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Introduction

For the assessment of skull bones CT is recommended as first-line imaging modality. It is therefore considered indispensable, but radiation dose concerns have to be addressed especially in younger patients.

MRI offers optimal soft tissue contrast without the use of ionizing radiation rendering MRI the preferable modality. However, the challenge in MRI originates in the physical relaxation properties of targeted bone tissue. Bones are characterized by an extremely short transverse relaxation time (T2) caused by low hydrogen proton density. This results in a signal drop to zero before any emitted signal can be received by MRI coils.

Various solutions to this problem have been proposed. Ultrashort echo time (UTE) imaging requires fast and strong gradient coils that enable imaging of tissues at a T2 time of less than 0.5 ms. To date, UTE imaging is commonly used in research but has also been investigated in a variety of clinical applications e.g. for imaging cortical bone. Compared to 2D UTE, 3D UTE allows more accurate measurement of short T2 tissue properties due to its higher resolution.

Another approach is to use a modified three-dimensional multislice fast-field-echo (FFE) sequence with multiple gradient echo formations, which is referred to as FRACTURE (FFE resembling a CT using restricted echo-spacing) in the literature. This is a non-steady state imaging with a fast repetition time and small flip excitation angle maintaining a high signal-to-noise ratio and extracting short T2 tissues by increasing signal differences between all tissue types.

Both methods have promising ability to visualize skull bones with increased accuracy to standard MRI sequences, especially at the skull

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Both methods have promising ability to visualize skull bones with increased accuracy to standard MRI sequences, especially at the skull
The resulting mean volume CT dose index was 91 mGy. The skull base and viscerocranium present challenges when using bone imaging sequences because the signal intensities of air and bone overlap, making accurate delineation of bone structure difficult.

The study aimed to evaluate UTE and FRACTURE, two specific bone imaging MRI sequences for their ability to detect fractures of the skull vault, base, and viscerocranium using CT as the reference standard.

Materials and methods

Twenty subjects were included in this postmortem study who all underwent CT and MRI head scans within 72 h. Cases of both genders (m = 11, f = 9), all age groups (median age 68 years, range 5 – 93 years) as well as traumatic (n = 7, 4 non-displaced, 3 displaced fractures) and non-traumatic histories were included. Exclusion criteria were previous head surgeries and extensive soft tissue emphysema. The responsible ethics committee waived ethical approval as the decedents underwent imaging sequences for their brain.”

Image acquisition

All individuals were scanned using a 128-multi-slice CT scanner (Somatom Definition Flash, Siemens Healthineers, Forchheim, Germany). An optimized postmortem scan protocol was used with a tube voltage of 120 kVp, a tube current of 1000mAs, and without tube voltage modulation. The resulting mean volume CT dose index was 91 mGy. The image dataset was reconstructed transaxially at a slice thickness of 0.6 mm and an increment of 0.4 mm, using a bone kernel (H60) and a soft kernel (H31). A maximum field of view of 300 × 300 mm² with a matrix of 512 × 512 was applied.

Following CT, a head and neck MRI scan was conducted including UTE and FRACTURE MRI sequences. Therefore, a 3 Tesla MRI scanner (Achieva 3.0 TX, Philips Healthcare, Best, the Netherlands) with a 16-channel head and neck coil was used.

The UTE sequence was scanned transversally using a 230 × 230 mm field of view and a 0.8 × 0.8 × 1.2 mm³ voxel size. The following parameters were used: TE: 0.2 ms, TR: 10.2 ms, flip angle: 15°. The FRACTURE sequence was acquired in the same anatomic orientation using a 230 × 230 × 182 mm³ field-of-view and an isotropic voxel size (0.7 × 0.7 × 0.7 mm³). For this multi-slice multi-echo sequence four in-phase echoes (Starting TE: 4.61 ms, TR 20.7 ms, echo-spacing: 46 ms) with a flip angle of 15° were acquired. To avoid chemical shift artifacts due to signal reduction if the oscillating signal intensities of fat and water are out of phase, all echoes were acquired every 4.6 ms when fat and water are in-phase. Early images helped to increase the signal-to-noise ratio, whereas the last echo, which resembles T2 weighted images, improved image contrast. To prevent dephasing across voxels high-resolution acquisition was applied.

All images were analyzed at the same workstation using Syngo.via (version VB30A, HP91, Siemens Healthcare). For each modality a separate dataset was generated including the same subjects. Every dataset was anonymized and randomized for subsequent image analyses. All readers assessed the same datasets and could invert gray scales if considered helpful.

Qualitative assessment

Prior to the qualitative assessment, all readers had to perform a 12-case training, including all three imaging options. Training cases were not included in the final study population. Within three months, all data sets were read in 3 sessions. Only one imaging modality was visualized per session. More than three weeks were in each case between the readouts. Datasets containing MRI sequences were rated by the observers before the corresponding CT data. Two board-certified radiologists (6 and 7 years of experience) evaluated all datasets individually. To establish a qualitative reference standard rating, two board-certified radiologists (more than 8 and 13 years of experience) evaluated all sets in consensus.

Qualitative image characteristics were rated on a 4-point Likert-scale. Following imaging ratings had to be stated for the viscerocranium, skull base, and skull vault separately: overall delineation of the osseous structures conjointly considering the appearance of the internal/external table, diploe or cortical bone (0 – poor/non-diagnostic, 1 – moderate, 2 – good, 3 – excellent). Fractures had to be described specifically including location and displacement.

Quantitative assessment

To evaluate signal to noise ratios (SNR) and contrast to noise ratios (CNR) signal intensities (SI) were measured in specified regions of interest (ROI) with a diameter of 5 mm² by two independent readers. ROIs included areas in bone (internal occipital protuberance, odontoid process, and base of the dens), muscles (masseter and rectus capitis muscle on both sides), rain tissue near the bone-brain junction (cerebellum bilaterally and in the cortex in the postcentral gyrus bilaterally), as well as air outside the skull. The signal intensity (SI) and the standard deviation (SD) were used to calculate SNR (Eq. (1)) and CNR (Eq. (2)):

\[
SNR = \frac{SI_s}{SD_{air}} \tag{1}
\]
\[
CNR = \frac{SI_{bone} - SI_s}{SD_{air}} \tag{2}
\]

where for both equations Sl stands for the respective value of air, muscle, or brain tissue.

The individual SI values were indicated by the mean value within the ROIs (on CT: Hounsfield units and on MRI: voxel intensity values). Concerning the FRACTURE sequence, SD and SI were measured on inverted FRACTURE images because the use of these images in inverted form has been evaluated and recommended in the literature. SNP calculations were used for comparison within the respective bone imaging sequence. The same coil was used for UTE and FRACTURE, so correction for coil sensitivity was not considered relevant in this case.

Statistical analysis

All statistical analyses were conducted using SPSS, Version 26.0 (IBM, Armonk, New York). A P value of < 0.05 was considered significant. All image quality measurements were assigned numeric values. Interobserver reliability was calculated with a two-way mixed model and for all parametric values the intraclass coefficient (ICC), based on the terminology of McGraw and Wong, was applied. According to the commonly used interpretation of ICC, ICC values less than 0.5 were considered a poor, between 0.5 and 0.75 a moderate, between 0.75 and 0.9 a good, and greater than 0.90 an excellent reliability. Because of the small number of fractures detected, only descriptive values were documented for this part of the study and no statistical analysis was performed to evaluate differences between modalities.

To compare quantitative data (SNR and CNR) a Wilcoxon signed-rank test was applied, and the effect size was calculated. The approach of Rosenthal was applied to calculate the effect size.

Results

The results of the gradings and ICCs are summarized in Table 1.

Bone delineation

CT imaging was considered as a reference standard for all skull regions and obtained the maximum value of 3 for the visual...
There was good agreement between modalities, with a focus on expert reader ratings, between all modalities regarding bone delineation (ICC = 0.75 CI: 0.57 - 0.84).

### Skull vault

The overall bone delineation of the UTE sequence was 2.63 ± 0.42 and in the FRACTURE dataset 2.81 ± 0.32, which was not statistically different ($P = 0.09$). Compared to CT standard reference delineation quality, both MRI sequences performed significantly inferior, UTE ($P < 0.05$) and FRACTURE ($P = 0.03$). ICC representing the interobserver reliability between all three ratings showed in the UTE dataset an excellent (ICC = 0.94 CI: 0.88 - 0.98) and in the FRACTURE dataset a good agreement (ICC = 0.83 CI: 0.64 - 0.93).

### Skull base

On the UTE sequence bone delineation was rated with 1.48 ± 0.03 and on FRACTURE with 1.33 ± 0.33, which did not show any statistically significant difference between the two MRI sequences.

### Table 1

| Region            | Bone delineation (overall values) | Interreader correlation |
|-------------------|----------------------------------|-------------------------|
| Skull vault       | UTE: 2.63 ± 0.42                 | 0.94 (CI 0.88 - 0.98)   |
|                   | FRACTURE: 2.81 ± 0.32            | 0.88 (CI 0.76 - 0.95)   |
| Skull base        | UTE: 1.48 ± 0.03                 | 0.88 (CI 0.70 - 0.93)   |
|                   | FRACTURE: 1.33 ± 0.33            | 0.87 (CI 0.72 - 0.94)   |
| Viscerocranium    | UTE: 1.74 ± 0.02                 | 0.91 (CI 0.80 - 0.96)   |
|                   | FRACTURE: 1.37 ± 0.01            | 0.86 (CI 0.71 - 0.94)   |

All mean grading values are given with their standard deviations. FRACTURE showed better grading values at the cranial vault than UTE, but slightly lower grading values than UTE at the skull base and viscerocranium. Interrater correlation was higher for UTE than for FRACTURE in all regions.

### Fig. 1

Transaxially view of the head on CT (A) and on both MR sequences FRACTURE (B) and UTE (C). Bone delineation on CT was considered as gold standard. On FRACTURE bony structures resemble the image on CT, although with less details, but with additional information on brain tissue, enabling the diagnosis of an intracranial hemorrhage (star), which is also slightly detectable on UTE. The visualization quality of the skull bones was rated higher on UTE than on FRACTURE, especially the contours of the cortex are better defined on UTE.

### Fig. 2

Comparison of fracture line visibility showed differences between the evaluated examinations. On CT (A) a clearly visible fracture line can be seen. On FRACTURE (B) the fracture line is also visible, however with less defined borders. On UTE (C) the fracture line appears similar to CT imaging reference standard and was also detected by all readers. For better comparability we inverted the UTE image.
Both MRI sequences performed significantly inferior to CT for visual bone delineation quality (both UTE and FRACTURE $P < 0.05$). ICC ratings showed good agreement in assessing bone delineation to surrounding tissue in both, UTE ($ICC = 0.88 CI = 0.76 – 0.95$) and FRACTURE ($ICC = 0.87 CI = 0.72 – 0.94$).

**Viscerocranium**

The appearance of osseous structures on UTE sequence was rated significantly higher ($1.74 \pm 0.02$) than on FRACTURE sequence ($1.37 \pm 0.01$) ($P < 0.05$). Moreover, both MRI sequences were rated significantly lower compared with CT: UTE ($P < 0.05$) and FRACTURE ($P < 0.05$). ICC was calculated as excellent for the UTE ($ICC = 0.91 CI = 0.80 – 0.96$) and for the FRACTURE dataset as a good agreement ($ICC = 0.86 CI = 0.71 – 0.94$).

**Fracture detection**

Seven cases out of 20 were diagnosed with a skull fracture on CT, which were all detected and confirmed by all readers. Three fractures were detected in the skull vault (2 displaced, 1 non-displaced), two fractures were in the viscerocranium (1 displaced, 1 non-displaced) and another two fractures were located in the skull base (2 non-displaced). On MRI, detection rates varied between the observers depending on the region and used sequence (Fig. 2). At the skull vault, the detection rate was higher...
than at the other anatomical sites. On UTE, only one reader missed one fracture of the skull vault, whereas on FRACTURE two out of three readers (including expert consensus readout) missed one fracture. At the skull base, the expert readers detected both fractures diagnosed on CT on UTE and FRACTURE, however stated to rely on indirect signs such as fluid in the mastoid air cells. The fracture gap was not completely visible to its whole extent compared to CT. Both individual readers missed one of the two fractures on UTE and detected neither on FRACTURE in this region. Two cases showed fractures in the viscerocranium. Expert readers detected both fractures on UTE, but only one on FRACTURE (a displaced fracture). Only Reader 1 documented one fracture on UTE (a displaced one) and neither on FRACTURE.

Quantitative assessment

Signal-to-noise ratio analysis showed significantly higher values for FRACTURE sequence than for UTE and CT ($P < 0.05$ for both MRI sequences compared to CT). CNR resulted in highest values for CT, followed by UTE, whereas FRACTURE sequence showed the smallest ratio. Differences between the groups showed statistical significance between CT and UTE ($P < 0.5, Z = -3.92$), and CT and FRACTURE ($P < 0.05, Z = -3.88$). The calculated effect size was 0.7 for both comparisons and therefore showed a large effect size. Between the two MRI sequences, no significant differences in CNR were calculated ($P = 0.15, Z = -1.44$) (Fig. 3).

Discussion

We investigated the value of recent dedicated bone-imaging MRI sequences in visualization of osseous structures and fractures of the skull bone. Non-pathological bones and fractures at the skull vault were on both MRI sequences comparable to CT as standard examination. However, especially at the skull base and viscerocranium both MRI sequences delivered significantly impaired bone depiction quality and fracture detection compared to reference CT images.

Regarding intact bone regions, interobserver ratings of the bone appearance were coherent and showed good to excellent agreement in all regions, again with an advantage at the skull vault over the remainder. Therefore, results of previous studies, focusing solely on the skull vault, indicating an excellent agreement in assessing cortical skull bones can be confirmed.\footnote{15, 18} In both sequences, a major obstacle was the differentiation between bone and air-filled structures, resulting in impaired delineation of the viscerocranium. These subjective assessments were supported by the calculated CNR, which showed poor contrast between air and bone in both MRI sequences.

For fracture assessment, UTE resulted in higher detection rates at the skull base than at the viscerocranium. At the skull vault successful diagnosis of the fractures was achieved with UTE by all readers - only one reader missed one fracture. The successful fracture detection at the skull vault correlates with previously published results in children with skull bone fractures.\footnote{18} The missed fracture may also be due to misinterpretation of a suture. This also indicates high performance for bone depiction of skull vault as opposed to the remainder regions on UTE, possibly supporting the notion of air-bone interfaces as the main confounders to bone depiction quality. This obstacle of UTE sequences is well known and derives from residual intensity nonuniformities of tissues caused by radiofrequency-coil sensitivity variations across the field of view and the chemical-shift effect in the radial sampling.\footnote{11}

On FRACTURE bone visualization of the skull vault was rated higher than on UTE, providing more details on bone structure and delineation. Nevertheless, fracture detection was lower than on UTE regardless of the anatomical region. This again is certainly due to the markedly impaired differentiation between air and bone, even more severe than on UTE (Fig. 4). This correlates with previous stated impairments of this sequence in detecting subtle fractures or fractures in areas surrounded by gas.\footnote{7} Due to the small number of fractures in our study population, no conclusion can be drawn about a statistical difference between detection rates and needs to be further investigated in a larger study population. However, all observers commented, particularly on the FRACTURE sequence, that in both problematic anatomical areas air-bone interfaces became definable if a pathologic condition, such as fluid filled mastoid air cells were present. This was easily confirmed on CT. This may be a pitfall, as the apparently physiologic image of the fluid filled mastoid air cells on MRI is representing severe injury (Fig. 5). However, it must be mentioned that in our study population only single cases showed fluid-filled mastoid air cells and therefore we cannot conclude a evidenced causality. In summary visualization of the skull vault showed adequate and comparable results on both MRI sequences. The main impairment of both MRI sequences was related to pneumatized spaces e.g. mastoid air cells, and consequently more overlapping signal of bone and air than at the skull vault.

A limitation of our study was the postmortem setting and therefore it has to be considered that the characteristic T1 and T2 signal intensities may be slightly different because of the lower body temperatures,\footnote{19} however all images were reviewed before study inclusion to ensure proper comparability. Because postmortem changes would be expected to result in gas in both soft tissue and bone, we excluded cases with intraosseus gas or extended postmortem intervals. Furthermore, the potential advantage of the isotropic FRACTURE sequence over the plane UTE sequence in using multi-planar reformation for diagnosis was not evaluated in this study.

![Fig. 4. Imaging of the maxillary sinus on FRACTURE (A) and UTE (B) shows the impaired visualization of air-bone boarders. Although both MRI sequences are not of comparable quality to CT, UTE was considered as with greater diagnostic value than FRACTURE.](image-url)
Conclusion

We assume that both MRI sequences may provide an alternative e.g. for surgical planning, or follow up exams after traumatic injuries of the neurocranium. A clear advantage of one of the two sequences over the other could not be identified in terms of fracture detection in this study. However, this could also be due to the low number of fractures in our study population. Therefore, further evaluation of the UTE sequence compared to the FRACTURE sequence is necessary.

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Ethic form

This study was performed with human cadavers. Ethical approval was waived by the responsible ethics committee of the Canton of Zurich (waiver number: 2015-0686). This article does not contain any studies with (living) human participants. The decedents underwent postmortem imaging as part of the forensic judicial investigations.

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Fig. 5. Imaging of the skull base on CT (A) showed major advantages over FRACTURE (B) and UTE (C). The insufficient differentiation of bone and air resulted e.g. in impaired visualization of the petrous part of the temporal bone. In case of the pathologic presence of fluid and air in the mastoid cells, as shown here on the right side, the inner ear appeared nearly physiological on FRACTURE, whereas the intact left side is superimposed by air-induced artifacts. On UTE the differences between fluid and air-filled mastoid cells is slightly visible as well, but differentiation of small aerated cells from boney structures is markedly impaired as both appear dark on UTE images.
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