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TECHNICAL NOTE

Investigations on an isolated skull with gunshot wounds using flat-panel CT

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Abstract The use of computed tomography (CT) scanners is rapidly becoming established in forensic medicine. Current multislice CT (MSCT) scanners attain a resolution of 0.42 mm. An isolated skull with gunshot injuries was examined with a high-resolution eXplore Locus Ultra flat-panel CT (eLU-CT) and MSCT. Structures and minute fissures in the bone interior, which were neither visible macroscopically nor with the MSCT data, could be imaged with the eLU-CT data. In addition, a tiny interior impact defect from a retained missile could be detected by eLU-CT, which clearly aided the reconstruction of the gunshots in this case.

Keywords Gunshot wounds · Skull · Flat-panel CT · eLU-CT · Multislice computed tomography (MSCT) · Forensic osteology

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Introduction

The use of computed tomography (CT) scanners is rapidly becoming established in forensic medicine [3, 6, 12]. A major advantage of digital data sets from CT scans lies in the possibility of reconstructing the processes and mechanisms of trauma. In particular, for gunshot wounds, gunshot wound channels, etc., can be portrayed in a way that would not be possible in the course of a conventional, destructive autopsy. However, the methods of postmortem CT currently still show limitations and cannot be considered a substitute for an autopsy. These limits are imposed by the absolute resolution of the systems, as well as by the behavior of the tissues with respect to the X-rays. In the Virtopsy project, these weaknesses could, in part, be successfully compensated through the additional use of magnetic resonance imaging and surface scanners [5, 9]. Problems still arise in the depiction of surface areas (e.g., skin surface), minimal bleeding (e.g., seat belt marks), and very fine structures such as tiny bone injuries.

Current multislice CT (MSCT) scanners attain a resolution of 0.42 mm. Technical development is expanding in two directions: speed and resolution. The so-called 64-slice MSCTs, which, for example, allow heart actions or coronary functions to be recorded without loss in resolution, are already being used in clinics. The so-called eXplore Locus Ultra (eLU) flat-panel CT is still in a preclinical stage. This CT attains a resolution of 0.23 mm, with the drawback that the maximum diameter that can be scanned is approximately 16 cm. These so-called micro-CTs, which have a very high resolution, have been available for a longer period of time, but only very small samples can be examined [11]. So far, flat-panel CTs of similar make have been compared to clinical CTs in the areas of bone growth in rodents [7] and the examination of human teeth [2].

Our experiments were performed to examine whether a high-resolution eLU-CT could yield advantages or additional information in the examination of a skull with gunshot injuries compared to the examination with a standard multislice CT and a conventional macroscopic examination.

Materials and methods

Human skull specimen

The isolated skull bearing several gunshot holes was found in the woods as a solitary find—its identity has not yet been resolved. The skull was initially examined with conventional morphological methods, that is, macroscopically and with a stereomicroscope (Leica MZ 16, Planapo 2.0x). The skull was then scanned with a clinical MSCT as well as with the eLU-CT.

eXplore Locus Ultra investigation

The radiological investigation was performed with a flat-panel based eLU, a volumetric micro-CT system, developed by GE Healthcare, London, Ontario, Canada. This uses a flat-panel detector (GE Medical Systems, Milwaukee, WI, USA) for radiation detection. The area (field of view, FOV) that can be imaged in the *xy*-plane is 15.1×15.1 cm, independent of the length in the *z*-direction. Because the size of the human skull was larger than the FOV that can be imaged in a single scan, the object had to be scanned in different positions to obtain a complete scan of the skull.

The image reconstruction was performed on a Linux-based reconstruction cluster. We reconstructed the data with a cone beam-filtered back-projection algorithm into a $512\times512\times k$ voxel matrix, where k ranged from approximately 340 to 900 depending on the length in the *z*-direction of the specimen. The final 12-bit Digital Imaging and Communications in Medicine (DICOM) image data had isotropic voxel sizes in the range of $(0.13\ \text{mm})^3$ to $(0.295\ \text{mm})^3$. The small voxel sizes are smaller than the intrinsic system resolution but gave the best subjective visual impression of the images.

Clinical MSCT investigation

Imaging with a MSCT (LightSpeed[16], GE Medical Systems) was performed at 140 kVp and 100 mA. A “boneplus” edge-enhancing kernel was used for the reconstruction. The reconstructed voxel size was 0.418 mm in the *xy*-plane, and the slice thickness was 0.625 mm. The displayed field of view was 21.4 cm in the *xy*-plane. The modulation transfer function of the MSCT for use with a standard reconstruction filter was given by the manufacturer as 6.8 line pairs per centimeter at 10% modulation in the *xy*-plane and 14.2 line pairs per centimeter at 10% modulation in the *z*-direction.

Image analysis

The data of both CT systems were visualized and analyzed with an Advantage Workstation, version 4.1 (GE Medical Systems, Buc, France), a Linux-based dual 2.2-GHz processor personal computer with 4 GB RAM. The volume data were visualized using maximum intensity projection (MIP) [4] or surface rendering [15]. The comparison of MSCT and eLU image data was realized by the following procedure: a 2D image of the 3D image stack of the MSCT was selected in one of the viewports of the workstation. In another viewport, a 3D oblique view of the eLU image data was visualized. Because the eLU data set could be freely rotated in the oblique view modus, the eLU data could be positioned to correspond to the MSCT data. It was then possible to compare images from the different scanners in almost identical positions by scrolling through the 2D image stacks.

Results

Macroscopy, endoscopy, and stereomicroscopy

Four entry wounds and two exit wounds were found. The entry wounds were found in the following locations: left temporal squama, rostral; left temporal squama, dorsal; directly to the left of the median line of the frontal bone (Os frontale); and right temporal squama, rostral. The diameters of the circular entry wounds were 6 mm each on the outer table of the skull, with a slightly beveled enlargement on the inner table.

One exit wound was in the left parietal bone, about 2.5 cm above the left temporal squama and 3 cm behind the coronary suture, measuring 2×3 cm. The other exit wound was circular with a diameter of 2 cm. It was located on the right side of the occipital bone and included the middle section of the lambdoid suture, thereby causing a fracture in the right parietal bone. Starting from this exit wound, a long fracture line ran almost parallel to the sagittal suture up to the coronal suture. Based on the orientation of the beveling at the entrance sites, both of the exit sites could be matched to the respective entrance sites on the left and right of the rostral temporal squamum on the opposing side, and the wound channels could thus be reconstructed. For the two remaining entry wounds, no injuries were initially found on the opposite side of the neurocranium that would have suggested an exit site.

Multislice computed tomography

After the reconstruction of the data sets and surface rendering, freely rotatable 3D models were available, in which the gunshot wound channels could be transferred and reconstructed. By using software cutting tools, any view of the skull interior was possible. However, even the evaluation of the cross-sections did not yield any additional information or findings compared to the macroscopic examination.

In the MIP image, there was at least a suggestion of a possible further injury related to the fracture line originating at the exit site in the right half of the occiput (Fig. 1a). A directed search in the cross-sections of this area, however, did not yield any further injuries beyond the macroscopically visible fracture line (Fig. 2a).

eXplore Locus Ultra flat-panel computed tomography

Because of the limited scanning area, a complete coverage of the skull was not possible in one scan. Three scans were necessary. Therefore, an entire 3D model of the skull could not be made. Several reconstructions were generated for each scan to exploit the maximum resolution. These already showed more surface structure detail in the surface rendering compared to the MSCT. The cross-sections yielded the greatest gain of information. The delicate structures of the diploe and bone boundaries were clearly visible. In direct comparison to the MSCT, miniscule injuries of the bone interior structure, in particular, were visible that could also not have been depicted macroscopically (Fig. 3).

After surface rendering, the impression arose that the inner table of the skull bordering dorsally on the fracture line in the right half of the occiput might be slightly displaced in the direction of the diploic bone. In the MIP image of this area (Fig. 1b), a small fissure system originating at the fracture line could be seen, which was interpreted as a result of sharply localized trauma [14], such as from the impact of a missile. In the cross-sections of this area (Fig. 2b), the displacement of the inner table in the direction of the diploic bone as well as minute bone fissures extending outward in a funnel shape could be demonstrated.

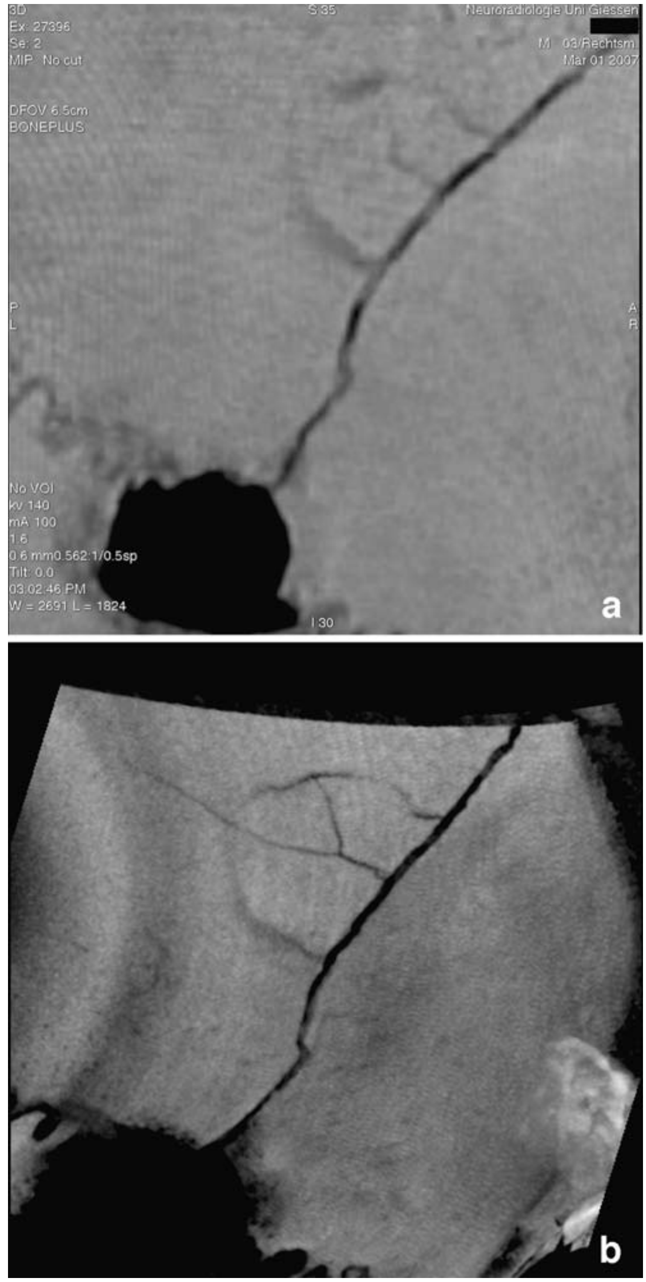

Fig. 1 **a**, **b** Maximal intensity projection (MIP) of the MSCT data sets (**a**) and of the eLU-CT data sets (**b**). A further injury that occurred after the fracture is visible in both; it is better demonstrated in **b**. This most probably developed as a result of sharply localized trauma

Discussion

The advantages of CT in the postmortem investigation of gunshot wounds to the skull have already been repeatedly demonstrated [1, 8, 10, 13]. We wanted to assess whether CT was also useful in the forensic osteology examination of gunshot wounds in an isolated skull that was free of soft tissues. In addition to the classic macromorphological examination supplemented by stereomicroscopy and endoscopy as well as with a modern 16-slice MSCT, a high-resolution eLU flat-panel CT was used for the first time in forensic science.

As expected, both the MSCT and the eLU-CT were inferior to classic morphology in the assessment of the surfaces. The image after surface rendering from the eLU-CT data showed slight advantages in the imaging of surface details, but these were not significant for the assessment of the injuries. In addition, this advantage in detail imaging

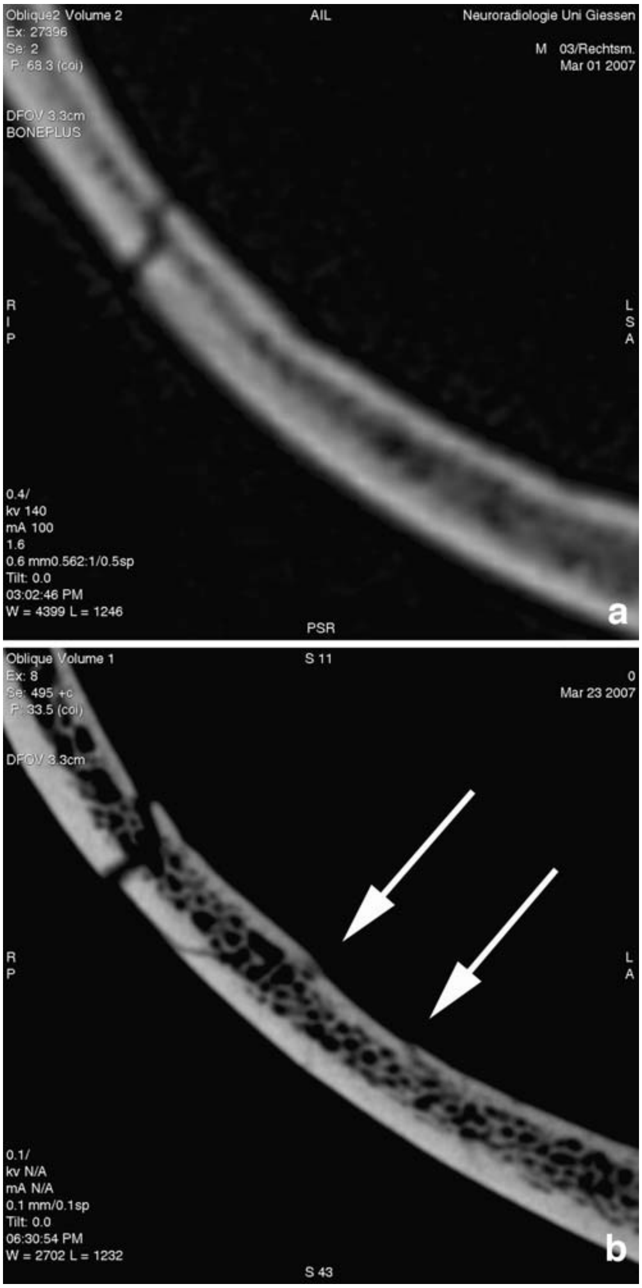

Fig. 2 **a**, **b** Comparison of two corresponding cross-sections from the MSCT (**a**) and eLU-CT data sets (**b**) for the area in the region from Fig. 1. The large fracture line at the *top left* can be discerned in both images. Apart from that, no further injuries are depicted for the MSCT. In the eLU-CT, a fragment from the inner table of the skull can be seen, which has been displaced toward the diploic bone and is bordered on both sides by minute fracture lines extending outward in the shape of a funnel

had to be traded off against the disadvantage of not being able to have an entire model of the skull.

No additional injuries or changes could be detected with the aid of the MSCT data beyond those found in the morphological examination. Only in the MIP image of the MSCT data, a vague indication of an additional injury could be found in conjunction with a macroscopically well-visible fracture line in the right half of the occiput.

Structures and minute fissures in the bone interior, which were neither visible macroscopically nor with the MSCT data, could be imaged with the eLU-CT data. In the right parietal bone, the impact of a retained missile coming from the entrance site in the left temporal squama could be discerned. The impact defect bordered on a fracture line that originated in the well-recognizable exit wound in the right occiput; the corresponding entrance wound was also

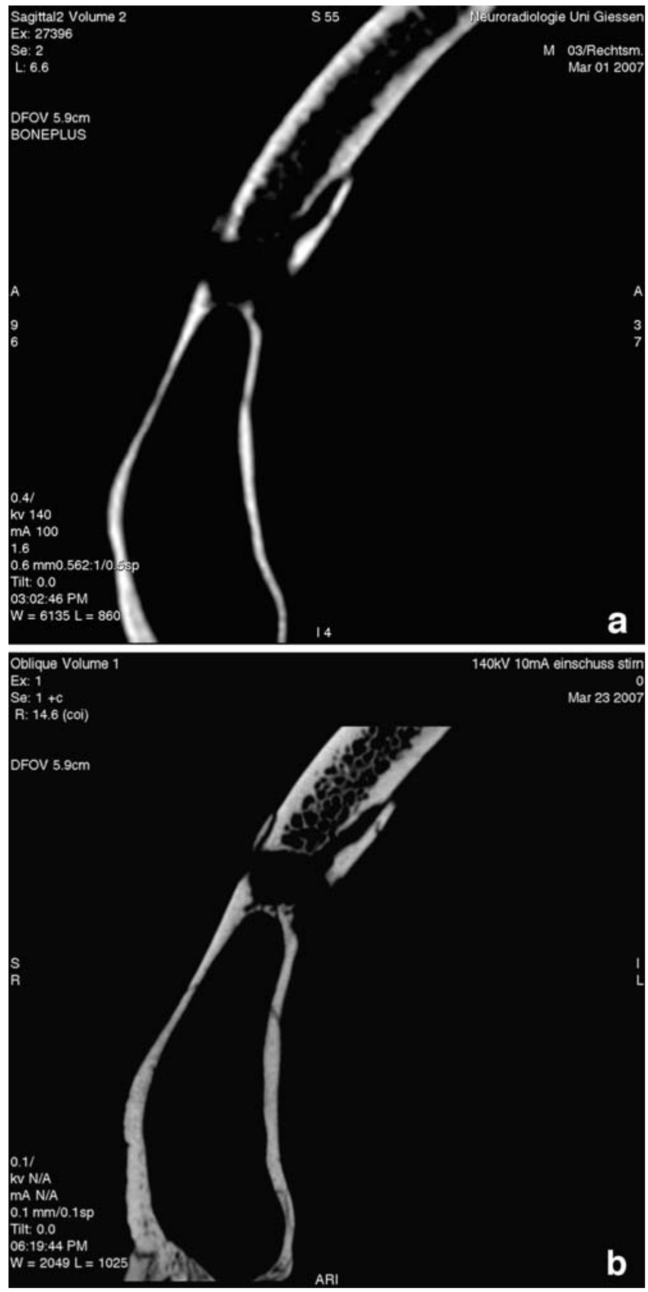

Fig. 3 **a, b** Sagittal section plane image of the entrance defect in the forehead: **a** after MSCT and **b** after eLU-CT. The picture from the eLU-CT shows a greater wealth of detail

in the left temporal squama. Following Puppe's rule, the sequence in which the entrance defects occurred could be determined: The penetrating gunshot wound followed the perforating gunshot wound.

In our examinations, the high-resolution eLU-CT system does show a considerable advantage over MSCT (and conventional) investigations in imaging internal bone structure. Due to the higher resolution, very fine bone fissures, structural inhomogeneities, and slight dislocations of bone, which were not visible in the MSCT, could be detected.

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