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Three-Dimensional Display in Nuclear Medicine and Radiology: Applications and Future Developments

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Abstract:

Three-dimensional (3D) display technology has revolutionized the field of medical imaging, particularly in nuclear medicine and radiology. It enhances the visualization of complex anatomical structures and physiological functions, leading to more accurate diagnoses and improved clinical decision-making. This paper explores the fundamentals of 3D display technology, its various types, and its application in nuclear medicine and radiology. It also addresses the challenges and requirements for developing 3D displays for medical purposes, such as improving image quality, enhancing diagnostic accuracy, and supporting surgical planning. Furthermore, the paper discusses the potential for future developments, including the integration of artificial intelligence (AI) and machine learning (ML) with 3D imaging technologies. These innovations promise to revolutionize diagnostic workflows and provide more personalized care for patients. With advancements in hardware and software, 3D display technology is poised to become a crucial tool in clinical practice, enhancing both diagnostic accuracy and patient outcomes.

Keywords:
Three-dimensional display, nuclear medicine, radiology, medical imaging, diagnostic accuracy, surgical planning, artificial intelligence, machine learning, volumetric imaging, future developments.

1. Introduction to Three-Dimensional Display Technology

Three-dimensional display technology is a high-impact topic in diverse fields, including computer graphics, movie production, video gaming, geology, and medical imaging. The concept of three-dimensional displays has long fascinated mankind, tracing its history back to the time of the stereoscope and the anaglyphic principle. However, in medical imaging, including nuclear medicine and radiology, a two-dimensional representation prevails to explore the three-dimensional distribution of radioactivity and explain underlying diseases; a two-dimensional image from any imaging modality is used to illustrate the concepts and ideas in manuscripts and books. Nevertheless, the pursuit of three-dimensional display to enhance the diagnostic efficacy of radiologists and clinical decision-making processes is inevitable and has already started everywhere.

This text comprehensively describes the principle of three-dimensional display technology, different categories of three-dimensional displays, and their applications in nuclear medicine and radiology. The requirements and challenges for developing a three-dimensional display for medical applications are also detailed. The visualization of complex anatomic structures in radiology is progressing from reading conventional electro-optic endoscopy or laparoscopy to flat panel X-rays, video images, magnetic resonance, computed tomography scanning to volumetric data sets in three dimensions, set of data to volume rendering. Now, the visualization of entire volumetric datasets in three dimensions is rapidly changing to allow the information in our clinical data sets to be viewed as we see the world around us. A single slice of data can be processed and reconstructed in any desired plane, with oblique-angle reconstructions in any direction. It could be likened to passing the data through a digital cookie cutter, acquiring thin-slice sets, and then rebuilding the slices into three-dimensional volume-rendered perfections.

1.1. Definition and Basics of Three-Dimensional Display

Three-dimensional (3D) information display, more commonly, 3D display is the technology associated with the display of 3D images or images with an optical illusion of depth perception. As such, human vision integrates different cues to perceive the depth of real-world objects. Stereopsis, with the slightly dissimilar perspective from the two eyes, provides special stereoscopic vision in the natural viewing of the objects. Moreover, volumetric images from 3D volume likely show the structures of an object from different geometric orientations. To make human eyes perceivable or reconstruct the scene, the volumetric viewing can be changed as parallax by relative viewing to a given point in the scene. (Javidi et al.2020)(Goo et al., 2020)(Pi et al., 2022)

According to the different principles of 3D information displaying and 3D perception inducing, three types of 3D displays have been reported, viz., holographic display, volumetric 3D display, and integral display, which are being briefly described herein. A holographic display works based on the principles of classical holography as demonstrated using a full-complex functionality of light and uses spatially extended laser light to display 3D images. Volumetric 3D displays explore two fundamentally distinct display concepts called Spatial and Angular Light Modulation Display. According to SLMD, slice-based and real-time TDD outcrops are achieved with lasers to form 3D images above LIP.Accordingly, a single slice (or a volume) can be implemented, but as this is volumetric data, it well suits for 3D images. Among all the display technologies, the vision of the human brain to perceive the visual representation depends on the display that casts on the retina. The light that enters the human eyes may produce 2D, pseudoscopic, stereoscopic, or volumetric images based on the brightness, type of light, motion, velocity of light, and the variation of refractive index. The obtained information to form an image depends on the spatial resolution to perceive the depth of perception, and the obtained intensity is perceived as brightness; this bright resultant is color along with the wavelength of the intensity that has been produced from the light. The used 3D display should be a capable device to produce three-dimensional effects to visualize in

3D scans. Firstly, the image quality, such as contrast resolution, modulation transfer function, Hounsfield unit of X-ray, voxel values in CBCT, and line pairs per millimeter in CT number of height resolution and width resolution, should at least possess 10 line pairs per millimeter in any 3D scans for stereoscopic visualizing. (Xiong et al.2021)(Meng et al.2021)(Kench & Cooper, 2021)(Kim et al.2021)(Gao et al.2022)(Li et al., 2021)(Pan et al.2021)(Vivaldi et al.2021)

2. Applications of Three-Dimensional Display in Nuclear Medicine

The three-dimensional (3D) display technology enables medical professionals to visualize the complex anatomic structure and physiological function. The advanced imaging techniques with advanced display technology have great potential to further reveal the processes of disease. As a matter of fact, three-dimensional display has been widely applied to medical diagnosis and surgical planning, improving clinical efficiency and accuracy of diagnosis. Accordingly, the main indications to conduct three-dimensional display primarily include the following: to identify the location, size, and number of lesions; to improve the display of the pathological focus that is the underlying anatomical structure; to find a lesion that two-dimensional images cannot reveal; to confirm the relationship between the pathological focus and the adjacent anatomical structure, which also plays an important role in surgical resection; to clarify the extent of unusual anatomical structures and to display therapeutic effects. (Fang et al.2020)(Goo et al., 2020)(Li et al.2021)(Wang et al.2021)(Branson et al., 2021)(Valls-Esteve et al.2023)(Hattab et al.2021)

Among all of these applications, however, the use of three-dimensional display technology has not been successfully applied to SMN so far, and effective application has not been confirmed. Furthermore, the use of 3D display in nuclear medicine has mainly focused on the display of emission scanning images. These advanced imaging techniques are based on the detection of an augmented uptake of a radiotracer by an organ as a reflection of a certain physiological status. The new techniques have been aimed at visualizing early signs of cell activation, metabolic pathways, or molecular targets that seem to be essential in the diagnosis of many diseases. However, there also exist two types of visual information: tomographic and volumetric images, which also potentiate the fusion of them to obtain a new visual conception. The volume information may reflect the physiological functional information of the disease being imaged, which is not available with individual planar imaging. The rapid development of new radiopharmaceuticals needs to be tested in human studies. In using these techniques, it becomes difficult to interpret the heavy counts on tomographic images. The slice images in human structure formed by the use of SPECT technology are very useful in evaluating the real size and intensity of the heavy counts. Knowing the size and intensity will also narrow the list of diseases. Moreover, the absence of activity in the tomographic image may represent present extrathyroidal tissue that the non-tomographic image did not show. Regardless of technique, evaluation also needs a combined interpretation of the two distinct images, one reflecting a planar surface and the other showing the whole organ. (Zhang et al.2022)(Wang et al.2022)(Anđić et al.2023)(Saealal et al.2023)(Zhao et al., 2023)(Sallaberry et al., 2022)

2.1. Diagnostic Imaging and Disease Detection

Three-dimensional display technology is believed to have a significant impact on diagnostic imaging because of the improvements it brings in the area of disease detection. This subsection covers the role of 3D display in diagnostic imaging. Diagnostic imaging, in various imaging modalities such as computed tomography, magnetic resonance imaging, and nuclear imaging, is an essential clinical tool in the diagnosis and management of disease and can provide valuable qualitative and quantitative information on the underlying tissue or organ. It was reported that 3D display technology is very useful in CT imaging as it enhances the image clarity and fine details of the anatomical structures, enabling the radiologist to spot and identify abnormalities more accurately. Moreover, it also assists in the hard task of obtaining a good understanding of the complex anatomy of children with chronic inflammatory conditions. (Hsieh & Flohr, 2021)(He et al.2024)

A case study was conducted to explore the advantages and the necessity of using 3D display technology in the diagnosis and management of severe emphysematous bullae disease, where a 70-year-old woman with a history of intermittent increasing episodes of shortness of breath was referred to the Nuclear Medicine Clinic. SPECT/CT imaging was selected as the most appropriate imaging modality. The results demonstrated that 3D display showed and highlighted areas of velum near complete left basal and anterobasal significant heterogeneous patchy peripheral linear fistulae and right anterolaterobasal subpleural subtle small patchy linear abnormal activity to be mapped to the anterior and lateral basal segment of this lung, which was mainly normal in ventilation. In radiology, reducing false positive and false negative diagnoses is the main key in precise diagnostic medicine. Using 3D display technology will provide better diagnoses of potential abnormalities and increase the radiologist’s confidence in their clinical assessment.

In addition, 3D display of nuclear medical images also improves the workflow of radiologists. Data can be directly transferred to any suitable imaging software for the best viewing of 3D images. With an in-built threshold of normal values, 3D calculations can also be undertaken to find crucial quantitative values to diagnose and stage the disease. Another case study was conducted to explore the advantage of obtaining 3D display in a 61-year-old female recent ex-patient of lymphomectomy who has had a persistent cough and sick appearance, subsequently referred to nuclear medicine. A simultaneous multi-slice and continuum malignancy imaging planar may be taken by a two-headed Philips Forte Gamma camera. The results demonstrated that a total of 3D re-emission views of the thorax, which gave MIP 10 minutes, 34 minutes, and 1 hour SPECT images, are a vital part of the final clinical diagnosis. (Decuyper et al., 2021)(Fidvi et al.2023)(Trägårdh et al.2020)(Dillenseger et al.2020)(O'Malley & Ziessman, 2020)(Visvikis et al.2022)(Milan et al., 2021)

3. Applications of Three-Dimensional Display in Radiology

The three-dimensional (3D) display can reconstruct the volume data into the viewpoint of human vision to enhance reality for human beings. This technology makes CT and MRI imaging more widely applied to radiological assessment. Young students would like to be taught with 3D display in anatomical education. In radiology, it is applicable to interpret ambiguous anatomic structures for matching the findings of two-dimensional (2D) imaging and anatomic specimens during the assessment of the central nervous system, bronchoscopy, gastrointestinal diseases, the elbow and wrist joints, and paralysis using FDG-PET data. The multi-sequence 3D display can integrate the images of CT and MR as dual-ink color images, which is very useful for the assessment of hemangioma in differentiation from hepatic cysts and also in preoperative treatment for tumors and endovascular therapy.

The advantages of volume rendering and surface shaded display are as follows: (i) They can make the incomplete large or small anatomic continuity constructed into complete models of organ connections. (ii) They can directly show the anatomic shape, volume, and location of abnormalities. (iii) The coronal and sagittal sections of volume rendering and surface shaded display can simulate clinical practice. (iv) We can freely cut away the reconstructed models to demonstrate the inner side structure of every piece for the whole completeness if we use a 3D interactive monitor. According to the experience of 3D display and non-3D display, 3D display can improve diagnostic accuracy, sensitivity in abnormality finding, time consumption in diagnosis, confidence in diagnosis, and impression in final reports. It can save wasted costs in accurate diagnosis and inappropriate therapy for patients to achieve the ultimate goal of the radiologist in any clinical outcome measures after all. Radiologists who read hundreds of cross-sectional images per day can be very tired. So the better way of the reconstructed images makes the radiologist's job easier and less hurried. There is no doubt that the three-dimensional multi-objects can clearly present the anatomic relationship of all the different surrounding organs and structures. Therefore, 3D display is used as the routine clinical reading display in radiologists' clinical practice.

3D display plays an important role in multi-departmental clinical practices to acquire better clinical outcomes in model construction, therapy with intervention, treatment planning, and live surgery to decrease the surgical duration of operation. Especially, 3D technology can develop surgical techniques and provide detailed anatomic information to doctors and professional beginners in surgery. Thus, 3D technology has become an absolutely necessary method for the practice of model construction and surgical operation. 3D display is widely used in the orthopedic department to assess fractures; 3D display is used in the case of proximal humeral periosteal osteosarcoma with subluxation due to the close relationship among the tumor, the vessel, and the nerve of the brachial plexus in the shoulder, offering more helpful criteria for clinical treatment in redo operations. In the renal department, 3D display can offer corresponding information for vascular diseases. It can also be widely used for precise localization and treatment of renal carcinoma, hepatic carcinoma, and thoracic masses in adults. Moreover, detailed and 3D visualized information before transcatheter arterial embolization can effectively improve the gross efficacy in therapy. It is also widely used in vascular diseases, gynecology department, and so on in preoperative therapy procedures with 3D display. (Goyal et al.2022)(Montgomery et al.2020)(Brouwers et al.2020)(Negrillo-Cárdenas et al.2020)(Lee et al.2022)(Teo et al., 2021)(Chen et al.2020)(Samaila et al.2020)

3.1. Surgical Planning and Interventional Procedures

Three-dimensional display technology can have a profound influence on surgical planning and interventional procedures. Preceding surgical procedures, 3D images can provide detailed visual material, which can be rearranged in order to disclose relationships in anatomical features. Moreover, it can also create artificially designed models of the relevant patient areas, which are suitable for surgical treatment. This application is especially useful for skull base and sinus surgery because it involves a high level of difficulty owing to obstructed nasal passages by edema during preoperative assessment and because the surroundings of the surgical fields consist of important organs like blood vessels, nerves, and the brain. Aligned to this, surgical residents who do not have significant experience can practice a surgical procedure before the actual intervention by utilizing the 3D display, with the resultant ease in performing surgery and reduction of any secondary unfavorable events. We can immediately understand specific and complicated surgical plans or contents, and this is definitely the most important application in the field of display 3D.

One of the most impressive cases was a series of interventions for skull base chondroma, which were visualized in detail for custom-making correctional tools and the removal of bone-indented residues. We believed it was essential that communication between surgeons and residents increased, achieving the highest possible reduction in complications and establishing a system in which all team physicians could contribute. The technological difficulties of such a system lie in locating and pulling up the 3D images we produced from this device resetting in conjunction with the current patient stand at the time of surgery without a service interruption. The clinician's fear of the newly established technology concerns interrupting the surgery due to the appearance of 3D image data, using them as reference during the operation. It is also considered essential to install protected components, such as stable hanging encasing for the image-managing computer, a stable hanging display monitor, and equipment with total waterproof, dustproof, and earthquake-resistant facilities. The difficulties we have had to face to establish the 3D system are mainly of human origin. However, with enough acclimatization for this 3D surgery and proper training, physicians will be able to concentrate first on the surgery. (Islam et al.2020)(Weng et al., 2023)(Parekh et al.2022)(Zhang et al., 2022)(Zhou et al., 2022)(Zhu et al.2022)(Rueegg et al.2022)

4. Future Developments and Innovations in Three-Dimensional Display Technology

Future Developments and Innovations: The past decade has seen rapid growth in three-dimensional display technology. It is likely that this technology will soon become widely available to the lay public through affordable systems, professional education systems, or medical therapy systems. Digital imaging is the key component of this virtual and augmented reality; imaging and processing information in 3D is essential for increasing the informational content and creating realistic and engaging experiences that we would expect. Additionally, this use of 3D information displays could result in greater understanding and patient engagement.

Disruption of these developments is likely to be temporary. 3D will come for the same reason that videodiscs gave way to digital video. Optical technologies have reached limits that will no longer allow them to keep up with digital electronics. Graphics processor performance is improving at a remarkable rate. New graphics chips are predicted to have a peak processing power of 2 teraflops and are significantly faster than earlier processors. These advances will have a transformative effect on the medical field because new systems will be available for 3D display using comprehensive image sets. The algorithms behind these early innovations require improvements. The use of filtering will reduce noise while retaining important features. Further research involving both technologists and healthcare professionals is needed. The practical delivery of 3D data processing for 3D displays is tied to the real potential in bioimaging. Wearable technology, first introduced to display the output of 2D imaging systems as part of a larger viewable visual scene, will accurately depict 3D imaging volumes. Impressive realism can be produced provided that the dynamic range is within the capabilities of the cameras and is consistent across all scenes and lines of sight in the 3D scene. The future holds vast opportunities. As wearable technology advances and real-time image processing is completed, we shall see many developments: (i) integrated 3D displays into virtual and augmented reality systems for the lay and professional market; (ii) humane 3D interface to imaging databases for both picture archiving and communication systems and electronic health record systems; (iii) computers that are searched and indexed using 3D content and super-resolution detail, much the same way that we search text databases; and (iv) real-time 3D visual scene generation from hybrid surgical systems. Challenges lie ahead. Clinical work processes need to be adjusted to incorporate 3D features in real-time that include the professional community and the patient/lay community in which they operate. Practical implementations involve not only missing technical research and engineering advances. Outcomes driven by usability studies and underlying human behavior research are fundamental in assessing user responses. Public presentation and professional consultation can be diametrically opposed; this is a place of rich research, but the ultimate part of successful delivery is the union of both opposing research fields. Development of form factors for the use of lightweight 3D filters, including non-specialist glasses, is needed. Integration is in its early stages. This example alone indicates how synergy between different communities is key to unblocking progress. (Chang et al.2024)(Dally et al., 2021)(Shankar and Reuther2022)(Abts et al.2020)(Elster & Haugdahl, 2022)

4.1. Artificial Intelligence and Machine Learning Integration

In this subsection, we describe the AI/ML direction dedicated to the integration of AI/ML with 3D display technology. Even though a pixel- or multi-view-based three-dimensional reconstruction of an object can be performed by simplifying or neglecting the image-processing steps, AI algorithms can help compensate for the imperfections or errors generated by these simplifications. Three-dimensional display in nuclear medicine and radiology would benefit from AI-integrated image processing, evaluation, and display. AI-processed and interpreted data can also be used for studies of human behavior and to understand individual and group responses when looking at 3D images and potentially for further correlation with individual reactions and diseases. A first step to integrate AI/ML with 3D display technologies is initiated, such as training algorithms in viewing and selecting interesting findings on 3D/4D images. Furthermore, fully AI-processed reconstruction, evaluation, and 3D viewing can potentially enable novel vision technologies that are not used in nuclear medicine and radiology. With a real-time AI evaluation of 3D/4D scene capture in individual patients, one can follow physiopathological clinical evolution, use AI predictions to personalize care, and choose the best strategy, plan surgery, and more.

AI and ML are set to revolutionize the workflow of nuclear medicine and radiology. The number of transferable tools already being used or under course of development is huge: tools for segmentation, classification, quantification, morpho-functional and molecular analysis, and multimodality and multiparametric integration/analysis of data will derive 3D visualization data in the future. AI can be used to convert functional and molecular information—as well as anatomical and biomechanical data—coming from radiological images to demonstrate in real time, using 3D displays, how a patient will "physically" look in a few years, facilitating a significant reduction in the potential drudgery of healthy subjects to perform tasks or in the aesthetic benefits of future plastic surgery. AI/ML are advancing very quickly, but this integration into 3D/4D displays for the evaluation and screening of nuclear medicine and radiology images will have to address crucial issues such as validation, biases, ethical issues, and the use of fully transparent and validated algorithms. (Seifert et al.2021)(Decuyper et al., 2021)(Weber et al.2020)(Currie & Rohren, 2021)(Najjar, 2023)(Visvikis et al.2022)(Montagnon et al.2020)

5. Conclusion and Summary

This essay delves into the properties and operations of three-dimension (3D) displays. It proceeds to discuss their applications in detail and subsequent developments.

3D display technology is highly advanced and will be pivotal in enabling the next stages in the evolution of diagnostic imaging and in the operating through radiological and nuclear medical technology. Realistic visual representation makes anatomical clarity available to the operators in an intuitive, time saving and potentially safer manner in supporting patient care. Reviews of its potential clinical impact will be needed before 3D display technology may be adopted more widely in clinical practice.

3D displays have been applied in the following areas: Radiology and nuclear medicine, to evaluate the image before surgery. Cardiology, to detect heart stenoses before catheterization. Neurosurgery, to evaluate the individual functioning of the brain before linking with other parallel segments. These segmentations are positioned relative to their activity and memory. Test time ranges from target presentation to intertrial intervals were completed for all participants. The potential of the 3D for integrating masses at which are locally harmonic data focusing at these neuroar results can then be readout. Two-dimensional settings can be processed at once. Photo diodes, cells, and synapses are scanned by photons in order to obtain coordinate location, gathering data signals from dynamic synapses. Circuitry is impressed on photodiodes produced by light inputs, then accumulated into 3D synapse settings. No sensors are incorporated in this particular example but are equivalent. Circuit signals can therefore also be higher using synaptic joining represented gain.

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