Performance of fast and ultrafast T2-weighted MRI sequences for common cerebral lesions in children

Wertigkeit von schnellen und ultraschnellen T2-gewichteten MRT-Sequenzen bei häufigen zerebralen Läsionen bei Kindern

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ABSTRACT

Purpose The use of fast and ultrafast T2-weighted sequences allows for low-motion-artifact imaging of the cerebrospinal fluid spaces and can thus avoid sedation in young children for cranial MRI (cMRI). It is still unclear to what extent these sequences can also depict other common cerebral findings in children. The aim of the study was to compare the potential delineation of common intracranial findings in pediatric cMRI with two fast and one ultrafast T2-weighted sequences.

Materials and Methods Children who had undergone a single-shot spin-echo and gradient echo sequence, as well as an ultrafast volume coverage (VC) sequence, in addition to a standard T2-weighted fast spin-echo (FSE) sequence as reference were retrospectively included. Visualization of findings was assessed using a Likert scale from 0 to 3. Differences between groups of findings were quantified using a Kruskal-Wallis test.

Results 284 findings in 126 patients (median age: 10.6 years, interquartile range: 5.1 to 15.0 years) were analyzed. Overall, in fast T2-weighted sequences, the percentage of visible (score 2 or 3) findings was between 60 % and 100 %. There was little difference between the two fast sequences and the ultrafast VC.

Conclusion Ultrafast VC as compared to conventional fast sequences allows for almost the same discrimination of common neuropediatric pathologies but at seven times the speed. Although not an equivalent substitute for T2 FSE in parenchymal findings, it can contribute to triage at little expense and thus reduce the burden on both patients and staff.

Key Points

- Fast T2-weighted sequences can depict many types of neuropediatric findings
- They cannot fully replace a T2 fast spin-echo sequence
- An ultrafast volume coverage sequence shows similar quality to conventional fast sequences

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ZUSAMMENFASSUNG

Ziel Schnelle und ultraschnelle T2-gewichtete Sequenzen ermöglichen eine Darstellung der inneren und äußeren Liquorräume weitgehend ohne Bewegungsartefakte. Hierdurch kann auch bei jüngeren Kindern eine kraniale MRT (cMRI) ohne Sedierung erfolgen. Inwieweit diese Sequenzen auch andere häufige zerebrale Läsionen bei Kindern darstellen können, ist nicht bekannt. Das Ziel der Studie war zwei schnelle und eine ultraschnelle T2-gewichtete Sequenz bezüglich der

Darstellbarkeit häufiger intrakranieller Läsionen bei Kindern zu vergleichen.

Material und Methoden In die retrospektive Studie wurden Kinder, die sowohl eine single-shot spin-echo-Sequenz, eine schnelle Gradientenecho-Sequenz als auch eine ultraschnelle Volume Coverage (VC)-Sequenz, sowie eine konventionelle T2-gewichtete fast-spin-echo-Sequenz als Referenz erhalten hatten. Die Sichtbarkeit von Läsionen wurde auf einer Likert-Skala von 0 bis 3 bestimmt. Unterschiede zwischen den Gruppen wurden über den Kruskal-Wallis-Test quantifiziert.

Ergebnisse 284 Läsionen bei 126 Patienten (mittleres Alter 10,6 Jahre, Interquartilsabstand 5,1 bis 15,0 Jahre) wurden eingeschlossen. Insgesamt waren zwischen 60 % und 100 % der Läsionen in den schnellen T2-gewichteten Sequenzen sichtbar (Score 2 oder 3). Die beiden schnellen und die ultraschnelle VC-Sequenz unterschieden sich kaum.

Schlussfolgerung Die ultraschnelle VC-Sequenz ermöglicht, verglichen mit konventionellen schnellen Sequenzen, eine annähernd gleiche Abgrenzung häufiger neuropädiatrischer Pathologien mit etwa siebenfacher Geschwindigkeit. Obwohl die Sequenzen die T2-FSE bei Parenchymläsionen nicht ersetzt, ermöglichen sie eine niedrigschwellige Triage und könnten so Patienten und Gesundheitssystem entlasten.

Kernaussagen

- Schnelle T2-gewichtete Sequenzen können viele neuropädiatrische Läsionen abbilden.
- Sie ersetzen jedoch keine konventionelle T2 fast spin-echo Sequenz.
- Eine ultraschnelle Volume Coverage-Sequenz hat eine mit konventionellen schnellen Sequenzen vergleichbare Qualität.

Introduction

Conventional cranial MRI (cMRI) in young children between 3 months and 6 years of age is complicated by a lack of patient compliance and subsequent motion artifacts. With more recent fast and ultrafast sequences, the patient's gross motion can be compensated to a high degree. Due to the application of these sequences, children in this age group currently rarely need sedation for the evaluation of inner and outer cerebrospinal fluid (CSF) spaces [1].

With regard to T2 weighting, two sequence schemes have been established for this purpose: fast balanced steady-state free precession sequences (bSSFP) [2] and single-shot fast spin-echo sequences (ssFSE) [3]. A novel third gradient-echo sequence, the volume coverage (VC) sequence, originates from the real-time MRI spectrum and enables the highest temporal resolution with up to 50 images per second [4, 5, 6]. Fast or, in particular, ultrafast sequences provide low-artifact images even with very young, motorically restless children.

The terms "fast" and "ultrafast" are arbitrary and should be seen in a temporal context. In the following study, the term "ultrafast" is used for an acquisition speed that is above the individual visual resolution of images, so that the image sequence is perceived as a smooth motion [7]. The threshold value for this is around 12 frames per second [8].

However, the diagnostic value of a fast or ultrafast sequence depends not only on its lack of artifacts, but also on image noise, contrast, and spatial resolution. At present, however, the three sequence types mentioned above have only been evaluated for the assessment of high-contrast CSF spaces and trauma screening. It is not clear how accurately the three fast sequence types identify and confidently diagnose issues with other findings such as masses, gliosis, edema, demyelination, and hamartomas.

The aim of this study was to assess the potential delineation of common intracranial findings in pediatric cMRI using the three aforementioned fast T2-weighted sequences.

Materials and Methods

Cohort

The retrospective study covered a period between 05/2020 and 11/2020 at a tertiary center with a pediatric clinic and institute for pediatric radiology. Children between 5 and 18 years of age who had received a cMRI without sedation for clinical reasons were included. Younger children, who are known to rarely lie still during MRI, were not included as the aim of the study was the greatest possible visualization of the findings and not their resistance to artifacts. The standard cMRI protocol of our institution contains three fast T2-weighted sequences. Acquired directly after the scout sequence, those sequences deliver informative images even in the case of a premature abortion of the examination. Informed consent by the patients or their legal guardians regarding the fast sequences was obtained. The local ethics committee approved the retrospective study.

MRI protocol

First, the three fast T2-weighted sequences (VC, bSSFP and ssFSE) were acquired in axial orientation based on the institute's in-house standard protocol for the respective indication. Subsequently, a T2 fast spin-echo (FSE) sequence was acquired as a reference. The sequence parameters are described in ▶ **Table 1**.

The concept of the new, ultra-fast VC has already been described elsewhere [4, 5]. In short, the VC is a highly undersampled gradient-echo sequence with radial K-space readout, which is visualized on the operator console with only a minimal delay. Through non-linear inverse reconstruction by a separate reconstruction server, the sequence achieves a very high temporal resolution (71 ms without view sharing) with a decent spatial resolution (1.0 × 1.0 × 3.0 mm without interpolation) (▶ **Table 1**). A large volume is scanned in a short time with highly overlapping slices largely free of motion artifacts by introducing a tiny slice shift for each of the ultra-fast individual image acquisitions. This results in a continuous, 3 D sequence-like viewing impression, be-

▶ **Table 1** Sequence parameters for the T2 FSE sequence as a reference and for three fast T2-weighted sequences.

	FSE	VC	bSSFP	ssFSE
Slice thickness (mm)	3	3	5	4
In-plane (mm)	0.6×0.4 (0.4×0.4)	1.0×1.0	1.2×0.5 (0.8×0.8)	0.9×0.7 (0.7×0.7)
TR/TE (ms)	8220/100	4.2/2.1	379/2.1	556/97
Flip angle (°)	150	50	52	150
Slice gap (%)	10	-85	20	10
Averages (#)	2	1	2	1
Time per image (ms)	n.a.	71	758	556
Time per 15 cm (s)	189	24	19	20

FSE: fast spin-echo; VC: volume coverage; bSSFP: balanced steady-state free precession; ssFSE: single-shot fast spin-echo

cause the respective slice shift of the overlapping 3 mm slice is only about 15 %, i. e. 0.45 mm. In principle, the VC can be adapted to all gradient echo weightings, whereas for this study a steady-state free precession with T2/T1 weighting was chosen.

Findings

Each pathology that could be clearly spotted in the T2 FSE sequence was sought out in the 3 fast sequences and classified on a Likert scale regarding its ability to be delineated (0 = not visible, 1 = only visible in knowledge reference, 2 = visible but not with the same information as the reference, 3 = clearly or equally visible compared to the reference). Each finding was evaluated by two readers (DG and HS with 14 years and 10 years of pediatric imaging experience, respectively) in independent examinations and blinded to each other, on a conventional PACS viewer. Other sequences and weightings that may have been acquired in clinical context were not considered in the context of this study to compare only the T2 features of the pathology in the fast or ultrafast sequences. Since motion artifacts are hardly comparable between the different sequence types (different types of artifacts and rather subjective thresholds), the visibility of findings for this study was evaluated solely on patients lying quietly.

Statistics

RStudio 2023.9.1.494 (Posit Software, PBC, Boston, MA) was employed for descriptive statistics. The interobserver correlation was determined using Kendall's tau. The effect size of the correlation was considered small at 0.1–0.3, moderate at 0.3–0.5, and large at more than 0.5 [9]. Differences in the scores of the 3 sequences were determined for each finding using a Kruskal-Wallis test followed by Dunn's post-hoc test with Bonferroni correction.

In practice, visibility is often only relevant if reliable. Thus, the Likert scale was further simplified with only findings that were well imaged (score 2 or 3) and classified as visible, while findings that were not or barely imaged (score 0 or 1) were classified as not visible. The percentage of visible findings was determined for each type of finding. The level of significance was set at 0.05.

Results

284 findings in 126 patients (median age: 10.6 years, interquartile range: 5.1 to 15.0 years) were registered in the T2 FSE as the reference sequence. No study had to be excluded due to motion artifacts. The most common findings were tumors (n = 65), demyelination (n = 43), gliosis (n = 31), catheters (n = 21), and edema (n = 21) (▶ **Table 2**, ▶ **Fig. 1**, and **Supplemental Figure 1**). In their assessment of finding detectability, the two readers strongly agreed for bSSFP sequences (tau = 0.56, p < .001) and VC sequences (tau = 0.54, p < .001) and moderately agreed for ssFSE sequences (tau = 0.49, p < .001).

On average, over all three fast sequences analyzed, atrophy (100 % of findings visible), hygromas (100 %), pneumocephalus (96 %), defect cavities (90 %), and tumors (90 %) were best visible in terms of percentage.

For most types of findings, the differences in visibility between the three fast T2 sequences were small and not statistically significant. However, some types of findings achieved significant differences (asterisk on ▶ **Fig. 2**). In clips, VC was superior to ssFSE (p = .04) and bSSFP was better than ssFSE (p = .04). For edema, both bSSFP (p = .03) and ssFSE (p = .48) were superior to VC. For heterotopia, bSSFP was superior to both ssFSE (p < .001) and VC (p = .04).

Discussion

This study was the first to assess the ability of the three fast to ultrafast T2 sequences, insensitive to macromotion, to delineate different pathological findings in the pediatric brain compared to a conventional T2 FSE sequence.

The two fast sequences are common, conventional sequences that are implemented by every MRI manufacturer: the ssFSE as HASTE, single-shot TSE or FASE, and the bSSFP as TrueFISP, FIESTA, Balanced FFE, True SSFP or balanced SARGE. The VC, the third sequence examined, plays a special role on account of its high speed (around seven times faster than the ssFSE and bSSFP). In sedation-

▶ **Table 2** Proportion of the number of visible findings (scores 2 and 3) compared to the total number of findings (scores 0 to 3), each assessed in different fast T2-weighted sequences.

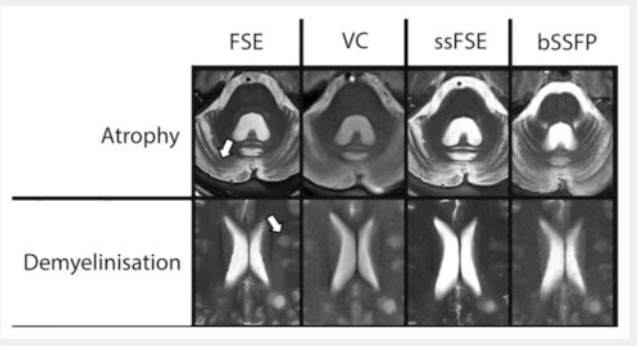
Lesion type	*No. of findings*	*VC*	*bSSFP*	*ssFSE*	*Total*
Atrophy	6	100 %	100 %	100 %	**100 %**
Hygroma	8	100 %	100 %	100 %	**100 %**
Pneumocephalus	9	100 %	100 %	89 %	**96 %**
Cavity	14	86 %	93 %	93 %	**90 %**
Tumor	65	83 %	94 %	94 %	**90 %**
Linear defect	6	83 %	83 %	100 %	**89 %**
Catheter	21	81 %	95 %	86 %	**87 %**
Edema	21	62 %	90 %	95 %	**83 %**
Cyst	9	78 %	67 %	100 %	**81 %**
Clip	3	100 %	100 %	0 %	**67 %**
Gliosis	31	61 %	61 %	71 %	**65 %**
Heterotopia	10	80 %	90 %	20 %	**63 %**
Hamartoma	10	60 %	70 %	60 %	**63 %**
Hemorrhage	18	59 %	67 %	59 %	**61 %**
Demyelination	43	56 %	65 %	58 %	**60 %**
Tuber	10	30 %	50 %	60 %	**47 %**

VC: volume coverage; bSSFP: balanced steady-state free precession; ssFSE: single-shot fast spin-echo

free examinations, the term ultrafast refers primarily to the acquisition time per image. This is the most relevant parameter for freezing motion. Whether the acquisition time of the entire sequence is extended by 5–6 seconds (as for the ultrafast VC sequence) in this context is of little relevance for the patient's discomfort. Although in principle applicable to any MRI, this sequence has so far only been implemented for Siemens MRI machines and is commercially available from the developers [5].

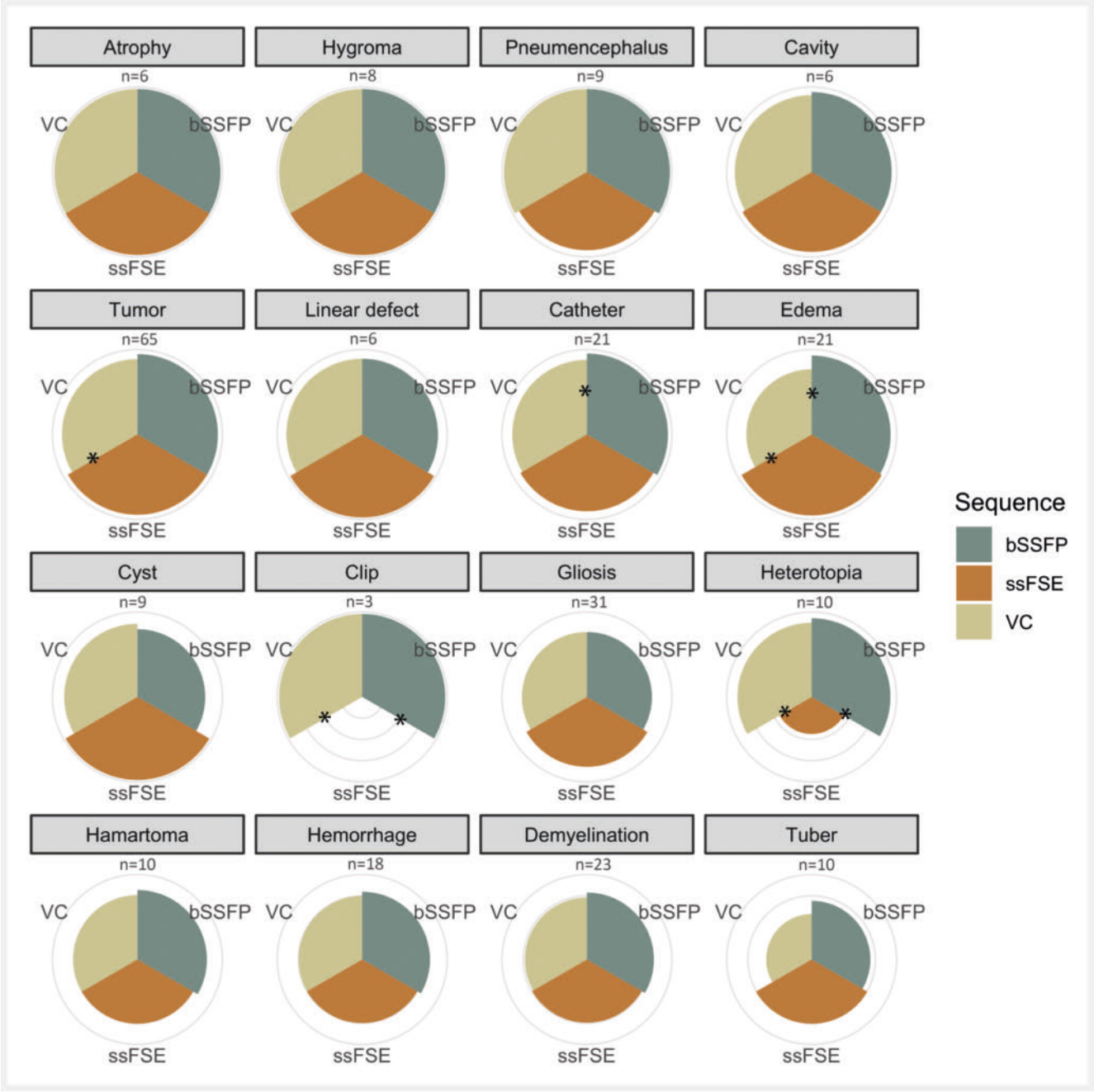
For most of the 16 different types of findings, no significant differences were found between the three fast sequence types. A large proportion of the findings diagnosed in T2 FSE, including findings whose delineation was not exclusively attributable to the well-known excellent parenchyma-to-CSF contrast (i. e., tissue-to-tissue contrast, tissue-to-air contrast, tissue-to-foreign-body contrast), were also visible in VC, ssFSE, and bSSFP in more than 80 % of cases.

However, this essentially positive finding is countered by the fact that fast and ultrafast sequences cannot always achieve the same diagnostic power of a standard T2-FSE sequence. 10 % of the tumors and 20 % of the edemas could not be reliably differentiated in the fast sequences, and for some entities the fast sequences only reached detection rates of 47 % (tuber in tuberous sclerosis) to 60 % (demyelination in multiple sclerosis). With ultrafast VC, the visualization of edema was slightly worse compared to the two fast T2 sequences. The ssFSE sequence as spin-echo sequence was expectedly inferior in the visualization of metal clips due to their susceptibility artifacts but also in the depiction of heterotopias.



▶ **Fig. 1** Illustration of two representative types of findings in the T2 fast spin-echo (FSE) sequence as a reference as well as in the volume coverage (VC), single-shot fast spin-echo (ssFSE), and balanced steady-state free precession (bSSFP) sequence. An arrow indicates a representative pathology in the T2-FSE.

The question arises as to which indications justify the use of fast and ultrafast T2 sequences. There is broad agreement that they can be applied in hydrocephalus imaging, especially in follow-up imaging [10, 11]. For other indications, such as trauma, rapid and sedation-free protocols have also been successfully described in conjunction with other weightings [12, 13, 14]. However, the success of the latter measurement protocols is not directly comparable to the aim of our study, which only relates to the visualization of pathologies in T2 weighting.

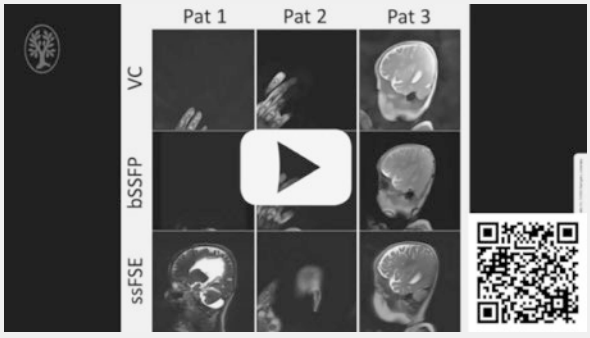


▶ **Fig. 2** Delineation of different types of findings in two fast or one ultrafast, T2-weighted sequences. The larger the slice of the pie, the more findings of this type were visible, with a T2 fast spin-echo sequence as reference. When the outer ring of the pie was reached, 100 % of the findings were visualized. Significant differences are marked with an asterisk. The lesion type "Clip" was not detected in ssFSE (ssFSE: single shot fast spin-echo; bSSFP: balanced steady-state free-precession; VC: volume coverage).

Concerning brain findings other than CSF alterations, the figures presented in this study are somewhat sobering. That said, in everyday clinical practice, it is often not necessary to rule out every differential diagnosis with 100 % confidence. In many situations, it is sufficient to make threatening diagnoses less likely. For example, in many situations it will be satisfactory for the treating physician if hydrocephalus as the causative pathology can be reliably ruled out with sedation-free fast MRI in an infant with persistent vomiting, therefore making a space-occupying hemorrhage or tumor very unlikely.

A fast MRI examination can reduce the urgency of a further, more detailed, MRI workup or, in the best case, make it unnecessary if the symptoms have subsided in the meantime or if an alternative cause for the symptoms has been identified. This approach is beneficial for the children as well as for the economic resources of the hospital by dispensing with anesthetists and employing a relevantly short overall MRI examination time [15]. Finally, the

OP-VIDEO



▶ **Video 1** Comparison of artifacts in three infants with active spontaneous gross motion. The sagittal plane is shown for volume coverage (VC), the balanced steady-state free-precession (bSSFP) and the single-shot fast spin-echo (ssFSE) sequence. The figure serves to illustrate the different artifact characteristics. Neither the patients nor the sagittal acquisition was part of this study.

soft-tissue contrast of MRI, even with fast sequences, is known to be superior to that of CT but without the use of ionizing radiation, even though this was not part of the study.

The aspect of resistance to movement artifacts, which is equally important for application in young children, was not part of the study, but has already been studied elsewhere [2, 3, 4]. To get an impression of the artifact resistance of the three fast sequences employed in this study, there are supplemental ▶ **Video 1** recordings of 3 different infants and toddlers with clear gross motion.

This study has some limitations. First, the different resistances to artifacts of the three fast T2 weightings was not a criterion for the visualization of the findings, although in a real clinical setting the two are closely linked and different types of motion artifacts could obscure the findings in different ways. However, resistance to gross motion has already been described separately [2, 3, 4]. Secondly, it cannot be ruled out that a change in specific sequence parameters would shift the result in favor of or against one or the other of the fast sequences. The parameters for the fast sequences were not harmonized in the context of the study. However, reasonable sequence parameters established over many years of clinical practice were used and led to good subjective image quality. Finally, six groups of findings contained fewer than 10 samples, which reduced the study's statistical power.

In summary, apart from the known reliable assessment of the CSF space, none of the three fast sequences evaluated allowed equally precise visualization of the examined brain parenchymal changes as the T2 FSE sequence. The ultrafast VC sequence, at seven times the speed of conventional fast sequences such as bSSFP and ssFSE, allowed a largely equivalent differentiation of the examined neuropediatric pathologies (except mainly for edema) and thus can help with low-threshold triage of patients.

Clinical relevance:

- Fast T2-weighted sequences are a valid alternative for depiction of many common cerebral findings in children (such as atrophy, hygroma and many tumors).
- The ultrafast volume coverage sequence allows a very similar delineation of findings at seven times the speed of conventional fast sequences.
- When fast T2-weighted sequences do not already solve the clinical question, they might facilitate further triage.

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Conflict of Interest

Jens Frahm and Dirk Voit are co-inventors of a patent and software describing the real-time MRI technique used here. The other authors declare no conflicts of interest.

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