ORIGINAL RESEARCH

Comparing CT-like bone images based on FRACTURE MR with CT in pediatric congenital vertebral anomalies

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ABSTRACT

BACKGROUND AND PURPOSE: Congenital vertebral anomalies are commonly associated with underlying spinal cord anomaly which necessitates imaging both the spinal cord and the bony vertebral column to understand the extent of the deformity better. While MRI is the gold standard for spinal cord imaging, it does not provide CT-like bone details. Many MR bone imaging techniques have been tested in various adult spine conditions in the past decade but not much has been described on their reliability in pediatric spine. We elaborate on our experience with Fast field echo resembling a CT using restricted echo spacing (FRACTURE) MR bone imaging in congenital vertebral anomalies in children.

MATERIALS AND METHODS: 11 pediatric patients referred to the imaging department for CT and MR study of congenital vertebral anomaly were prospectively included. After receiving informed consent from these patient's guardians, both studies were performed in a single setting and under a single sedation. FRACTURE MR was accelerated using the compressed SENSE technique to reduce the imaging time. We then compared FRACTURE MR and CT images for image quality and studied parameters like formation or segmentation anomalies, anomalous shape of vertebrae, and alignment deformities.

RESULTS: FRACTURE MR showed acceptable image quality with diagnostically limiting artifacts in only 1 patient. The inter-reader agreement was perfect in the assessment of vertebral body segmentation or formation anomaly and alignment abnormalities, and it was substantial for posterior element anomalies. The bone signal was lower in children under the age of 3 years of age due to a more immature and cartilaginous skeleton.

CONCLUSIONS: FRACTURE MR provides images of acceptable quality in pediatric spinal anomalies. The addition of this novel sequence can be complementary to conventional MR in providing osseous details and CT can be reserved for certain specific indications like post operative cases. This can help in reducing the radiation dose to this group of pediatric patients who will be serially followed up with imaging during their management.

ABBREVIATIONS: FRACTURE – Fats field echo resembling a CT using restricted echo spacing, CS – Compressed SENSE, KF – Klippel Feil, GRE – Gradient echo, UTE – Ultrashort Time to echo, ZTE – Zero Time to echo, CNR – Contrast-to-noise ratio, SNR – Signal-to-noise ratio, MSK - Musculoskeletal

Received month day, year; accepted after revision month day, year.
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Philips Healthcare provided the MR sequence "FRACTURE" for trial purposes to the institute with which both authors are affiliated. There are no financial disclosures.

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SUMMARY SECTION

PREVIOUS LITERATURE: The feasibility of different MR bone imaging techniques like T1GRE, UTE, ZTE, and SWI has been described in the past decade mainly focusing on adult vertebral pathologies. Their results showed acceptable image quality and reliability in morphometric assessments of vertebral disorders. Not much has been described about their use and challenges in pediatric spine, the age group that can benefit the most from avoiding radiation-based imaging techniques. We describe our experience with one such MR bone imaging technique called FRACTURE (Fast field echo resembling a CT using restricted echo spacing) MR in pediatric congenital vertebral anomalies and compare it to CT.

KEY FINDINGS: The image quality of FRACTURE MR images was acceptable with excellent performance in the assessment of the extent of deformity when compared to gold standard CT. The bone signal and cortical trabecular differentiation are excellent in older children, but the bone signal is lower in younger children (<3 years) with more cartilaginous bones.

KNOWLEDGE ADVANCEMENT: FRACTURE MR can complement conventional MR in comprehensive imaging of vertebral anomalies in children by providing osseous details, reducing the need for additional study, and avoiding radiation. The age of a child can have an impact on the bone signal, but it is not usually limiting in the diagnosis of formation and segmentation anomaly.

INTRODUCTION

Congenital anomalies of vertebral segmentation or fusion are frequently associated with underlying cord abnormalities, ranging from 35-53%. [1,2] This necessitates imaging both the osseous and neural components of the spinal deformity. MRI is the gold standard for imaging the spine, provides excellent soft tissue resolution and multiplanar images, and is free of ionizing radiation. However, one major drawback of the conventional MR sequences is the inability to provide bone details as they lack free water. CT is the current gold standard for bone imaging, but it uses ionizing radiation. Imaging a patient with two different modalities for the comprehensive study of pathology results in complexity in the workflow and patient transfer with increased time and cost. All these factors altogether become more important when imaging young children and infants where sedation comes into play to reduce motion artifacts and obtain optimal image quality. This can be streamlined if we can obtain CT-like bone images on MR, but this is a challenge as bone lacks free protons and the dark signal of the cortical bone obtained on conventional MR bone sequences is not specific to it. Routine MR protocols for musculoskeletal imaging employ the use of T1W SE or GRE images for structural bone imaging with fat suppression or water excitation techniques. In recent years, clinical radiology has been introduced to a few MR-based bone imaging techniques that increase bone specificity on MR by providing uniform soft tissue contrast or giving CT-like images. These newer techniques include SWI, ultrashort and zero TE techniques, 3D GRE techniques, and synthetic CTs with advanced post-processing techniques to generate CT-like images.[3] Each of these techniques has its strengths and weaknesses when factors like large-scale applicability, cost, scanning time and post-processing time, susceptibility to artifacts, and its ability to differentiate cortical and cancellous bone are considered. The feasibility of these MR bone imaging techniques has been studied in a few adult and pediatric conditions like head trauma, musculoskeletal pathologies, and craniosynostosis. [4,5] [6,7,8,9,10] But most commonly, the utility of these techniques has been studied in adult vertebral degenerative changes, mainly comparing the diagnostic performance of UTE and GRE bone imaging.[11,12,13,14] These studies in adult vertebral disorders have shown acceptable results with good agreement with CT or histology as the gold standard in the morphological and quantitative assessment of the adult spine. There is not much literature on MR bone imaging in pediatric spinal disorders. We describe our experience with a novel MR bone imaging technique called Fast field echo Resembling A CT Using Restricted Echo spacing (FRACTURE) MR in complex pediatric spinal anomalies. FRACTURE MR is a high-resolution 3D GRE technique that uses multiple constantly spaced echoes at the in phase of a 1.5T or 3T magnet. [10,15] Our study aimed to determine the reliability of FRACTURE MR for bone details in pediatric spinal anomalies as compared to the gold standard CT and to see if it can provide the intuitive CT-like bone appearance which is preferred by radiologists and spine surgeons.

MATERIALS AND METHODS

Study Design: The study was carried out prospectively after receiving approval from the institutional ethics board. The patient or their guardians were informed about the additional MR sequence that will be performed in imaging the child in addition to conventional MR and CT. An informed consent was obtained from them as per the consent forms approved by the ethics committee. The STROBE checklist was used to ensure completeness of this study.

Patient characteristics: Inclusion criteria – (1) Age under 18 years of age (2) Referral for both MRI and CT imaging of the spine (3) No contraindication to MRI or sedation. Exclusion criteria – (1) Patients more than 18 years of age (2) Only one of the two imaging modalities from MR and CT requested by the referring team (3) Patients uncooperative for imaging without sedation but have a contraindication to sedation (4) Postoperative patients with metallic implants.

Imaging technique: MRI was performed on a 3Tesla Ingenia (Philips Healthcare, Netherlands) using a pediatric spine coil. FRACTURE sequence was acquired as a part of the routine conventional MR spine protocol and was accelerated using compressed SENSE (CS). Parameters of the FRACTURE MR sequence are listed in Table 1. A CS factor of 8 was used to reduce the scan time. CT imaging was performed on a 64-slice Siemens scanner with the following protocol parameters: 80kV, 130 mAs, 1 mm slice thickness utilizing bone-specific kernel.

Post-processing: This step includes a summation of the magnitude of all echoes to increase the signal-to-noise ratio (SNR) and then subtracting the image formed by the last echo from the summation to invert the greyscale and give the bone a CT-like image. The resultant image has better contrast between bone, bone marrow, and surrounding tissues.[15]

Image Analysis: Both the CT and FRACTURE MR images were analyzed on the Osirix DICOM image viewer independently by 2 radiologists, one with 13 years and another with 3 years of experience in radiology. All the studies of both modalities were anonymized using the Osirix tool. Different parameters like fusion of the vertebral bodies, posterior elements, presence of anomalous vertebrae (like hemi vertebra, flattened, block or butterfly vertebra, end plate irregularities), and alignment deformity of the spine were studied and described. These parameters were selected based on the rationale that these bony abnormalities need to be assessed or ruled out on imaging to determine the extent of spinal deformity and formulate a definitive surgical plan tailored for each patient. These parameters were first evaluated on FRACTURE MR to remain blinded to the gold standard CT and after a gap of about 3 weeks to avoid memory bias, the same were assessed on CT. The quality of the FRACTURE images was graded on a 4-point Likert scale considering CT as the gold standard as 1- Nondiagnostic 2- Artefacts causing diagnostic dilemma 3- Minimal artifacts not affecting diagnosis and 4- excellent image quality with no artifacts. In addition, the signal-to-noise ratio was calculated by ROIs placed on the vertebral body and in the background air for noise on FRACTURE MR and then using the ratio of mean signal intensity of the bone to standard deviation (SD) of the background noise. Similarly, the contrast between the cortical and cancellous bone was calculated using the ratio of the difference between the mean SI of the cortical and cancellous bone to the SD of the background noise. [14]

Data Analysis: For quantitative analysis of the descriptive data, the findings of both the radiologists on FRACTURE MR and CT were coded and compared to calculate interrater and inter-modality agreement. Minor description variabilities about the deformity were disregarded but major differences like missed or overcalled deformities were considered as disagreement.

Statistical Analysis: All the data was collected using MS Excel and Statistical analysis was performed by the SPSS program for Windows, version 28.0. Agreement between 2 radiologists' opinion was assessed using Cohen's kappa value and compared using Fisher exact test.

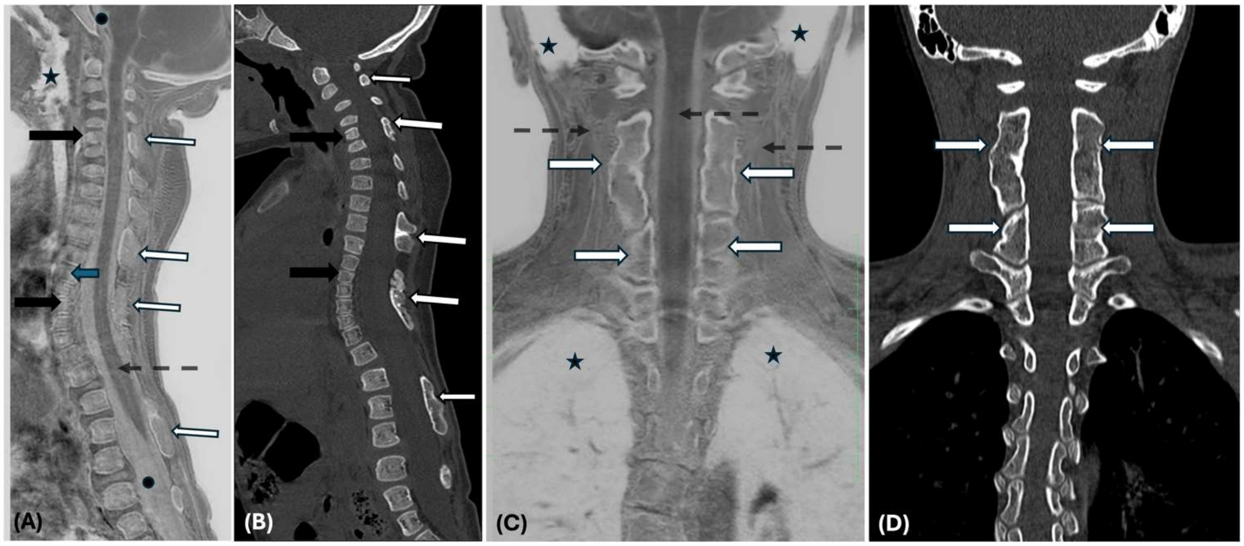


FIG 1.(A) Sagittal CS-FRCATURE MR and (B) CT bone window images of the whole spine of a 2-year-old with Klippel Feil (KF) anomaly show multilevel partial fusion of the cervical and thoracic vertebral bodies (black arrows) and fusion of posterior elements (white arrows). The bone details are well seen on the FRACTURE MRI, but lack of cortical maturation can be seen on images of both the modalities. There are artefacts along the fused lower thoracic vertebrae from adjacent cardiac motion (white arrowhead in a). (C) Coronal CS-FRACTURE MR and (D) CT bone window image of a 13-year-old with KF anomaly show fusion of multiple cervical vertebrae and their posterior elements (white arrows). Also note various normal signal intensities, very bright signal of air in the upper airway, lungs and mastoid air cells (black star in A and C respectively). CSF in the thecal space appears less bright than air (black dot in A), cord and other paraspinal soft tissues appear grey (dotted black arrows in A and C).

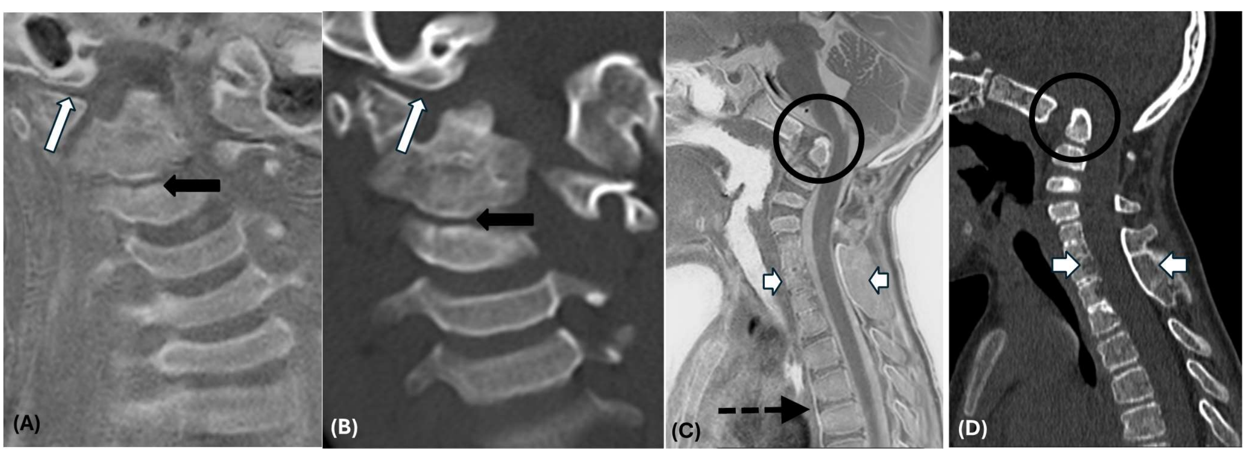


FIG 2. (A) Coronal CS FRACTURE MR mean intensity projection and (B) CT bone window images of a 5-year-old with KF anomaly show right occipital condyle hypoplasia (long white arrows), partial fusion of C2-C3 vertebrae (black arrows) and their posterior elements (not shown) resulting in left torticollis. (C) Sagittal CS-FRACTURE MR and (D) CT bone window in a 6-year-old with KF anomaly show fusion of multiple cervical vertebrae (short white arrows), atlantooccipital assimilation, hypoplastic dens and basilar invagination (black circle). In addition, the acute angulation and effacement of the anterior CSF space at the cervico-medullary junction caused by the changes at the craniovertebral junction are well seen on FRACTURE MRI. The ligaments show a similar bright signal as CSF (dotted black arrow in 2c for anterior longitudinal ligament).

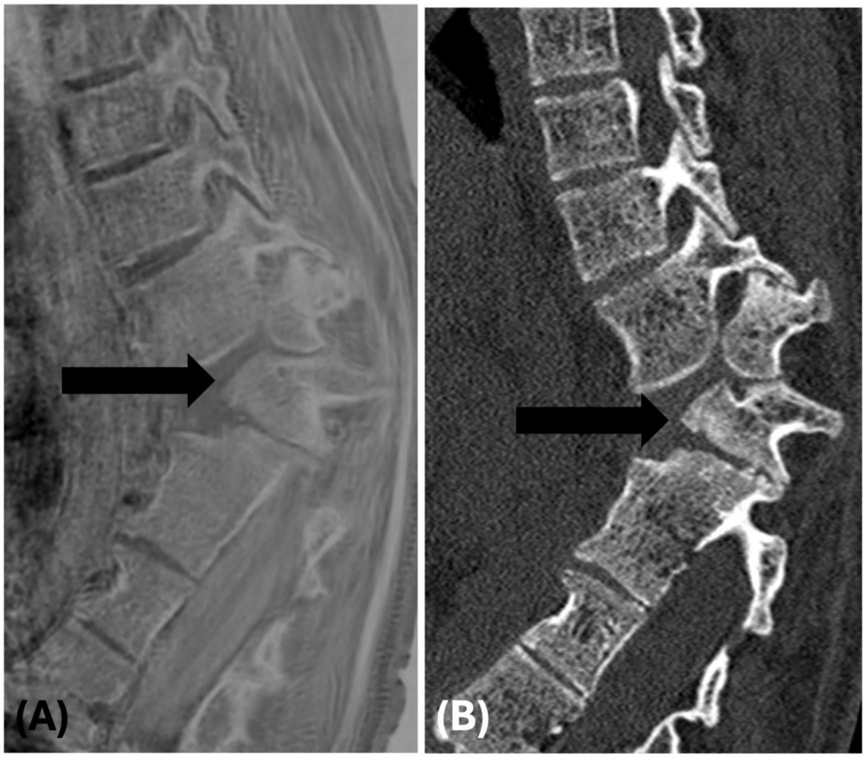


FIG 3. (A) Sagittal CS-FRACTURE MR and (B) CT of the thoracolumbar junction of a 12-year-old show complex fusion segmentation anomaly in form of block and hemivertebrae resulting in a sharp kyphotic deformity (black arrows).

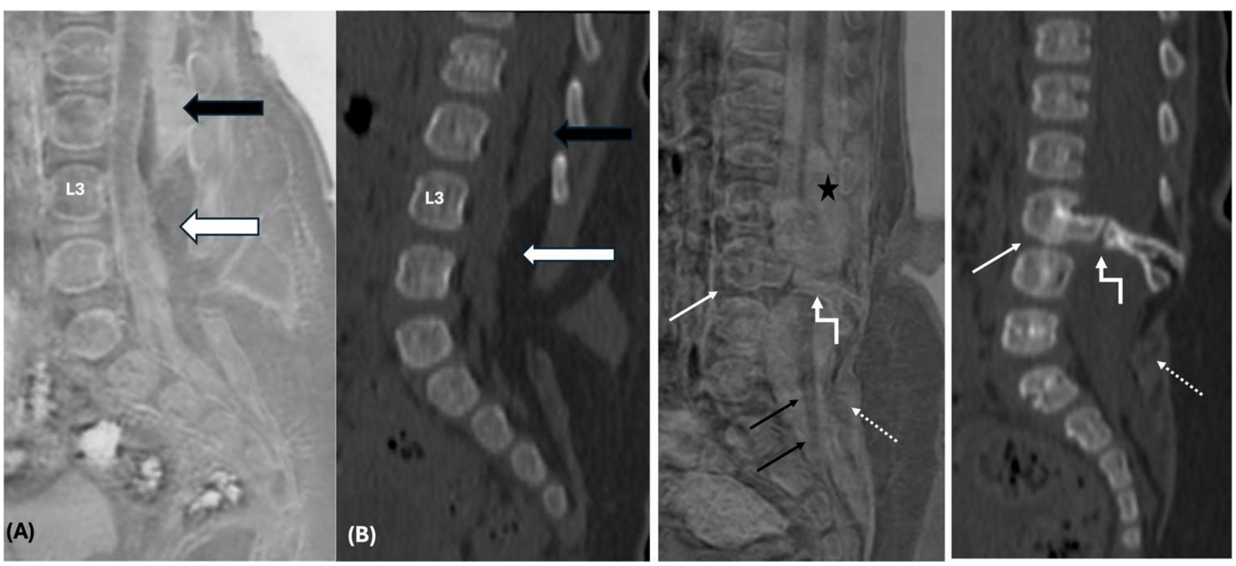


FIG 4. (A) Sagittal CS-FRACTURE MR and (B) CT bone window images in a 6-month-old show defect in the posterior elements from L3 level down with a closed spina bifida deformity. In addition, there is an arachnoid cyst (black arrows) which shows CSF like signal on FRACTURE MRI. The cord is seen low lying and lipoma-neural placode interface lies within the spinal canal suggesting a lipomyelocele (white arrows). (C) Sagittal CS-FRACTURE and (D) CT bone window images in a 6-month-old show partial fusion of L3 and L4 vertebral bodies (white solid arrow), posterior element defects from L4 below (dotted arrow). An osseous bar (elbow arrow) is seen at L3-4 level resulting in hemi cords suggestive of Pang type 1 diastematomyelia. Syrinx (star) and low-lying cord (black arrow) are well seen on FRACTURE images. Also note the low bone signal and lack of cortical maturation in both the patients due their very young age and cartilaginous vertebrae.

RESULTS

11 children with congenital spinal deformities ranging from Klippel Fiel anomaly (n= 6), thoracolumbar vertebral formation-segmentation anomalies (n= 1), and spinal dysraphism (n=4) were included in this study. The youngest patient was 1 month old and the eldest was 13 years old with 8 girls and 3 boys in the study sample.

Image Quality:

The average Likert score of the ratings of all patients by both radiologists was 3.4 for the FRACTURE MR image quality. Minimal artifacts were seen in 3 patients and artifacts limiting the diagnostic quality of FRACTURE MR images were seen in one patient, in the remainder of the 7 patients the image quality was optimal. The total scan time for FRACTURE MR varied from 6-8 mins which was reduced to 2-3 mins using compressed SENSE.

Considering the differences in the fields of view (FOV), matrix size, and slice thickness in different patients, the lowest SNR was 70 and the highest was 150. The contrast of the cortical to cancellous bone was calculated for 5 children who were older than 5 years of age and the average was 19.2, the lowest being 19 and the highest value being 21. The remainder of the 6 children were less than 3 years of age showed immature vertebrae and lacked a well-formed cortex. The CT images in these younger patients also lacked a mature cortex.

Tissue Signal:

The different tissues in the anatomic region of interest on FRACTURE MR images appear as black, white, or in shades of gray. For example, the air in the airway and the lungs appear bright white, and CSF fluid appears bright but less than that of the air signal. Soft tissues like the spinal cord, muscles, solid viscera, cerebellum, and the brainstem appear gray. Rapidly flowing blood in the arteries and the pulmonary vessels appears as a dark signal void similar to their signal on conventional MR. The vertebrae, ileum, sternum, ribs, and all other bones show differential signals for the cortical and trabecular bone. These normal tissue signal intensities have been demonstrated in the images in Figures 1-4. In addition, in 2 of our patients with lipomyelocele and subcutaneous lipoma, there was an anomalous soft tissue that mimicked bone on FRACTURE MR images but lacked ossification on CT, which we presumed represented cartilaginous dysraphic hamartoma with microscopic mineralisation, but the pathology diagnosis could not be traced as the patients were lost to follow up. (Online supplemental figure 2c,d and Figure 4 a, b).

Deformity Variables:

Vertebral Body Fusion: FRACTURE MR performed excellently in assessing the fusion of vertebral bodies with perfect interrater agreement. In one patient with multiple cervical vertebral fusion, the extent of fusion was overcalled and the extent of abnormality also varied in the FRACTURE MR findings of both the readers (Online supplementary Figure 1).

Posterior elements: The results in the assessment of posterior element segmentation or formation anomalies were not consistent. The fusion was underestimated and varied between both readers on FRACTURE MR in one patient with segmentation anomaly and kyphoscoliotic thoracolumbar spine. The extent of fusion was overcalled by the readers in one patient each with right lateral lipomyelomeningocele (Online Supplemental Figure 2a and b) and Klippel Feil anomaly. The second reader underestimated the fusion in a patient with a unilateral segmentation anomaly. Overall, there was substantial to nearing perfect inter-rater and inter-modality agreement.

Anomalous vertebral formation: FRACTURE MR performed excellently in determining the anomalous formation of the vertebra. Both the readers missed mild butterfly deformity with a very faint midline cleft in the cervical spine. In another patient, the artifact across the vertebrae at the level upper to mid thoracic spine were called as abnormal vertebra. Reader 1 interpreted this artifact along the superior end plate of T7 as subtle end plate erosion on a background of end plate erosions at a few other levels in the same patient. Whereas reader 2 interpreted a horizontally oriented artifact as a cleft in the T1 vertebra. Overall, the inter-rater and inter-modality agreement was substantial to perfect.

Alignment deformity: FRACTURE MR images provided optimal details of the alignment deformity like kyphosis, scoliosis, torticollis, and basilar invagination with perfect inter rater and inter modality agreement due to their ability to reformat. Disagreement in one patient was due to inter-rater variability in the description of the cause of left torticollis.

The results of the inter reader and inter modality agreement for different parameters are described in Table 2.

DISCUSSION

In this study, we evaluated the feasibility of the FRACTURE MR images in pediatric congenital spinal anomalies. The quality of the FRACTURE MR images was acceptable in most of our patients with diagnostically limiting artifacts in 1 patient and minimal artifacts in 3 patients. The artifacts in these patients arose from different factors, for example in a patient with a false positive vertebral anomaly on a coronal image acquisition of FRACTURE MR, the horizontally oriented artifact was believed to be from the motion of pulsating aortic arch branches or breathing. Interestingly, this artifact was also seen on CT images at the same level and was believed to be due to breathing artifacts. In another patient with thoracic lordosis, the artifacts were minimal but seemed to be a result of cardiac motion and its proximity to the spine due to thoracic lordosis. In the other 2 patients, the artifacts were from mild motion resulting from the fading effect of sedation. It has been described that GRE, UTE, and ZTE techniques are all prone to motion and susceptibility from air in the lungs or metallic implants in the vicinity. However, UTE is known to be more prone to pulsation and motion, and GRE is more likely to be affected by susceptibility artifacts. ZTE is believed to be robust to motion due to its rapid k-space sampling. [3,13,14.]

The signal-to-noise ratio of the bone was in the acceptable range but lower in children less than 3 years of age due to their immature cartilaginous skeleton. There was a good contrast of the cortical to the trabecular bone in all patients more than 5 years of age with relatively mature skeletons than the younger children with more cartilaginous skeletons. (Figure 1a, 4a and 4c, OS Figure 2a and 2c). However, the lower bone signal in younger children was not diagnostically limiting. The agreement between the two modalities for each reader was perfect in assessing vertebral fusion, anomalous shape, and alignment deformity but was moderate to substantial for posterior element segmentation and formation anomaly. The misinterpretations of posterior elements were mainly in children with complex spinal anomalies with multilevel fusion and formation anomalies. We believe that the small size and abnormal orientation of the dysplastic posterior elements on a background of paraspinal soft tissue details results in a diagnostic dilemma. Most studies on GRE bone imaging in adult vertebral pathologies focus on evaluating vertebral endplate changes, neural foramen stenosis, or spondylolysis. However, these studies do not address pathologies necessitating detailed assessment of the posterior elements, which is primarily required in pediatric congenital vertebral anomalies. These studies describe GRE images to have a higher spatial resolution, better bone-to-soft tissue contrast, and sharper images as compared to UTE.[3,11,13] UTE/ ZTE MR bone images have a flatter contrast of the soft tissues making bone stand out as bright structures on a background of uniform gray signal of the surrounding soft tissue structures.[14]

Special considerations in pediatric MR bone imaging include the need for sedation, smaller anatomy, and immature ossification of the skeleton in neonates and early childhood which can potentially pose challenges in obtaining optimal signal from osseous structures. Our experience with FRACTURE MR showed that it is feasible to use this novel MR technique in pediatric spine especially in older children (more than 3 years age) with better ossified vertebrae as compared to the very young. The sedation needed for the added sequence can be covered under the same sedation of conventional MR sequences or may require tailoring for the length of the study, this varies among children. The images obtained have optimal bone contrast with good resolution. But there are some challenges with GRE bone images like FRACTURE MR which have been described with adult vertebral imaging as well. Ligaments, tendons, fascia, air, and edema all appear white on these GRE-based MR bone images (demonstrated in Figure 1a and 2c) which can cause diagnostic errors and interfere with bone segmentation. Based on this, we can presume that marrow edema due to subtle vertebral fractures, trabecular injuries, or infection can be missed as it will appear white on these inverted scale images and can alter management. This becomes particularly important in cases suspected of non-accidental injuries. In the use of these sequences in adult vertebral pathologies, it has been suggested that conventional fluid-sensitive MR images can be helpful in such cases to identify areas of bone marrow edema.[3,13,16] For diagnosis of true sclerosis, GRE images were found to be superior to UTE and SWI.[17,18] Calcification of the ligaments and intervertebral air are not commonly encountered in pediatric spine pathologies but these factors in general become important if we intend to use these in pediatric MSK imaging and head injuries. In head trauma, we presume that the fractures in the vicinity of the pneumatized bones like paranasal sinuses and mastoids can be missed on FRACTURE MR as has been described with black bone imaging due to similar signals of air and bone.[5]

Of the different techniques available for bone imaging, FRACTURE MR holds many advantages. Being a 3D GRE technique-based sequence, it is widely available on most of the commonly used scanners and is also independent of the magnetic field strength, allowing wide-scale applicability. Second, the images obtained have high spatial resolution with good bone-to-soft tissue contrast. Also, the images obtained are 3D making reformations possible. Third, the post-processing is simple and minimal to obtain CT-like images.[15] On the other hand, techniques like UTE and ZTE have high-end software hardware requirements and provide CT-like images of lesser CNR as compared to the GRE images. They also have spatially nonselective excitations which induce large FOVs and reduce their flexibility with respect to other parameters. Hence not much trade-off between the spatial resolution, FOV, and time for imaging can be achieved with this sequence. SWI bone imaging though easily accessible with minimal post-processing is dependent on field strength.[3,11,13,19] A negative correlation was found between the sensitivity of SWI black bone imaging and magnetic field strength in pediatric head imaging for traumatic brain injuries.[5]

It is worthwhile to mention that there are some limitations to the use of FRACTURE MR in routine practice across different age groups and indications. First, it is the scan time which can be up to 6-8 minutes in pediatric spine and even higher in larger FOVs like adult spines. This drawback is more or less common to all MR bone imaging sequences The scan time can be reduced nearly to half by using parallel imaging techniques like compressed SENSE as in our case. This duration is still longer than the acquisition time of the CT spine which is a matter of a few seconds. This increases the possibility of motion artifacts in non-sedated children and makes it an impractical choice in acute trauma patients. The other drawback is its limited use in post-operative patients with metallic implants due to susceptibility artifacts. Third, compatibility of FRACTURE MR images with neuro navigation systems is not yet established. Synthetic CTs and artificial intelligence-guided post-processing techniques might help in the future in achieving these shortcomings.[20,21]

There are also some limitations in our study which we acknowledge. First, the cohort of pediatric patients is small and from a single center, thereby not considering the technical differences between the studies. Second, we have focused only on congenital spinal anomalies and have not studied their use in pediatric spine trauma, vertebral tumors, or osteomyelitis. Third, we did not compare the performance of FRACTURE MR with the conventional MR sequences or other MR bone imaging techniques.

Table 1: Parameter settings of the FRCATURE (Fast field echo resembling a CT using restricted echo spacing) MR sequence

Number of slices	80
Slice gap (mm)	0.6-1mm
Sensitivity encoding	Yes
Stacks	1
Fold over suppression	Oversampling
Flip angle (°)	8
TR (ms)	11.2
TE (ms) (in-phase)	1.8
Echo-spacing (ms)	2.3
Shim	Default

Table 2: Parameter settings of the FRCATURE (Fast field echo resembling a CT using restricted echo spacing) MR sequence

Parameter	Radiologist 1			Radiologist 2			Inter Reader Reliability
	CT-MR agreement (%)	Sensitivity (%)	Specificity (%)	CT-MR agreement (%)	Sensitivity (%)	Specificity (%)	
Vertebral body fusion	91	100	75	91	100	75	91
Posterior elements fusion	82	89	50	64	78	50	64
Anomalous vertebral shape	82	80	82	82	80	83	91
Alignment	100	100	100	100	100	100	91

CONCLUSIONS

FRACTURE MR is reliable for bone imaging in pediatric complex spinal anomalies with substantial to perfect agreement between the two modalities. The bone signal is lower in children less than 3 years due to a more cartilaginous skeleton. Despite some drawbacks of the sequences, it has the potential to complement conventional MR sequences in place of CT for bone assessment in pediatric complex spinal anomalies. This can reduce the radiation dose and an additional study in this group of pediatric patients who will be serially followed up with imaging during their management. We believe that FRACTURE MR still in its naïve form cannot replace CT at least in trauma due to time constraints and post-operative studies due to susceptibility from metallic implants. Whether it holds potential in pediatric spine trauma or other vertebral pathologies needs to be evaluated by additional studies.

ACKNOWLEDGMENTS

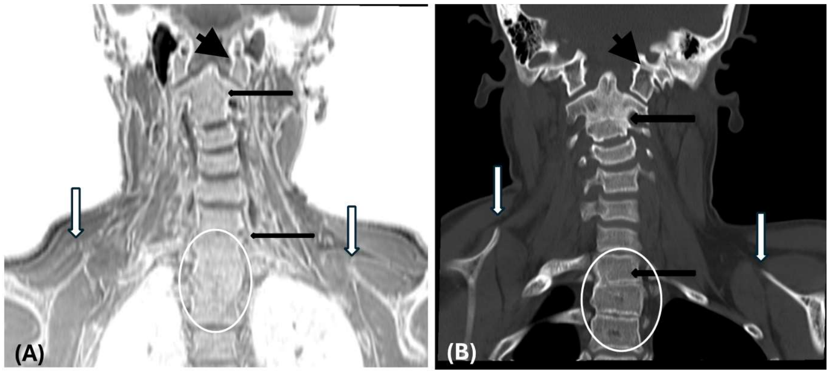
We acknowledge the contribution of Walmik Mistri in statistical analysis of the data.

REFERENCES

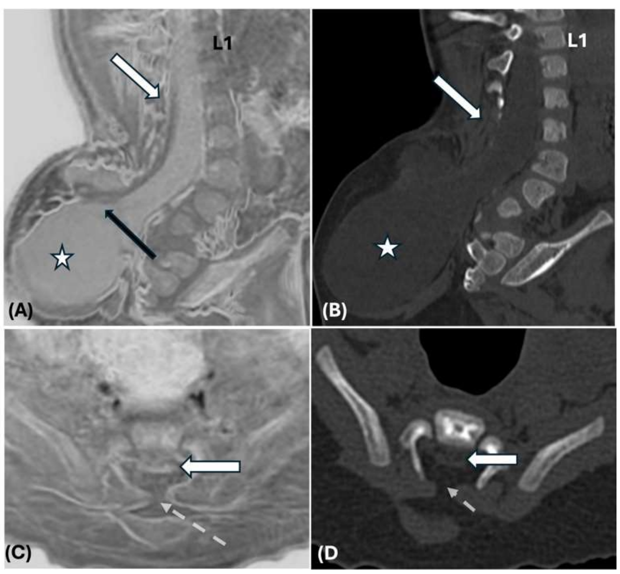
1. Trenga AP, Singla A, Feger MA, Abel MF. Patterns of congenital bony spinal deformity and associated neural anomalies on X-ray and magnetic resonance imaging. J Child Orthop. 2016;10(4):343-352. doi:10.1007/s11832-016-0752-6
2. Prahinski JR, Polly DW, McHale KA, Ellenbogen RG. Occult Intraspinal Anomalies in Congenital Scoliosis: J Pediatr Orthop. 2000;20(1):59. doi:10.1097/01241398-200001000-00013
3. Florkow MC, Willemsen K, Mascarenhas VV, Oei EHG, Van Stralen M, Seevinck PR. Magnetic Resonance Imaging Versus Computed Tomography for Three-Dimensional Bone Imaging of Musculoskeletal Pathologies: A Review. J Magn Reson Imaging. 2022;56(1):11-34. doi:10.1002/jmri.28067
4. Cho SB, Baek HJ, Ryu KH, et al. Clinical Feasibility of Zero TE Skull MRI in Patients with Head Trauma in Comparison with CT: A Single-Center Study. AJNR Am J Neuroradiol. 2019;40(1):109-115. doi:10.3174/ajnr.A5916
5. Dremmen MHG, Wagner MW, Bosemani T, et al. Does the Addition of a "Black Bone" Sequence to a Fast Multisequence Trauma MR Protocol Allow MRI to Replace CT after Traumatic Brain Injury in Children? AJNR Am J Neuroradiol. 2017;38(11):2187-2192. doi:10.3174/ajnr.A5405
6. Kralik SF, Supakul N, Wu IC, et al. Black bone MRI with 3D reconstruction for the detection of skull fractures in children with suspected abusive head trauma. Neuroradiology. 2019;61(1):81-87. doi:10.1007/s00234-018-2127-9
7. Sandberg JK, Young VA, Yuan J, Hargreaves BA, Wishah F, Vasanawala SS. Zero echo time pediatric musculoskeletal magnetic resonance imaging: initial experience. Pediatr Radiol. 2021;51(13):2549-2560. doi:10.1007/s00247-021-05125-5
8. Gersing AS, Pfeiffer D, Kopp FK, et al. Evaluation of MR-derived CT-like images and simulated radiographs compared to conventional radiography in patients with benign and malignant bone tumors. Eur Radiol. 2019;29(1):13-21. doi:10.1007/s00330-018-5450-y
9. Low XZ, Lim MC, Nga V, Sundar G, Tan AP. Clinical application of "black bone" imaging in paediatric craniofacial disorders. Br J Radiol.

2021;94(1124):20200061. doi:10.1259/bjr.20200061
10. Leonhardt Y, Kronthaler S, Feuerriegel G, et al. CT-like MR-derived Images for the Assessment of Craniosynostosis and other Pathologies of the Pediatric Skull. Clin Neuroradiol. 2023;33(1):57-64. doi:10.1007/s00062-022-01182-x
11. Deininger-Czermak E, Gascho D, Franckenberg S, et al. Added value of ultra-short echo time and fast field echo using restricted echo-spacing MR imaging in the assessment of the osseous cervical spine. Radiol Med (Torino). 2023;128(2):234-241. doi:10.1007/s11547-023-01589-7
12. Gassert FT, Kufner A, Renz M, et al. Comparing CT -Like Images Based on ULTRA-SHORT Echo Time and Gradient Echo T1-WEIGHTED MRI Sequences for the Assessment of Vertebral Disorders Using Histology and True CT as the Reference Standard. J Magn Reson Imaging. 2024;59(5):1542-1552. doi:10.1002/jmri.28927
13. Schwaiger BJ, Schneider C, Kronthaler S, et al. CT-like images based on T1 spoiled gradient-echo and ultra-short echo time MRI sequences for the assessment of vertebral fractures and degenerative bone changes of the spine. Eur Radiol. 2021;31(7):4680-4689. doi:10.1007/s00330-020-07597-9
14. Vucevic D, Malis V, Yamashita Y, et al. Ultrashort Echo Time and Fast Field Echo Imaging for Spine Bone Imaging with Application in Spondylolysis Evaluation. Computation. 2024;12(8):152. doi:10.3390/computation12080152
15. Johnson B, Alizai H, Dempsey M. Fast field echo resembling a CT using restricted echo-spacing (FRACTURE): a novel MRI technique with superior bone contrast. Skeletal Radiol. 2021;50(8):1705-1713. doi:10.1007/s00256-020-03659-7
16. Gascho D, Zoelch N, Tappero C, et al. FRACTURE MRI: Optimized 3D multi-echo in-phase sequence for bone damage assessment in craniocerebral gunshot injuries. Diagn Interv Imaging. 2020;101(9):611-615. doi:10.1016/j.diii.2020.02.010
17. Diekhoff T, Hermann KGA, Greese J, et al. Comparison of MRI with radiography for detecting structural lesions of the sacroiliac joint using CT as standard of reference: results from the SIMACT study. Ann Rheum Dis. 2017;76(9):1502-1508. doi:10.1136/annrheumdis-2016-210640
18. Diekhoff T, Greese J, Sieper J, Poddubnyy D, Hamm B, Hermann KGA. Improved detection of erosions in the sacroiliac joints on MRI with volumetric interpolated breath-hold examination (VIBE): results from the SIMACT study. Ann Rheum Dis. 2018;77(11):1585-1589. doi:10.1136/annrheumdis-2018-213393
19. Tsuchiya K, Gomyo M, Katase S, Hiraoka S, Tateishi H. Magnetic resonance bone imaging: applications to vertebral lesions. Jpn J Radiol. 2023;41(11):1173-1185. doi:10.1007/s11604-023-01449-4
20. Lombardi AF, Ma YJ, Jang H, et al. Synthetic CT in Musculoskeletal Disorders: A Systematic Review. Invest Radiol. 2023;58(1):43-59. doi:10.1097/RLI.0000000000000916
21. Chong LR, Lee K, Sim FY. 3D MRI with CT-like bone contrast – An overview of current approaches and practical clinical implementation. Eur J Radiol. 2021;143:109915. doi:10.1016/j.ejrad.2021.109915

SUPPLEMENTAL FILES



Supplemental Figure 1 (A) Coronal CS-FRACTURE MR reformats and (B) CT bone window images of the cervical spine of a 12-year-old with KF anomaly show atlanto-occipital assimilation (black arrowhead), fusion of C2-C3 and C7-T3 vertebrae (black arrows) and bilateral Sprengel's shoulder (white arrows) with the superomedial angle of right scapula at C7 and that of left scapula at T1 level. Note how the rudimentary intervertebral spaces seen on CT between T1-T3 vertebrae are not appreciated on FRACTURE MR (white oval).



Supplemental Figure 2 (A) Oblique coronal reformatted CS-FRACTURE MR and (B) Oblique coronal CT bone window images of the lumbar spine in a 2-year-old show spina bifida from L1 level down to sacrum (white arrow) with a large lipomyelomeningocele through it (white star). The lipoma-neural placode interface is seen outside the spinal canal in the CSF filled sac on the FRACTURE MR (black arrow). (C) Axial CS-FRACTURE MR images and (D) CT bone window images of a 1-month-old with closed spina bifida show posterior elements defect at L4 level (red arrow) and further down. The cord is low lying and lipoma-neural placode interface lies within the spinal canal suggesting a lipomyelocele (white arrows). Again, we see the low bone signal and lack of cortical maturation in both the patients due to their young age.