designed an augmented reality ultrasound guidance system. This system tracked an ultrasound probe by an electromagnetic tracking system that enabled visualization of the detected probe and needle. They conducted it on a human phantom for facet joint injection therapy and demonstrated a remarkable improvement in the precision of needle placement by pain specialists.

They concluded that the combination of real-time ultrasound and needle tracking systems could replace CT and fluoroscopic guidance. It could reduce radiation exposure. Moreover, it would reduce health care expenses because the cost of tracking technology is less than fluoroscopy and ultrasound [6].

Because ultrasound images had low quality, scientists searched for the augmentation of ultrasound images for better accuracy results. Therefore, they have embarked on combining different imaging modalities. In 2010 Chen et al. combined computed tomography with ultrasound as guidance for needle navigation system for spine interventions. They called it an ultrasound-guided, CT-augmented navigation system. First, they constructed 3-D ultrasound volumes from a series of 2-D ultrasound images by recalibration of the ultrasound transducer [7]. Then they obtained a preoperative CT of the patient and registered it to the intraoperative 3-D ultrasound volume through a biomechanically constrained registration algorithm. They got two renderings, a digital rendering radiograph (DRR) that provides a familiar visualization to the interventionist and a surface rendering that complements DRR via giving both spatial perception and depth of bone anatomy [8].

Computed tomography has its own limitations as well. It uses ionizing radiation, and when it comes to soft tissue, it has low image quality in comparison to other modalities like MRI. On another level, the scientists tried to augment ultrasound with MRI. In 2017, Behnami et al. used the preoperative MRI as ultrasound-augmentation for a needle tracking system. The spine ultrasound images can generally represent posterior surfaces of bone while, MRI images display a better view of the anterior structures. Consequently, they described a larger accuracy error in comparison with the registration obtained from the CT-ultrasound [9].

This outcome was expectable because of several factors. Firstly, precise and complete bone surface extraction is not possible with MRI because MR images have thicker slices compared to CT. Furthermore, ultrasound has the limitation of depth, and MRI cannot image the bony structures as CT delivers. The reason stated for this issue is the lower quality of bone margins in MRI versus CT images [10].

Alimohamadi et al. compared three modalities to get better results in 2020. Low-resolution CT, High-resolution CT, and MRI images were used for the registration of the navigation system. The comparison of the outcomes indicated that if we use the information of all parts of the vertebrae and maintain accuracy, MRI images can be used rather than CT images [11].

In 2012, Fritz et al. used a 1.5 T MRI as ultrasound-augmentation for lumbar spinal procedures. They tried to examine the efficacy and accuracy of the navigation system on a human spine phantom. The data revealed the new system is sufficiently accurate and time saving for spinal injections. They concluded that it could simplify the current method of MRI-guided spinal interventions [12]. They also utilized the same needle tracking system for shoulder and hip joint procedures in human cadavers. They used MR imaging to ensure the right position of the needle tip, monitor procedures, and perform MR arthrography. Accuracy was evaluated by needle adjustment rate, target error, and intraarticular injection rate. They assessed the efficiency according to the time of the procedure. The results demonstrated that image overlay technology prepared efficient and accurate MR guidance for accurate hip and shoulder arthrography in cadavers [13]. In early 2013, they published another study about the same augmented reality tracking system. They conducted 187 lumbar spine procedures such as spinal nerve root block, facet joint injection, epidural injection, discography, and medial branch block on 12 human cadavers. They utilized MRI to verify the right position of the needle tip. They reported that all accessible targets were successfully injected. There were no accidental punctures of vulnerable structures. Finally, they concluded that image overlay navigated MR-guided spinal procedures were technically precise [14]. Again, in 2013 the same group planned and published an osseous biopsy of 16 lesions in four human cadavers with osseous metastases. They monitored the process of the drill insertion and the final position of the drill using intermittent MRI images. They showed MR imaging could demonstrate successful drill location in all 16 target lesions. One needle pass was sufficient for accurate targeting of all lesions. They concluded image overlay technology prepared precise navigation for MR-guided biopsy (at 1.5 T) of bony lesions, especially in the pelvis and spine regions in human cadavers [15]. In 2014, their project was about vertebroplasty, Twenty-five unilateral vertebroplasties in 5 human cadavers. They used intermittent MRI imaging to monitor the position of the MRI-compatible vertebroplasty needle. All planned techniques were carried out. They employed 16 out of 25 (64%) transpedicular and 9 out of 25 (36%) parapedicular approaches. They did not have any inadvertent punctures. They reported adequate position for the needle tip and cement placement in all cases. They concluded that MRI-guided vertebroplasty by image overlay navigation was practical and precise in human cadavers [16]. In 2017, Marker et al., in cooperation with Jan Fritz, used their MR-guided virtual reality needle navigation system on human cadavers for paravertebral sympathetic plexus injections. All of the 46 thoracic, lumbar and hypogastric plexus targets were injected accurately with no puncture of critical non-target structures [17].

Massone et al. published one of the few clinical studies in the field of interventional pain practice under needle navigation guidance in 2018. They selected 65 consecutive patients for facet joint injection under fusion-imaging technology or CT guidance. The pre-procedural CT or MRI of the patients was loaded to the image fusion technology (EcoNav; MASMEC, Modugno, Italy) for registration. In both CT-guided and fusion-guided interventions, a solution of 0.5 ml corticosteroid plus 0.5 ml local anesthetic was injected in each facet joint, and all patients were followed. There was no significant difference between the two groups regarding baseline conditions or in the follow-up time. However, they did not observe any significant differences between fusion-MRI and fusion-CT methods in procedure time and clinical results. Finally, they concluded that the EcoNav fusion-imaging guided system is a safe, feasible, effective, and reproducible guiding option for facet joint injections. Finally, they concluded the EcoNav fusion-imaging guided system is a practical, safe, efficient, and reproducible guiding choice for facet joint injections [18].

4. Conclusions

From the beginning of modern medicine, technology has helped to be more accurate and less invasive. The term "intervention" was invented when physicians found that many open surgeries could be done in less invasive manners. However, they needed some sort of guidance, something to visualize the body inside when it is not open. Technology helped them with optical cameras and light fibers for laparoscopic surgeries. Ultrasound and x-ray based technologies like fluoroscopy made percutaneous interventions possible. Still, there were deficits. Fluoroscopy and CT cause radiation damage to personnel, ultrasound images have depth and quality problems, and MRI is very expensive and time consuming. Therefore, the need for a new guidance system that is as safe as ultrasound and as accurate as x-ray modalities has become more evident. Technology has combined all of these imaging modalities, and the result was named needle navigation systems [19-21].

After the introduction of virtual reality based tracking systems and their use in medicine, many interventional procedures were performed with this technology. Nowadays, prostate, bone lesion biopsies, and many other interventions like thermal ablative procedures are done with needle navigation systems. Stereotactic neurosurgeries like biopsies and deep brain stimulator implementations are conducted with this guidance. To date, all experiments in the field of interventional pain utilizing this unique technology are conducted on human phantom or cadavers. The promising results of these non-clinical studies have paved the road for translational projects to embark upon clinical studies [22-24].

Author Contributions

A.F., S.H., S.H.I., E.E, A.A., S.A.E., N.A.N.Y, M.S. contributed to data collecting and manuscript drafting. H.M., contributed to the conception, and design of the manuscript and critically revised manuscript. All authors approved the final manuscript.

Conflicting of Interests

The authors declared no conflicts of interest.

Acknowledgements

We thank Pain Research Center, Neuroscience Institute, Imam Khomeini Hospital Complex, Tehran University of Medical Sciences, Tehran, Iran

Funding

The author received no financial support for the research, authorship, and publication of this article.

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