How 3D immersive visualization is changing medical diagnostics

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ABSTRACT

Originally the only way to look inside the human body without opening it up was by means of two dimensional (2D) images obtained using X-ray equipment. The fact that human anatomy is inherently three dimensional leads to ambiguities in interpretation and problems of occlusion. Three dimensional (3D) imaging modalities such as CT, MRI and 3D ultrasound remove these drawbacks and are now part of routine medical care. While most hospitals 'have gone digital', meaning that the images are no longer printed on film, they are still being viewed on 2D screens. However, this way valuable depth information is lost, and some interactions become unnecessarily complex or even unfeasible. Using a virtual reality (VR) system to present volumetric data means that depth information is presented to the viewer and 3D interaction is made possible. At the Erasmus MC we have developed V-Scope, an immersive volume visualization system for visualizing a variety of (bio-)medical volumetric datasets, ranging from 3D ultrasound, via CT and MRI, to confocal microscopy, OPT and 3D electron-microscopy data. In this talk we will address the advantages of such a system for both medical diagnostics as well as for (bio)medical research.

Keywords: Virtual reality, volume rendering, medical imaging, immersive visualization, stereoscopic displays.

1. INTRODUCTION

For most of human history the only way to obtain information on what was inside the human body, was to open it up. Understandably not much was known about the functioning of the human body until scientist began to experiment on living animals in the 16th century. Even today clinicians are loath to perform surgery just to be able to come up with a diagnosis. Therefore the discovery of X-rays in 1895 and their application to view inside the human body was an enormous step forward in the history of medicine. However, as the inherently three dimensional human body is reduced to two dimensions by this process, the regular X-ray image suffers from problems of ambiguity and occlusion. Modern three dimensional imaging equipment such as Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) scanner overcome these problems by creating a fully three dimensional, so-called volumetric image of the human body. This three dimensional volumes however, are generally still reviewed in a slice-wise manner, although nowadays most hospitals use computer equipment (PCs or workstations) instead of film and light boxes. Occasionally 3D reconstructions are made using volume rendering techniques, but in the end these are still being viewed on a 2D medium. Although a trained radiologist can obtain a wealth of information using these techniques, the data is presented in a way that is far from intuitive, information is lost, and the interaction with data on a 2D computer screen is completely different from the way surgeons and other clinicians interact with the human body.

1.1 3D displays

While the world in which we live is three dimensional, and the human visual system allows us to perceive all three dimensions, almost all depictions of the world made by us are two dimensional. The principle of stereoscopic vision, by which depth information is obtained from the two slightly different images each eye receives simultaneously from the same object, was discovered in 280 A.D. by Euclid. And while Leonardo da Vinci studied depth and unlike most contemporaries showed an understanding of shading, texture and viewpoint projection, it was Giovanni Battista dela Porta who around the year 1600 produced the first binocular drawings. The word ‘stereoscopique’ was coined in 1613 by the Jesuit Francois d'Aguillio.

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Human Vision and Electronic Imaging XVI, edited by Bernice E. Rogowitz, Thrasyvoulos N. Pappas,
Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 7865, 786503 · © 2011 SPIE-IS&T
CCC code: 0277-786X/11/$18 · doi: 10.1117/12.881511

In 1833 Sir Charles Wheatstone invented the first stereoscopic display system and at the World's Fair in London in 1851 stereoscopes were a big hit with the enthusiastic attendees. The first 3D movie was demonstrated to the public in 1893. Various types of 3D computer displays have been around since the 1980s, ranging from shutter glasses and lenticular screens to head mounted displays (HMDs) and fully immersive projection based systems such as the CAVE™ [1]. Still, 2D images (drawings, paintings, photographs, movies, television and computer displays) are the norm in medicine today as they are in everyday life.

Nevertheless a number of 3D display systems have been used, and some even commercialized for medical applications, ranging from simple auto-stereoscopic (lenticular) LCD panels, to special purpose hardware such as the Dextroscope [2], which is specifically aimed at neurosurgical procedures. Virtual reality type display systems like HMDs and CAVEs have been used for various types of psychotherapy, for instance in the treatment of vertigo and various other phobias.

1.2 Volume rendering

Ever since Levoy's seminal paper "Display of surfaces from volume data" [3] direct volume rendering has been associated with medical data. This is illustrated by the fact that many technical papers on volume rendering contain one or more images of a volume rendered MRI scan of the brain. They usually show the cerebral cortex, which is remarkable considering that there are very few cases in which a clinician would find such an image useful. As mentioned earlier, almost all medical diagnoses made by radiologists are done by reviewing the volume data in a slice-wise manner. There are several reasons for this.

First of all radiology has a history of 2D diagnosis, as the field started off with 2D X-rays, which were the standard for many years, and for some applications still are today. This can also be observed by the DICOM standard, which is used by scanners and PACS systems to communicate and store medical imaging data. The DICOM standard treats 3D datasets as collections (series) of individual slices, instead of as a single entity. Secondly, in order to reduce radiation dose (in case of CT) and scanning time (in case of MRI) up until recently most scanning protocols used too few slices to allow high quality 3D reconstructions to be made. Thirdly, humans in general resent change, especially when this change threatens their job security. While CT and MRI scans are traditionally examined by radiologists, ultrasound images are frequently viewed directly by the clinician who is providing the bedside care, e.g. a gynecologist or cardiologist. These two medical fields are therefore a notable exception, as they over the last decade they have started to routinely use volume renderings of 3D ultrasound data to study the heart and the embryo or fetus.

1.3 Combining the two: immersive volume rendering

Given the overall limited use of volume rendering in the medical field, it is not surprising that the use of 3D display systems for volume rendering has been restricted to certain niche applications, such as neurosurgery. Nevertheless research has shown that the use of 3D display technology can aid in the interpretation of 3D structures and six degree-of-freedom (DOF) manipulation makes interaction feasible that is too complex or time-consuming when limited to the 2D world of a regular mouse and computer screen. When the Dutch national super computing center SARA acquired a fully immersive CAVE™ virtual reality system in the late 1990s, the author was hired as consultant in order to aid both academic and commercial customers of SARA in using the system. Having completed a Ph.D. thesis on the use of parallel computers to speed up volume rendering, the CAVE™ and the SGI Onyx2 InfiniteReality graphical supercomputer driving it seemed like an ideal instrument to interactively explore volumetric datasets.

As the first CAVE™ system was shown to the public at SIGGRAPH '93, a few public domain implementations of volume rendering algorithms for immersive virtual reality systems already existed at that time: notably Crumbs [4] and VRen [5]. As both did not meet our requirements, a new application, dubbed CAVORE (short for CAVE™ Volume Renderer) was developed [6]. Over the years at SARA CAVORE has been used to visualize and explore a wide variety of volume data, both from the medical field as well as from others, such as seismic data from the oil and gas industry. While researchers and clinicians from local hospitals showed an interest in this new development, the use of the CAVE™ for medical visualization stayed limited to a few proof-of-concept projects. In addition to those described in the previous section, the most important reason (as given by the participating clinicians) for this being the fact that the CAVE was located on the university campus, and not in the hospital itself.

When in 2003 Erasmus MC University Medical Center in Rotterdam founded a new Bioinformatics department, and the newly appointed head of the department, Peter van der Spek, unfolded his plans to have a CAVE™-like VR system installed, this seemed like the ideal opportunity to bring immersive volume visualization to the clinicians.

2. APPLICATIONS OF IMMERSIVE VOLUME RENDERING

Starting off with SARA's CAVORE application in the new Erasmus MC I-Space, as Barco's (Kuurne, Belgium) implementation of the CAVE™ is called, we quickly attracted the attention of various researchers and clinicians. Among the first to bring data into the I-Space were the departments of gynecology and obstetrics, cardiology, pulmonary disease, neurology, neurosurgery and the department of radiology of the adjacent Sophia Children's hospital. Some of these 'projects' were limited to providing a kind of second opinion on a single patient, while others tried to establish the benefits of immersive volume rendering by examining small cohorts of patients.

The first scientific 'discovery' came when examining prenatal ultrasound images of a meningomyelocele, a rare birth defect where the spine of a fetus hasn't closed completely, and there is a 'pouch' attached to the back containing nerve endings [7]. The I-Space images showed these nerve endings for the first time. Another example of these new insights was the session in which a terminally ill 28 year old lung cancer patient was able to view her own CT scan. She noticed that the very large tumor (more than one liter in volume) was infiltrating the ribcage, a fact that she wasn't aware of at the time. Now she understood the pain in her side she had been feeling lately.

2.1 Cardiology

The department of cardiology was also one of the early adopters, and after some initial trials started an evaluation of the I-Space for visualizing 3D echocardiography (i.e. ultrasound) data. Unlike most prenatal ultrasound, cardiologists use time series to visualize the beating heart. In this study six such datasets, two normal and four with different forms of mitral valve pathology were examined by ten observers (5 cardiologists, 3 cardiologists-in-training and 2 cardiothoracic surgeons) [8]. The observers were each given 10 minutes training in orienting the dataset and using the 6 DOF virtual pointer to make cut planes (clipping away part of the dataset to view inside). All 10 observers were able to correctly assess normal and pathological mitral valves, with an average analysis time of around 10 minutes, which is similar to the time that would be needed using a traditional workstation. This study showed that very little training is needed to use an immersive volume rendering system and that it can be used to correctly asses heart pathology.

A second study also performed by the department of cardiology, focused on the question whether details that may be missed on ordinary displays, are visible in the I-Space [9]. To this end a postoperative analysis of tricuspid valve functionality after surgical closure of a ventricular septal defect was performed both on the ultrasound machine, using an ordinary 2D screen, as well as in the I-Space. Twelve datasets from intraoperative epicardial echocardiography studies in five different operations were used in the analysis. Based on the 2D analysis none of the datasets showed tricuspid valve stenosis or regurgitation, and valve leaflet mobility was considered normal in all cases. However, when studied in the I-Space, three datasets (in three different patients) showed a restriction of the mobility of the septal valve leaflet (the tricuspid valve has three leaflets hence its name), that was not appreciated in the 2D analyses. Although the numbers are small, the fact that in three out of five cases details could be visualized that were missed in the routine procedure, clearly proves the additional value of using a 3D display system.

2.2 Obstetrics and gynecology

The department of obstetrics and gynecology performed a number of trials examining different types of 3D ultrasound data. One of these trials showed that in four cases of ambiguous genitalia, visualization in the I-Space would lead to a correct diagnosis, while 2D and 3D ultrasound examination had provided a incorrect classification in three of the cases [10]. It was decided to start a Ph.D. project focusing on data from early pregnancies (starting from 6 weeks gestational age - GA, actually 4 weeks after conception - untill 12 weeks GA). In order to validate this new technology we decided to concentrate on normal pregnancies first in order to establish some form of baseline measurements. Crown-Rump-Length measurements, also known as greatest length measurements, are the golden standard to determine the gestational age of an embryo, and are performed routinely with 2D ultrasound equipment. We compared I-Space length measurements and measurements performed on a PC with specialized 3D ultrasound software (4DView), with the golden standard 2D measurements that were originally obtained on the ultrasound machine for a total of 28 patients [11]. Both methods showed very high correlation with the standard 2D measurements, with Intraclass Correlation Coefficients (ICCs) of at least 0.92, but on average 0.98 to 0.99. Inter- and intraobserver ICCs also were in the same range for both methods.

At the same time we validated the visualization methods by assigning so-called Carnegie-stages, which describe embryonic development, based on the external morphological characteristics of the embryo, and comparing these stages with the known gestational age [12]. We found that we could accurately determine these Carnegie-stages using the I-

Space with little effort, while it would take a very skilled observer using normal 3D ultrasound, and is considered almost impossible using only 2D ultrasound.

Having established the validity of length measurements in the I-Space cleared the way for a number of studies on first trimester embryonic growth. We expanded our patient cohort and constructed new first trimester growth charts based on 125 datasets from 32 different normal pregnancies [13]. We also conducted umbilical cord and vitelline duct measurements in the same cohort [14]. The next step was to implement some form of volume measurement, as we suspected that certain aspects of embryonic growth could be more accurately studied using volumetry. By this time we did a full reimplementation of our volume rendering application, to allow more complex visualizations and interactions. Semi-automatic volume measurements with the new V-Scope application [15] were first validated ‘in vitro’ using phantoms consisting of water filled balloons with known volumes [16]. The method was also tested ‘in vivo’ by measuring yolk sac volumes and comparing the results with a manual volume measuring method implemented in the specialized 3D PC software we also used for the length measurements. We used the volume measuring method to expand our first trimester growth charts with embryonic volume measurements [17].

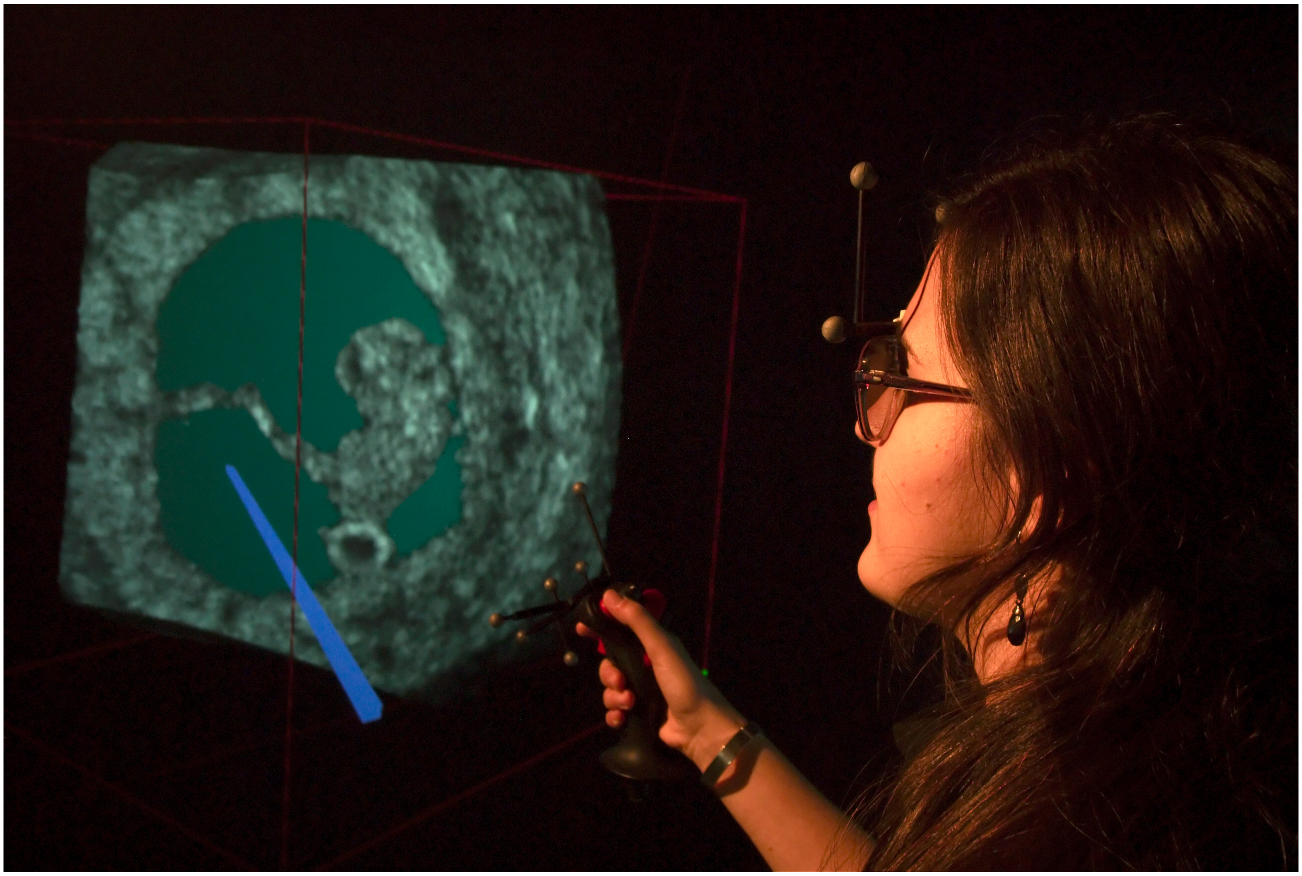

Figure 1. A researcher is performing semi-automatic gestational sac volume measurements on 3D ultrasound data using the V-Scope immersive volume rendering application. An embryo can be seen in the center of the volume.

Currently numerous other projects have been started, ranging from charting first trimester brain development to linking environmental factors to first trimester embryonic growth and development (figure 1). We have also started investigations into early diagnosis of rare birth defects in the first trimester using the I-Space and are studying the pelvic floor muscles, which are frequently damaged during child birth.

2.3 Other applications

As can be gathered from the previous sections a major part of the research using the I-Space focuses on ultrasound data from the fields of cardiology and obstetrics/gynecology. This seems in concordance with the observation that these fields are also the ones who have been using volume rendering techniques on a routine basis. Nevertheless, we also conducted a number of projects using either CT or MRI data. One of the first projects in this category investigated the value of using the I-Space to localize epileptigenic malformations in MRI scans of the brain. An experienced pediatric neuro-radiologist and a medical student both evaluated 21 MRI scans for malformations that could lead to epileptic seizures. In half of the cases were the MRI was considered normal during the regular (2D) examination, a malformation could be found using the I-Space. The medical student performed the evaluations twice, first prior to training by the neuro-radiologist, and again after receiving training. Both observers were blinded with regards to patient data and each others results. Datasets were presented in a random order as well. After training the Cohen's Kappa score for agreement between the student and the expert was 0.5, showing fair to good agreement between the observers and proving even a relatively inexperienced observer can obtain significant results using the I-Space.

The I-Space can also be used to aid in 2D measurements, as we did in a project with the department of Plastic and Reconstructive Surgery. They were faced with the problem of validating skull shape measurements of children with cranial deformities obtained with a thermoplastic ring against the golden standard of CT images [JCFS]. CT scans were obtained of patients wearing the plastic rings, but while the rings were visible, markers placed on the rings according to anatomical landmarks were not, and this proved to be a problem in the data analysis. We used the I-Space to virtually replace the markers and obtain 2D slices in which these markers were visible. The slices were then used for further 2D analysis.

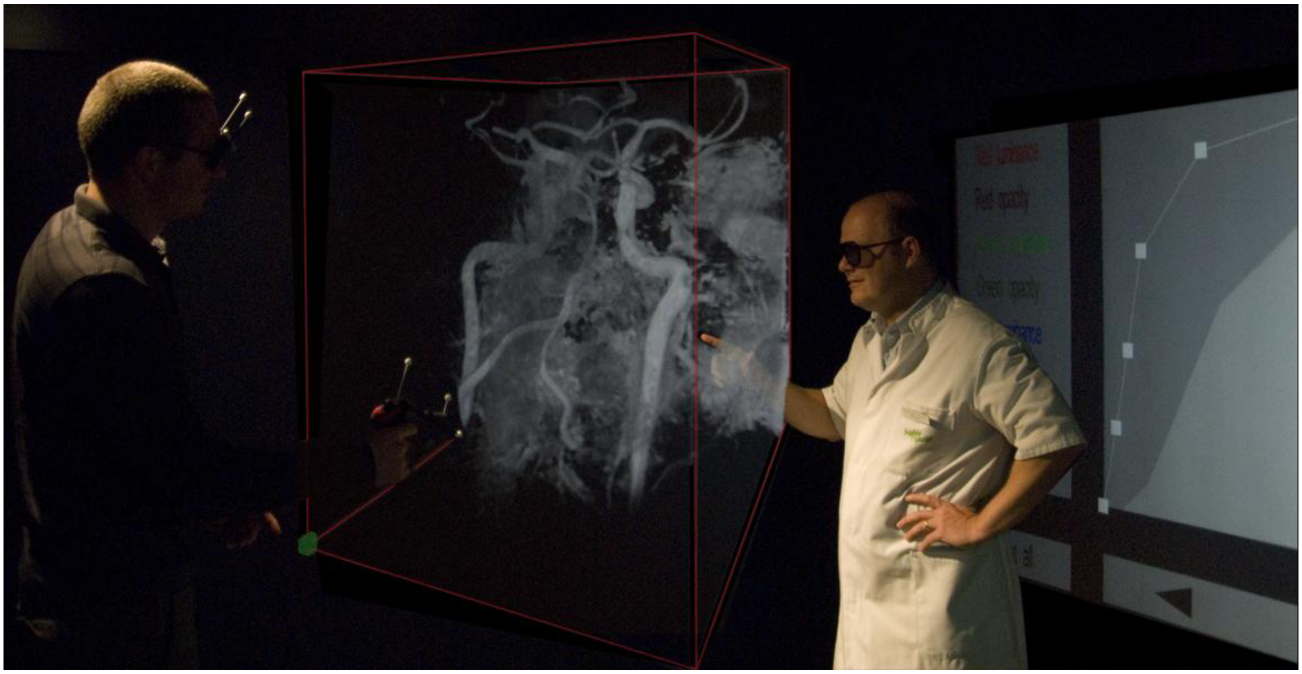

Figure 2. Carotid arteries as imaged with a 7 Tesla MRI scanner are being visualized in the Erasmus MC I-Space.

A number of other projects and single case studies have been performed in the I-Space using CT, MRI (figure 2) and ultrasound data, including, but not limited to the planning of complex neurosurgical operations, evaluation of cruciate ligament reconstructions and patient education in cases of pediatric stroke. We plan to start a project studying breast cancer using MRI scans in the near future. Also worth mentioning are the projects we are involved in using an Optical Projection Tomography scanner to obtain high-resolution volumetric data of whole mount embryo or tissue samples, ranging in size from 1mm to 1cm. The I-Space is an ideal tool to examine these large (up to 1 Gigavoxel) datasets. In general these samples are stained using visible or fluorescent anti-bodies to show specific RNA or protein expression. The first publication in this area describes the use of the OPT scanner and I-Space to study the development of blood vessels in the placenta [18]. We have, among other applications, also used the OPT to study brain development in zebrafish and heart development in chicken embryos.

3. DISCUSSION AND FUTURE PERSPECTIVES

Our research projects show that the I-Space can be used to obtain reliable measurements, many of which are not feasible when using 2D display and interaction systems. In addition details that are missed when examining the data on 2D displays may be seen as a result of the depth perception the system offers. The greatest drawback of a fully immersive VR system like the I-Space, is the fact that because of its size and cost, it generally will be a centralized facility, meaning people have to change their regular workflow and get out of their office to use it. The most frequently heard question therefore is: “Can I have one on my desk?” Because of this we have developed a desktop version of the V-Scope application, that will run on a ordinary PC, and uses a 3D LCD flat panel display as well as a 6 DOF tracking system and 6 DOF mouse. The 3D LCD flat panel monitor uses a polarizing screen, that although it requires the user to wear lightweight stereo glasses, offers stereoscopic vision in a wide horizontal viewing angle at a high resolution. The 6 DOF tracking system is used to track a pointing device to interact with the data, while the 6 DOF mouse can be used simultaneously to orient the dataset. As the desktop system allows the same interaction with the data as the fully immersive version, but uses a single 24 inch screen instead of the four 128 inch screens of the I-Space, we will have to compare the two systems with regard to precision, easy of use and ability to observe detail.

As hinted at in the introduction, although 3D display systems have been available for many years, none have gained wide acceptance in the medical community for the display and evaluation of imaging data. A search of PubMed, the online database containing titles and abstracts for almost all papers published in the medical field, for “virtual reality” comes up with surprisingly few hits (only 3244 out of 20 million articles, “ct imaging” for example returns 59178 hits), most of which involve either psychotherapy or simulation/training. However our research shows that 3D systems have a number of significant benefits over 2D systems when studying 3D imaging data. Now 3D movies and even 3D televisions are starting to catch on and people are becoming more familiar with 3D display technology, it is expected that its acceptance in the medical world will increase. However, this also means that significant changes in the field of radiology will have to take place in order to complete the paradigm shift from 2D to 3D. Judging from the comments our papers generally get from reviewers with a background in radiology, this will require a lot of effort from both computer scientists as well as their fellow medical professionals.

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