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Virtual Endoscopy and 3D Volume Rendering in the Management of Frontal Sinus Fractures

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A B S T R A C T

Frontal sinus fractures (FSF) are commonly caused by traffic accidents, assaults, industrial accidents and gunshot wounds. Classical roentgenography has high proportion of false negative findings in cases of FSF and is not particularly useful in examining the severity of damage to the frontal sinus posterior table and the nasofrontal duct region. High resolution computed tomography was inavoidable during the management of such patients but it may produce large quantity of 2D images. Postprocessing of datasets acquired by high resolution computer tomography from patients with severe head trauma may offer a valuable additional help in diagnostics and surgery planning. We performed virtual endoscopy (VE) and 3D volume rendering (3DVR) on high resolution CT data acquired from a 54-year-old man with with both anterior and posterior frontal sinus wall fracture in order to demonstrate advantages and disadvantages of these methods. Data acquisition was done by Siemens Somatom Emotion scanner and postprocessing was performed with Syngo 2006G software. VE and 3DVR were performed in a man who suffered blunt trauma to his forehead and nose in an traffic accident. Left frontal sinus anterior wall fracture without dislocation and fracture of tabula interna with dislocation were found. 3D position and orientation of fracture lines were shown in by 3D rendering software. We concluded that VE and 3DVR can clearly display the anatomic structure of the paranasal sinuses and nasopharyngeal cavity, revealing damage to the sinus wall caused by a fracture and its relationship to surrounding anatomical structures.

Key words: *frontal sinus fractures, high resolution computer tomography, virtual endoscopy, 3D volume rendering*

Introduction

The frontal sinus is situated in the frontal bone. It develops from anterosuperior ethmoidal cells in the area of the frontal recess. Pneumatization of the frontal sinus is variable. In 4% to 15% of the population, a developmental failure of one of the frontal sinuses is present[1].

One of the frontal sinus functions is to absorb shock to the head. The anterior wall is the strongest of the frontal sinus walls and is twice as thick as the posterior wall[2,3]. Its posterior wall forms the anterior limit of the anterior cranial base. The floor of the sinus also functions as the supraorbital roof, and the drainage ostium is located in the posteromedial portion of the sinus floor[1].

Any fracture of the frontal bone carries the risk of an associated injury of the frontal sinus. Twelve percent of facial fractures, excluding mandibular and nasal fractures, are fractures of the frontal sinus. Frontal and ethmoidal involvement occur among 15% of patients with head injuries. Men and boys are injured more frequently than women and girls. The incidence of fractures of the frontal sinus is greatest in the third decade of life, although the fractures occur at any age. Motor vehicle accidents are the most common cause. Fractures of the frontal sinus can be complicated by meningitis and brain abscess. Frontal sinus fractures can be classified into fractures of the anterior table, the posterior table, or both. Isolated fractures of the posterior table are rare.

Classical roentgenography can result in underdiagnosis of frontal sinus fractures and is not particularly useful in examining the severity of damage to the frontal sinus posterior table and the nasofrontal duct region[4]. CT scanning is critical for the direct evaluation of the walls of the sinus. The scans also will provide indirect ev-

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idence of damage to frontonasal orifices that might lead to chronic obstruction of sinus drainage. Fractures of paranasal sinus or temporal bone were often misdiagnosed in polytraumas due to management of life threatening injuries. Nasofrontal duct injuries are the most difficult to diagnose and may not be visualized even on CT scan. The presence of persistent fluid level in the frontal sinus is a reliable sign of a nasofrontal duct injury. The appliance of high resolution computed tomography (HRCT) with computer generated frontal and coronal reconstructions has signifincantly improved diagnostics of frontal sinus fractures therefore HRCT was inavoidable in the management of patients with head traumas in current clinical practice.

The fractures may be simple, comminuted, displaced, or nondisplaced. Displacement of anterior table fragments, especially when through the inferior and/or base half of the sinus, can cause obstruction of the nasofrontal duct[5]. Displacement of the anterior table can also lead to depression of the forehead and a cosmetic deformity.

Virtual endoscopy (VE) and 3D volume rendering (3DVR) based on HRCT data may provide valuable additional information to head and neck surgeon or neurosurgeon during initial or preoperative management of such patients[6–8]. 3DVR and VE may also help in efforts to decrease rate of misdiagnosed frontal sinus fractures.

VE allows simulated three-dimensional (3-D) visualization of anatomical structures by computerized reconstruction of radiological images. VE turns out to be a promising technique to improve, or even in some procedures substitute, real endoscopy[6,7].

VE is a new method of diagnosis using computer processing of 3D image datasets (such as CT or MRI scans) to provide simulated visualizations of patient specific organs similar or equivalent to those produced by standard endoscopic procedures. VE is applied to explore hollow organs and anatomical cavities[9–11]. VE derives principally from digital medical imaging, and in particular from visualization of 3D CT and MRI datasets. A number of investigators have been working in this field. Some of the earliest work was published by Vining[12], Robb[9], Hara and Johnson[13] and Knezović[14]. VE is a method which produces very clear images. It is reliable to provide detailed information for optimal operative planning[15–18].

Three-dimensional (3D) medical images of computed tomographic data sets can be generated with a variety of computer algorithms. The three most commonly used techniques are shaded surface display, maximum intensity projection, and, more recently, 3D volume rendering (3DVR)[15]. Implementation of 3DVR involves volume data management, which relates to operations including acquisition, resampling, and editing of the data set; rendering parameters including window width and level, opacity, brightness, and percentage classification; and image display, which comprises techniques such as »fly-through« and »fly-around«, multiple-view display, obscured structure and shading depth cues, and kinetic and stereo depth cues. An understanding of both the theory and method of 3DVR is essential for accurate evaluation of the resulting images[15]. Volume rendering is a flexible, accurate 3D imaging technique that can help the radiologist or head and neck surgeon to more effectively interpret the large volumes of data generated by modern CT scanners. To obtain accurate results, however, the clinician must understand the effect of parameter selection on the resulting image. 3D volume rendering takes the entire volume of data, sums the contributions of each voxel along a line from the viewer's eye through the data set, and displays the resulting composite for each pixel of the display. Incorporation of information from the entire volume can lead to greater fidelity to the data; however, much more powerful computers are required to perform volume rendering at a reasonable speed[15].

VE and 3DVR can clearly display the anatomic structure of the paranasal sinuses, nasopharyngeal cavity and upper respiratory tract, revealing damage to the sinus wall caused by a fracture. VE and 3DVR also allows structural visualization with unconventional angles, perspectives, and locations not conventionally accessible[19].

Subject and Methods

High resolution helical CT (HRCT) was done in 54--year-old man with a history of forehead blunt trauma. Three-dimensional information obtained from HRCT data was used to explore and evaluate the nasal cavity and paranasal sinuses by simulated virtual endoscopy and 3D volume rendering. Thin-section helical CT was performed on a conventional CT scanner. Our goal was to demonstrate and evaluate benefits or shortcomings of 3DVR and VE in the management of frontal sinus fractures. Siemens Somatom Emotion 16 CT scanner was used for image acquisition. CT images were stored in DICOM format and transferred to Xeon-based workstation running standard postprocessing software 3D Syngo CT 2006G. Working area during fly-through was divided in four windows showing CT image reconstruction in three major planes and resulting 3D rendered virtual endoscopic view for current position of virtual endocamera. Key perspectives were selected, and a video »flight« model was choreographed and synthesized through the nasal cavity and sinuses based on the HRCT data. Initial postprocessing was performed by one radiologist and one ENT specialist.

Virtual endoscopy on the Syngo platform is performed using ray casting method with space leaping as major acceleration technique. 3DVR was performed by appropriate module of Syngo software platform.

Results

A 54-year-old man sustained blunt trauma to his forehead and nose in an traffic accident. He fell down from motocycle and at the first moment he did not visit a doctor. After a certain time period one grand mal epilepsy attack had occured therefore he was admitted to the hospital. He was initially examined by neurologist and general surgeon.

Fig 1. Dual Xeon Fujitsu-Siemens workstation equipped with HRCT data postprocessing software Syngo 3D 2006G.

Fig 3. Soft tissue oedema in the forehead of a 54-year-old man with both anterior and posterior frontal sinus wall fracture after a blunt trauma.

Standard plane X-ray examination was performed but its result was false negative since it was incapable to reveal frontal sinus fracture. Helical high resolution multislice CT of paranasal sinuses was performed and it was revealed fractures of both anterior and posterior wall of the left frontal sinus. 3D volume rendering was done and it showed fracture of posterior wall with moderate dislocation, as well as fracture of anterior wall of left maxillary sinus without dislocation. Virtual endoscopy was also performed and it revealed polypoid mass and thickened mucosa on the place of posterior frontal sinus wall fracture.

Our patient underwent final treatment on ENT clinic, with good outcome and no further complications. We showed the most important advantages of virtual endoscopy and 3D volume rendering: VE and 3DVR can clearly display the anatomic structure of the paranasal sinuses and nasopharyngeal cavity, revealing damage to the sinus wall caused by a fracture and its relationship to surrounding anatomical structures. VE and 3DVR are non-invasive, they may provide views from different angles and in comparison with classic sinus endoscopy there is no risk of complications. The same procedure may be repeated several times without discomfort for patients.

Since 3D images are easier for understanding and surgery planning than series of several hundreds 2D MSCT images, the whole process of patient management is improved. Educational value for residents and inexperienced surgeons is also important. We found Syngo 3D platform for postprocessing CT data easy to use and our 3DVR generated images and fly-through were of good quality with acceptable frame rate. Our generated im-

Fig 2. Figure presents 3DVR generated image that reveals fracture line on frontal sinus anterior wall in a 54-year-old man who suffered blunt forehead trauma. Significant bone dislocation was not found.

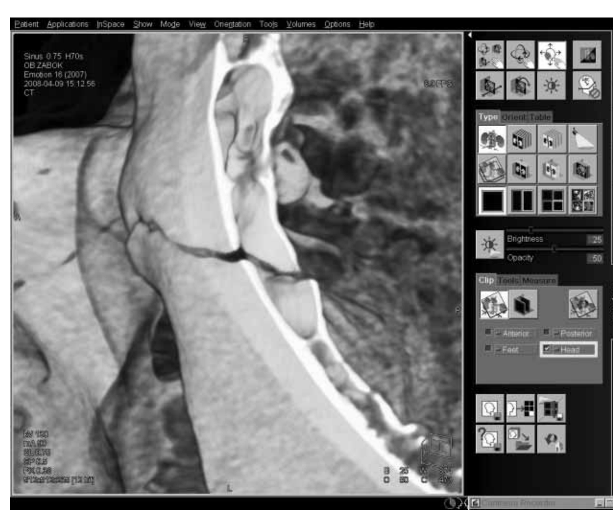

Fig 4. 3DVR visualization of fracture line and bone dislocation on both anterior and posterior wall of the left frontal sinus. Rotation, zooming or volume clipping is possible in real time with acceptable processing rate.

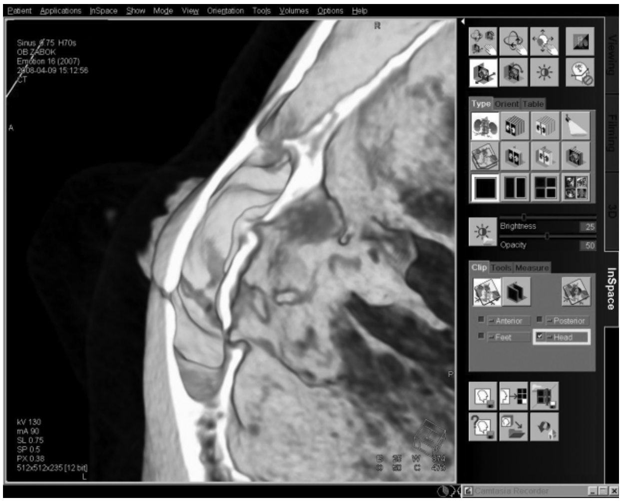

Fig 5. Volume rotation was done in order to present relationship of fracture lines to the entire left frontal sinus cavity as well as surrounding anatomical structures. Clinician may perform interactive volume clipping in all planes using mouse pointing device. Volume clipping reveals position of fracture lines on posterior frontal sinus wall and dislocated bony fragment.

ages and system accuracy were comparable or even better than those generated on other software platforms of similar purpose and described by other investigators.

Discussion

Patients with frontal sinus injuries usually come to medical attention in an emergency and often have other serious injuries. Initial management is directed at life-

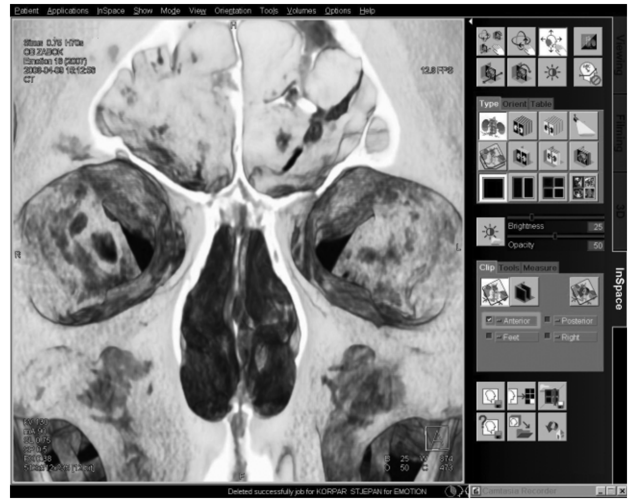

Fig 7. 3D Volume reconstruction. Volume clipping in frontal plane revealed appearance of both frontal sinus cavities as well as fracture lines on posterior wal of the left frontal sinus.

-threatening conditions and stabilizing the patient's condition. Patients with severe, compound, comminuted fractures usually are in a coma. A laceration over the forehead skin can reveal the interior of the sinus, and foreign material can be found, often a piece of glass. Cerebrospinal fluid can drain through the wound or nose.

The most common cause of frontal sinus fractures are motor vehicle accidents accounting for 52 to 72% followed by assault, industrial accidents, recreational accidents and gunshot wounds. The frontal sinus is absent in neonates and begins to develop by 2 years of age. It is the

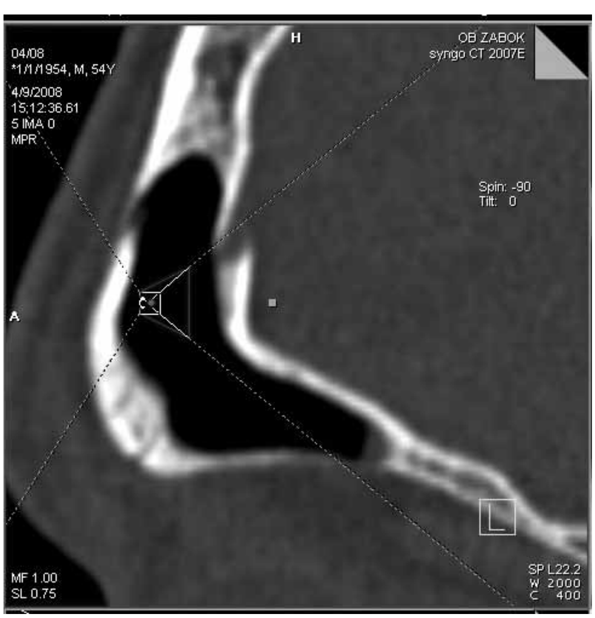

Fig 6. 3D volume reconstruction. Sagital HRCT reconstruction showed fracture of anterior wall without dislocation and fracture of posterior wall with dislocation.

Fig 8. Enlarged and rotated 3DVR image revealed dislocated bone fragment of the left frontal sinus posterior wall.

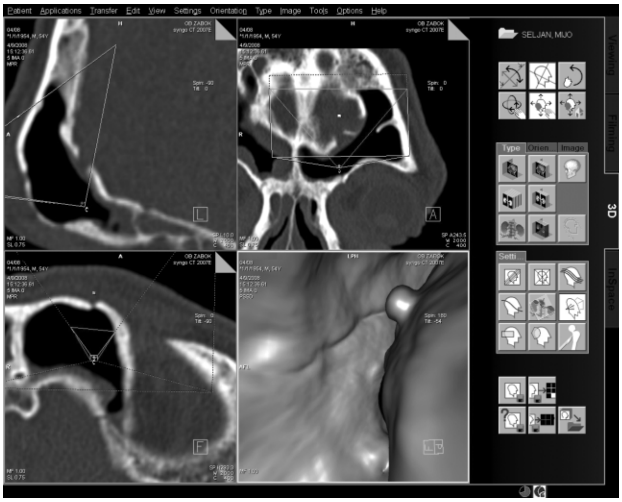

Fig 9. Working environment for fly-through is divided in four windows. First three windows showed main coordinate planes – frontal, sagital and axial. Fourth window represents view from a virtual endocamera. Virtual endocamera showed fracture line on anterior sinus wall as well as polypoid formation and submucosal thickening on the place of fracture on posterior wall and CSF leak.

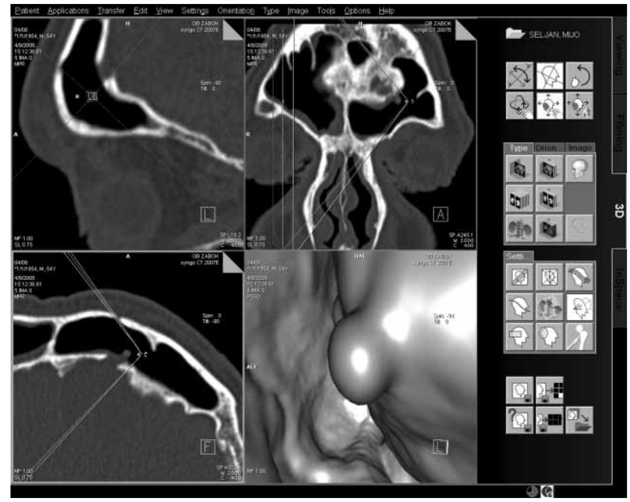

Fig 11. Virtual endocamera was directed towards the polypoid formation on the posterior sinus wall. Sagital HRCT reconstruction in the first window showed defect of the frontal sinus posterior wall and bone dislocation. Bone defect due to the fracture was also visible in the horizontal plane.

size of a pea at 4 to 5 years, approximates the adult configuration by 15 years, and is fully developed by 19 years of age. Ten percent of frontal sinuses are unilateral, 5% are rudimentary structures and 4% are absent altogether[1].

A fracture of the frontal sinus should be considered clinically when a gross depression or laceration is found over the supraorbital ridge, glabella, or lower forehead, as this is the most common finding on clinical examination. Lacerations should be examined gently to determine if any bony step-offs are present. As many as 59% of these patients may present with orbital trauma. Prompt ophthalmologic evaluation may be necessary. A large percentage of patients also may have associated fractures of the naso-orbito-ethmoid complex and midface, which may also suggest involvement of the nasofrontal duct. Gross CSF rhinorrhea may occur if the posterior table of the frontal sinus and the dura are involved in the injury.

Frontal sinus fractures can be classified into anterior wall, posterior wall frontonasal duct and through and through injuries. Anterior wall fractures that are linear and minimally displaced can be observed. Depressed anterior wall fractures should be explored, elevated and fixated if indicated. Compound anterior wall fractures should

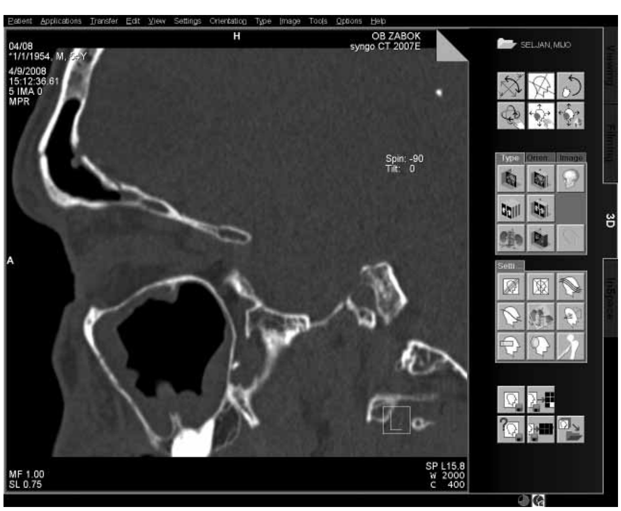

Fig 10. Enlarged sagital HRCT reconstruction showed fracture lines on both anterior and posterior wall of the left frontal sinus wall. It also showed anterior wall fracture of the left maxillary sinus without dislocation, as well as thickened and polypoid mucosa on the floor, roof and anterior maxillary sinus wall.

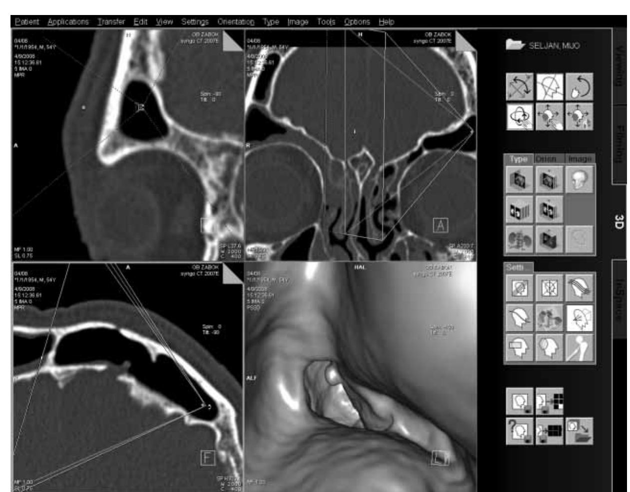

Fig 12. Virtual endocamera was situated on the lateral side of the left frontal sinus. Its view was directed towards the medial part of sinus cavity.

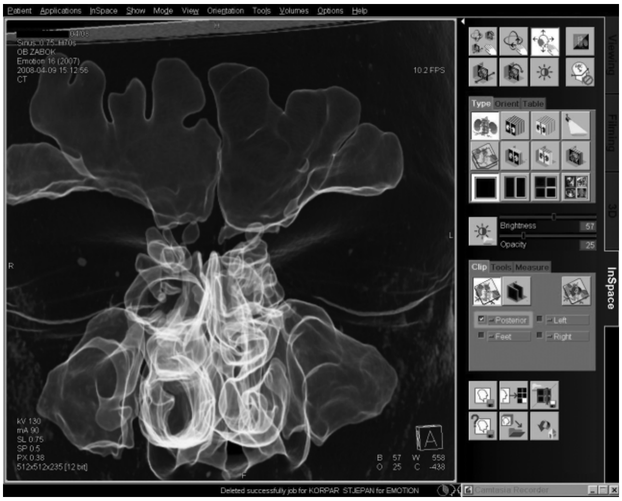

Fig 13. Double air-contrast 3DVR reconstruction showed cavities of both frontal sinuses. This method may be usable for evaluation of possible nasofrontal duct obstruction. In case of nasofrontal duct obstruction surgery would be recommended.

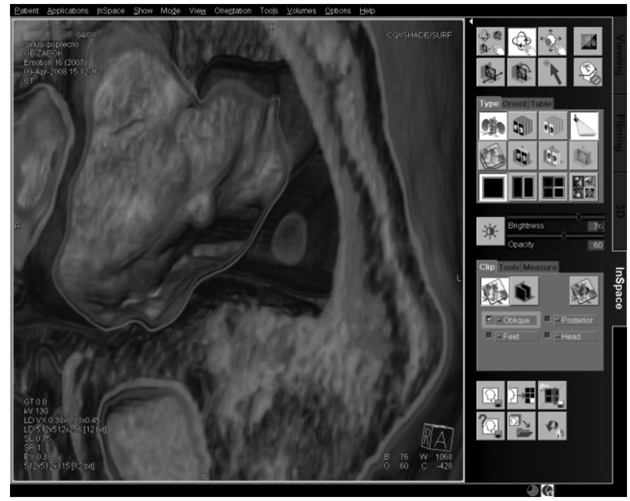

Fig 15. 3DVR reconstruction was enlarged and rotated to obtain better vision to the posterior inner surface of the frontal sinus.

be explored and foreign bodies removed. Comminuted fractures present a management problem when bone is missing. The sinus should be obliterated with fat and reconstruction of the anterior wall undertaken with free iliac, rib or split calvarial bone grafts or methyl methacrylate. Linear fractures of posterior wall require exploration and should be considered for obliteration if there is displacement or entrapment of mucosa. All depressed posterior wall fractures should be obliterated.

The management of non displaced posterior sinus wall fractures is more controversial. Some authors suggest that all posterior table fractures should undergo exploration and be examined directly via sinuscopy or otherwise. Others treat these injuries with close observation and explore if complications (persistent CSF leak) develop.

Extensively comminuted posterior wall fractures should be cranialized and if a CSF leak is present dural closure accomplished through the sinus if it is small or via anterior craniotomy if it is large. The posterior wall is thin and only minor deflections of the fragment are necessary to allow for the ingrowth of sinus mucosa into the anterior cranial fossa which can be a potentially lethal situation if a mucopyocele develops. For this reason many authors advocate obliteration of the sinus for all posterior wall fractures.

Three-dimensional images integrate a series of axial CT sections into a form that is often easier to interpret than the sections themselves. The most widely used 3D

Fig 14. 3DVR reconstruction that includes volume data for soft tissue with frontal plane clipped is probably more plastic than simple virtual endoscopy. This method revealed inner surface of the frontal sinus cavity. Oedema of the mucosa and submucosal tissue on the posterior wall was presented.

Fig 16. The same 3DVR method with oblique frontal clipping plane may be applied for inspection of frontal sinus ostia. Both ostia were not obstructed.

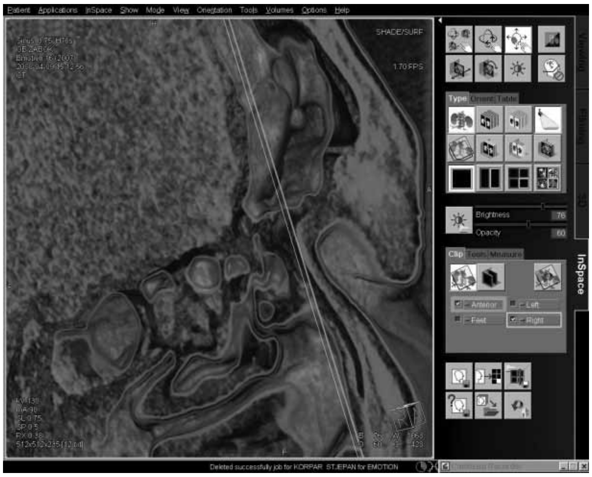

Fig 17. 3DVR reconstruction with volume clipping both sagital and frontal plane provides view from the right side into the left frontal sinus and also reveals its relationship to surrounding anatomical structures, ethmoid labyrinth and nose. Mucosa and skin was red coloured, whereas soft tissue was presented as grey and solid bone as black.

Fig 18. Four window classical fly-through screen showed CT reconstructions in three main coordinate planes as well as virtual endocamera view in the nasofrontal duct region. Virtual endoscopy of the nasofrontal duct showed that there was no nasofrontal duct obstruction.

imaging techniques to date have been shaded surface display (SSD) and maximum intensity projection (MIP)[20,21].

All 3D rendering techniques represent a 3D volume of data in one or more two-dimensional (2D) planes, conveying the spatial relationships inherent in the data with use of visual depth cues.

Volume rendering incorporates the entire data set into a 3D image[22,25]. Initially, image processing and display was very time consuming: Several hours were required to render an animation loop for viewing. However, recent advances in computer hardware have made volume rendering a practical, interactive technique that allows processing and display to occur in real time (minimum, 5–10 frames/sec) at relatively inexpensive workstations. The fundamental differences in the way SSD, MIP, and 3D volume rendering process and display medical data have important implications. Although static surface-rendered images of skeletal disease may appear more »3D« than those created with volume rendering, their clinical utility is compromised by an inability to show subcortical detail. MIP images have a tendency to misrepresent anatomic spatial relation. ships because the projected data do not take spatial location into account. MIP often requires extensive editing to eliminate unwanted data and thus create useful images.

SSD, also known as surface rendering, was the first 3D rendering technique applied to medical data sets. Its early development in the 1970s was a logical extension of new computer graphics. SSD is a process in which apparent surfaces are determined within the volume of data and an image representing the derived surfaces is displayed. The fidelity of the resulting images to actual anatomy depends in part on the value range selected. More advanced surface generation techniques such as »marching cubes«[26] use simple thresholding to select voxels but also use voxel values to generate surfaces that are placed and oriented more accurately. Surface contours are typically modeled as a number of overlapping polygons derived from the boundary of the selected region of interest. A virtual light source is computed for each polygon, and the object is displayed with the resulting surface shading. Multiple overlapping surfaces can be displayed on a single image with the additional implementation of partial opacities. Surface rendering is widely available in commercial CT image processing packages and is used clinically.

MIP is a 3D rendering technique that evaluates each voxel along a line from the viewer's eye through the volume of data and selects the maximum voxel value, which is then used as the displayed value). MIP is also widely

Fig 19. 3DVR showed the frontal sinus floor/medial orbital wall fracture line.

available in commercial 3D software packages. The clinical utility of MIP has been evaluated extensively, and MIP has proved to be particularly useful in its original application: creating angiographic images from CT and magnetic resonance (MR) imaging data. However, Schreiner et al.[27] have shown that different versions of the MIP algorithm can produce very different images. MIP has a number of related artifacts and shortcomings that must be taken into account to interpret the rendered images properly. MIP images are typically not displayed with surface shading or other depth cues, which can make assessment of 3D relationships difficult.

Volume rendering is a flexible, accurate 3D imaging technique that can help the radiologist or head and neck surgeon to more effectively interpret the large volumes of data generated by modern CT scanners. To obtain accurate results, however, the clinician must understand the effect of parameter selection on the resulting image[15].

In the emerging field of robot-assisted surgery, 3D volume rendering can provide a map of relevant anatomy for the surgeon and the robot. Applications such as the delivery of therapies to precise locations within the body are impossible without accurate volume reconstructions. With the availability of fast, inexpensive workstations that can support volume rendering and virtual endoscopy, many new clinical applications in addition to those discussed will likely emerge for this promising technology[15].

In this paper we showed our experience wih VE and 3DVR in the management of a patient with frontal sinus fracture. We showed that virtual endoscopy and 3D volume rendering can clearly display the anatomic structures, revealing damage to the sinus wall caused by a fracture. VE and 3DVR may offer to clinicians valuable additional data for the patient management planning. We found Syngo 3D platform for postprocessing CT data easy to use and our 3DVR generated images and fly-through were of good quality with acceptable frame rate. Our generated images and system accuracy were comparable or even better than those generated on other software platforms of similar purpose and described by other investigators[28–30].

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VIRTUALNA ENDOSKOPIJA I TRODIMENZIONALNO VOLUMNO RENDERIRANJE U OBRADI BOLESNIKA S PRIJELOMIMA FRONTALNIH SINUSA

SAŽETAK

Prijelomi zidova frontalnih sinusa često se previde u politraumatiziranih bolesnika radi zbrinjavanja ozljeda koje ugrožavaju život. Klasične radiografske pretrage zbog velikog broja lažno negativnih nalaza nisu naročito upotrebljive u dijagnostici ovih ozljeda, naročito u procjeni stanja nazofrontalnog duktusa. Prijelomi frontalnih sinusa mogu se klasificirati u prijelome prednje lamine, stražnje lamine i prijelome obje lamine. Najčešće su uzrokovani prometnim nesrećama, fizičkim obračunima, industrijskim nezgodama ili ozljedama od vatrenog oružja. Računalno postprocesiranje podataka dobivenih kompjutoriziranom tomografijom visoke razlučivosti u bolesniha s ozljedama glave može biti vrlo korisno u dijagnostici i preoperativnoj obradi. Mi smo napravili virtualnu endoskopiju (VE) i trodimenzionalno volumno renderiranje (3DVR) na temelju CT podataka prikupljenih od bolesnika s prijelomima frontalnih sinusa kako bismo demonstirali prednosti i mane ovih metoda u kliničkoj praksi. Akvizicija podataka je napravljena pomoću Siemens Somatom Emotion skenera dok je postprocesiranje obavljeno pomoću programskog paketa Syngo 2006G na radnoj stanici sa dvostrukim Xeon procesorom. VE i 3DVR su učinjeni u pedesetčetirigodšnjeg muškarca koji je zadobio tupu ozljedu glave u prometnoj nesreći. Pronađena je fraktura prednjeg zida lijevog frontalnog sinusa bez pomaka te prijelom stražnjeg zida s pomakom. Položaj i orijentacija frakturnih pukotina je prikazan pomoću softvera za 3D renderiranje. Zaključili smo da VE i 3DVR mogu jasno prikazati anatomske strukture paranazalnih sinusa i nosa kao i okolne anatomske strukture, prikazujući oštećenja zida sinusa izazvana prijelomom te njihove odnose prema okolnim anatomskim strukturama. Zbog toga zaključujemo da VE i 3DVR pružaju vrijednu, plastičnu i pouzdanu informaciju za kirurga glave i vrata ili radiologa.