# Functional High-Resolution 3D Examinations of the Cervical Spine with Magnetic Resonance Imaging

K. E. W. Eberhardt[1], M. Duetsch[2], R. Schindler[3], J. Liebisch[1], C. v. Stauffenberg[4], H. Fischer[4], J. Weigel[1], F. A. Fellner[5,6]

[1] *Division of Neuroradiology, Department of Neurosurgery, Erlangen-Nuremberg University, Erlangen, Germany*
[2] *Department of Neurology, Erlangen-Nuremberg University, Erlangen, Germany*
[3] *Inside, Functional Diagnostic Technology GmbH, Schweinfurt, Germany*
[4] *Siemens AG, Medical Solutions, Erlangen, Germany*
[5] *Institute of Radiology, Upper Austrian State Nerve Hospital Wagner-Jauregg, Linz, Austria*
[6] *Department of Radiology, Erlangen-Nuremberg University, Erlangen, Germany*

**Keywords**
• MRT • myelography • cervical spine functional study • HASTE 3D

## Introduction

Functional examinations of the cervical spine have been performed since the mid-1990s. In contrast to the lumbar spine, gravity has a limited effect on the function of the cervical spine. The primary task of mechanical support systems is therefore to allow passive movements of the cervical spine. Fast and ultrafast MRI sequences make it possible to image the cervical spine during movement. All of the mechanical systems implemented to date have specific disadvantages, such as the lack of reproducibility, the often unphysiological pattern of motions, the significantly poorer signal-to-noise ratio of the measurements as compared to studies in the standard position, and the general limitation to one plane of movement. Moreover, the lack of a sequence specifically adapted to the requirements of the neck region is another limiting factor that has prevented high-resolution examinations in the past. Even open MRI systems are subject to the same limiting factors in spite of their improved patient accessibility. As a result, although several functional examinations of the cervical spine have been published [1-6], they have not become a part of the clinical routine. The principal utility of cervical spine examinations is the detection of primary changes in the intervertebral disks and the bony spinal canal as well as lesions of structures important for movement, such as ligaments and vertebral joints. Certain pathologies can be imaged for the first time (such as lesions from whiplash injuries, displacement of vertebra during inclination and reclination, or lateroflexion as in spondylolisthesis [1-6]). Decisions regarding therapy (conservative or surgical) can be adapted better to the individual anatomic conditions of patients and surgical requirements, especially for extensive degenerative diseases. Surgical interventions have lower risks, and the rehabilitation phase after surgery can be shortened. For this purpose, the development of an auxiliary device for functional MRI examinations of the cervical spine has to address three primary requirements:

1. Enable reproducible high-resolution MRI examinations in all desired functional positions.
2. Permit rapid functional survey (screening) in all functional planes in less then 10 min as an aid for planning high-resolution examinations.
3. Offer sufficient reliability to allow standardization for routine use.

This paper demonstrates the first results of a study that examines the use of a newly developed device as well as a 3D myelography sequence specifically adapted to the requirements of the neck region.

## Materials and Methods

All measurements were performed using a 1.5 Tesla whole-body MRI system (MAGNETOM Sonata, Siemens AG, Medical Solutions, Erlangen). A combination of surface coils was used to optimize the signal-to-noise ratio. The following sequences were used:

SINOP, a gradient double-echo sequence with a bipolar readout gradient [7]: The TR of the sequence is 124.0 ms. The echo time ($TE_{1/2}$) is 2.4 or 4.8 ms, and the excitation angle $\alpha = 70°$. The measurement time is 35 s with a slice thickness of 3 mm, a FoV of 280 mm, and a 256 x 256 matrix. Bone matrix and bone margin appear in “oppose-phase” without signal compared to fat tissue and CSF, while in “in-phase” the bone matrix shows high signal; the bone margin and calcifications of the longitudinal ligament are remaining signal-free. Thus, the bone margin is displayed in “in-phase” with the highest contrast. This sequence was used to measure mobility with sagittal slice images in inclination and reclination.

HASTE-3D, this strongly $T_2$-weighted sequence has been used previously for functional examinations with the Single Shot technique to follow movements [8]. However, adapting it to susceptibility artifacts that occur more frequently in the cervical spine required readjustment of the sequence parameters to obtain sufficient resolution for 3D examinations. The following combination of parameters was used for the first time in functional cervical spine examinations: TR = 7200 ms; TE = 165 ms; slice thickness = 1 mm; FoV = 250 mm; matrix = 256 x 256. The bandwidth was reduced to 150 Hz to maintain an adequate signal-to-noise ratio. The fatty tissue was suppressed via frequency-selective excitation. The measurement time is 3.30 min.

MEDIC-2D and TSE: $T_2$- and $T_1$-weighted, as routine sequences with modified parameters:

MEDIC-2D: TR = 81 ms; TE = 27 ms; $\alpha = 14°$; slice thickness = 3 mm; FoV = 200 mm; matrix = 256 x 256 mm; bandwidth = 130 Hz. The measurement time for 30 slices was approx. 3.30 min.

$T_2$-weighted TSE: TR = 7200 ms; TE = 165 ms; slice thickness = 3 mm; FoV = 250 mm; matrix = 256 x 256; measurement time = 1.30 min.

$T_1$-weighted TSE: TR = 500 ms; TE = 27 ms; slice thickness = 3 mm; FoV = 250 mm; matrix = 256 x 256; measurement time = 1.30 min.

The subjects were positioned in a newly developed, pneumatically operated, device that allowed for steppless, i. e. smooth passive movement of the spine (Inside, Funktionelle Diagnosetechnik, Schweinfurt). This device can be moved passively into any desired position for inclination and reclination by means of an externally controlled pneumatic drive. Movement for lateroflexion and rotation can be either active or passive.

Combining movements in all three axes easily provides any desired position. The measurements are performed off-center, so that isocenter correction is needed for inclination and reclination, but not for lateroflexion and rotation. A combination of three surface coils (CP small flex-, CP Neck Array and Spine Array) is integrated into the device to obtain sufficient signal-to-noise ratio. Reproducibility of results is assured by inflation of the pneumatically operated device by a predetermined air volume allowing for comparable extents of inclination and reclination, and by the use of measuring scales for lateroflexion and rotation.

*Subject Information*

Four female and nine male subjects were examined. The average age of the subjects was 29.8 years (SDev: 6.1 years). The average height was 175.4 cm (SDev: 9 cm), and the average weight was 69.5 kg (SDev: 8.9 kg).

*Measurements*

One Flash, one HASTE-3D, one MEDIC-2D, and one TSE with $T_1$ and $T_2$-weighting was performed for each of the 13 subjects in the standard position, inclination, reclination, lateroflexion and rotation. The slices were performed sagittally for inclination and reclination, and coronally or axially for lateroflexion and rotation. The phase coding direction was craniocaudial except for the examination in rotation, when it was directed right-left. Reproducibility tests were performed with 5 subjects.

These measurements were repeated 5 times by three examiners, independently of each other.

*Post-Processing*

Post-processing including segmentation and 3D visualization was performed at a separate workstation (LEONARDO, Siemens AG, Medical Solutions, Erlangen).

*Segmentation*

Because of the heavy $T_2$-weighting and the frequency-selective suppression of fatty tissue, a threshold-based (implicit) segmentation of the 3D data sets from the HASTE sequence was adequate for visualization.

*Visualization*

Visualization enabled via Volume Rendering VR.

*Determination of the Ranges of Movement*

The data from the SINOP sequence was used for the measurements described in the following because bone and calcium could be distinguished accurately from the surroundings. To determine the segmental mobility, we measured the angle in the sagittal plane between the perpendicular to a tangent to the bony basis of the lower vertebra and a tangent to the rear edge of the upper vertebra for all segments from C2/3 to C7/Th1, as recommended by Penning [9]. The differences in the angles in the functional positions indicated the range of motion.

To determine the mobility in lateroflexion, we measured the angle between the tangent to the bony basis of the particular vertebra and a fixed line, which was a perpendicular through the bony basis of cervical vertebra 2 (Dens axis) in the standard position.

In rotation, a tangent to the rear edge of the particular vertebra was used to determine the angle. The reference line was a horizontal line through the hard palate in the standard position.

*Determination of Reproducibility*

Reproducibility was determined in each case by 5 repeated measurements at defined functional positions. Three examiners performed the examinations independently of each other on a total of 5 subjects. To determine the extent of sagittal motion (inclination-reclination), we determined the angle of a straight line between the rear edge of the Dens axis and the cranial end of the rear edge of thoracic vertebra 1 and a perpendicular. To establish the extent of coronal motion, we defined a straight line from the medial Dens surface to the vertical through the middle of the cover plate of thoracic vertebra 1 and determined the angle. The angle for the extent of movement in rotation was determined by a straight line through the middle of the hard palate and the rear edge of thoracic vertebra 1 to the perpendicular. That was done in each case by superimposing the first and last image of the motion examination.

*Evaluation*

The examinations were evaluated centrally by three experienced radiologists. The examiners were not involved in the evaluations performed using the LEONARDO workstation. Graphic motion diagrams were generated for the principal functional planes for each subject by plotting the segment level against the segmental angle.

*Statistics*

Mean values and standard deviations were calculated for all data and angular measurements using the program SPSS 9 (SPSS Software, Munich, Germany).

**Results**

The limited space in the magnet bore of the MRI system required "off-center" measurements for functional examinations. However, the MAP shim implemented in the sequence protocol was adequate to optimize the homogeneity of the magnetic field in the measured volume, preventing both artifacts and relevant signal loss.

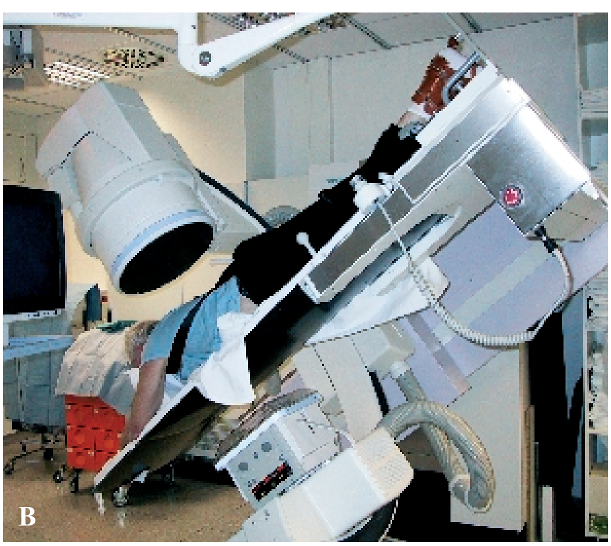

Fig. 1
Conventional myelography:

A) Puncture.
B) Positioning to show the neck region.

The HASTE-3D sequence visualized structures in the subarachnoid space with the highest spatial resolution and provided very good signal-to-noise ratio. The intradural resolution allowed good differentiation of the nerve fiber bundle up to the axilla, where the nerve fibers leave the dura. Extremely small extradural masses can be recognized very well indirectly at recesses for cerebrospinal fluid. Surrounding structures, on the contrary, cannot be differentiated adequately. Therefore, this sequence is particularly suitable for implicit segmentation, defined by a fixed transfer function, and subsequent visualization by VRT. Post-processing via VRT generates a three-dimensional image of the subarachnoid space (3D myelography) from the slice images of the HASTE-3D sequence. Analogous to conventional myelography, the spinal nerves are distinguished as low-signal structures within the subarachnoid space. Fig. 1 shows the complex procedure of conventional myelography for a patient with bony constriction of the spinal canal (spinal stenosis). After the puncture, the patient must be positioned in reclination in the prone position, so that the contrast agent applied in the subarachnoid space can reach the cervical spine. Fig. 2 shows, for comparison, conventional myelography and 3D MR myelography. To obtain an assignment to an anatomic segment, the MR myelographs were superimposed with $T_2$-weighted TSE sequences.

The intradural differentiation with the HASTE-3D sequence is better than with the MEDIC-2D sequence.

We did not observe signal attenuation due to flow (flow void artifacts) in the subjects with the HASTE-3D. With the isotropic set of volume data, slice images could be produced in any arbitrary reconstruction plane without loss of resolution (MPR).

*Angle Measurements and Motion Curves*

Fig. 3 shows the individual parts of the auxiliary system used and a subject positioned in different functional positions. Fig. 4 shows the results of a functional examination, also using a subject examination as the example. The examination, performed as a rapid survey, lasted only 8 min for all three planes. A reduced TSE matrix (measurement time 30 s) was used with $T_2$-weighting. The images show good motion function and an adequate range of motion. The motion curves (Fig. 5) confirm this finding in all planes of movement.

Table 1 presents the results for the segmental mobility, i. e., the maximum range of movement between inclination and reclination. The total range of movement was 84.9°, with a small standard deviation of 2.81°. The segmental mobility, in contrast, deviated substantially

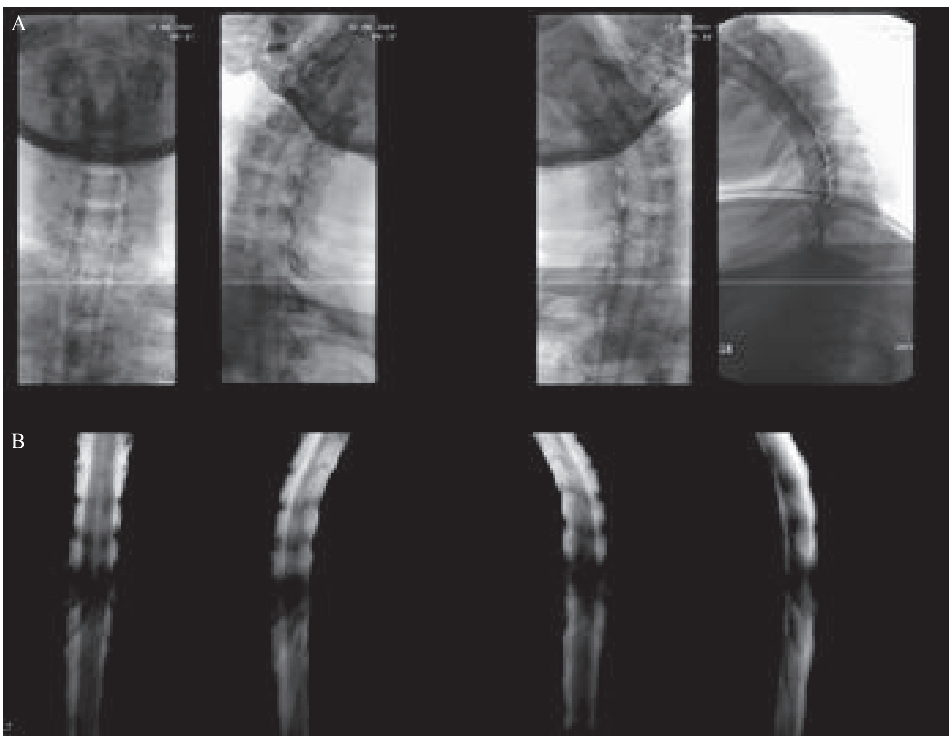


Fig. 2
Myelography.
Different perspectives.

A) Conventional myelography.

B) 3D MR myelography.


Fig. 3

Functional MRI of the cervical spine.

A) Hardware required.

B-F) The various functional planes can be selected freely.

Not only inclination and reclination are possible, but also lateroflexion and rotation, and combinations of all four planes.

(SDev: 2.4-5.5) and was distinctly greater in the caudal segments of the cervical spine than in the cranial segments (C2/3: 3.8°; C5/6: 10.8°). The values were determined from 13 young and healthy subjects.

Table 2 shows the results of the functional mobility for lateroflexion. The total range of motion was 25.3° on the left side and 22.5° on the right side, with small standard deviations (left: 1.3°; right: 0.9°). In contrast with the sagittal plane of motion, the mobility varies less among the individual segments (2.3° and 5.4°). The deviation is substantial (1.3°-4.3°), as in the sagittal plane.

Table 4 also confirms this for the third plane of movement, the axial plane in rotation. The total range of motion is 59.1° right and 56.9° left. The standard deviation is somewhat higher than in the sagittal and coronal planes (right: 12.5°; left: 13.6°). The segmental mobility deviates less and appears to be more uniform without great differences between the sides.

In summary, our results show clearly that although the total ranges of motion are comparable for the individual subjects, there are different segmental ranges of motion.

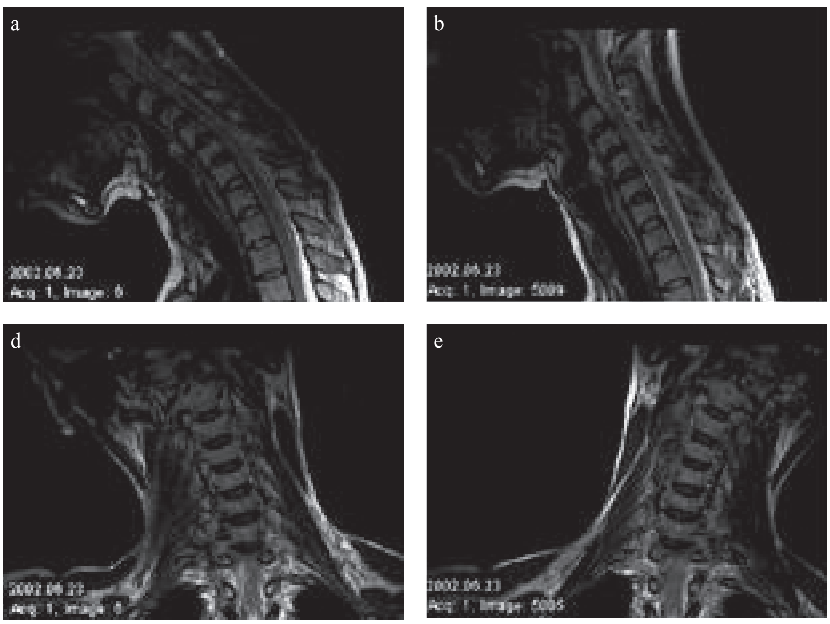


Fig. 4
Functional MRI.
Inclination, standard position.
Reclination and lateroflexion to both sides show normal findings in a healthy 25-year-old female subject.

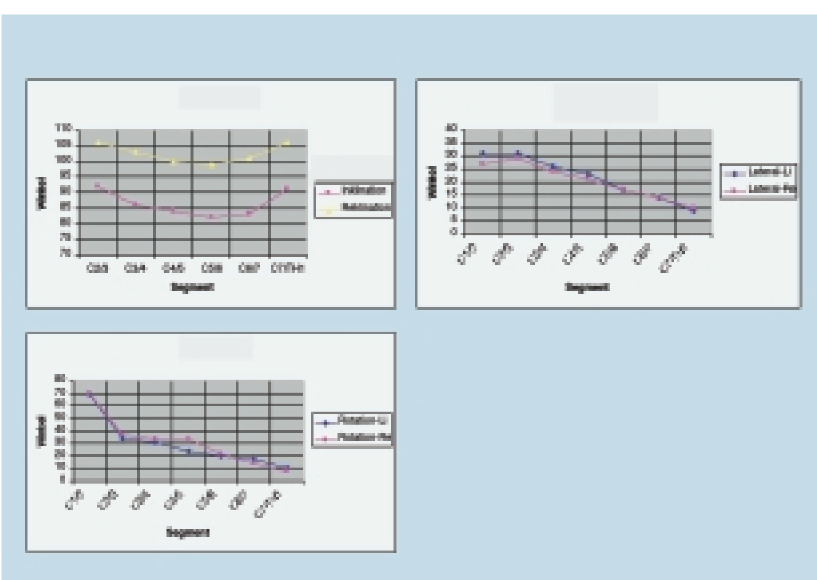

Fig. 5

Movement curves for the cervical spine. Large ranges of motion, equal on both sides, in inclination, reclination, lateroflexion and rotation.

Normal finding for a healthy 25-year-old female subject.

*Reproducibility*

Reproducibility tests were done with 5 subjects. Our results show that repeated examinations at defined functional positions are possible with high repetitive accuracy. In inclination, the standard deviation was from 1.5% to 3% of the initial value. In reclination, deviations from the expected value are between 3% and 8%. They are from 2.5% to 5% in lateroflexion and between 2% and 3% in rotation. In summary, our results show high reliability for functional examinations with the device used.

## Discussion

Numerous publications have appeared in recent years which treat functional examinations of the cervical spine in various conditions, especially degenerative, inflammatory, and post-traumatic conditions [1-6]. In these cases, functional examinations of the cervical spine are performed in the end position, i.e., at the maximum for movement, or in firmly defined stages [5, 6, 10]. One group used a device, which was continuously adjustable in the sagittal plane. To date, there have been no studies regarding the extent to which functional examinations of the cervical spine are reproducible; or at least they have not been reported in the applicable literature. Although body coils were required in the past for measurement, it is now possible to use surface coils with better signal-to-noise ratio.

One group has reported on the related possibility of improved spatial resolution [11]. In that case, however, gradient echo sequences were used (with all the associated disadvantages including high susceptibility to artifacts) to attain sufficiently high spatial resolution. Our group selected a sequence in (turbo) spin-echo technique for a high-resolution examination, and utilized parameters optimized for the examination. The spatial resolution obtained by other groups [11] using the gradient echo technique is limited, especially in the slice-selection direction. Multiplanar reconstructions have just as many limitations in application, because of voxel anisotropy, as do the more sophisticated visualization techniques such as VRT [11]. Until now, it has not yet been possible to establish a method comparable

| Segment | Inclination – Reclination | |
|---|---|---|
| | Mean | Standard deviation |
| Total | 84.90 | 2.81 |
| C2/3 | 9.80 | 2.98 |
| C3/4 | 13.3 | 2.39 |
| C4/5 | 16.1 | 5 |
| C5/6 | 18.1 | 4.9 |
| C6/7 | 17.5 | 3.09 |
| C7/TH1 | 10.1 | 5.49 |

Table 1
Ranges of sagittal motion between maximum inclination and maximum reclination (mean values and standard deviations) for n = 13 subjects.

| Segment | Lateroflexion, right | | Lateroflexion, left | |
|---|---|---|---|---|
| | Mean | Standard deviation | Mean | Standard deviation |
| Total | 22.45 | 0,88 | 25.25 | 1.26 |
| C2/3 | 3.8 | 2.17 | 3.25 | 2.22 |
| C3/4 | 3.6 | 2.41 | 5.6 | 4.34 |
| C4/5 | 3.8 | 2.59 | 5 | 4.08 |
| C5/6 | 2.25 | 1.26 | 5.4 | 1.52 |
| C6/7 | 5 | 3.08 | 3.2 | 2.86 |
| C7/TH1 | 4 | 2.94 | 2.8 | 2.05 |

Table 2
Ranges of motion at maximum lateroflexion (mean values and standard deviations) for 5 healthy subjects.

| Segment | Rotation, right | | Rotation, left | |
|---|---|---|---|---|
| | Mean | Standard deviation | Mean | Standard deviation |
| Total | 59.1 | 12.51 | 56.9 | 13.61 |
| C2/3 | 35.2 | 4.54 | 37.2 | 10.4 |
| C3/4 | 2.75 | 1.5 | 2.8 | 1.3 |
| C4/5 | 6.75 | 4.11 | 4.8 | 2.49 |
| C5/6 | 6.2 | 3.7 | 5.2 | 1.1 |
| C6/7 | 4.4 | 3.29 | 3.5 | 1.91 |
| C7/TH1 | 3.8 | 2.16 | 3.4 | 2.3 |

Table 3
Ranges of motion at maximum rotation (mean values and standard deviations) for the separate sides, for 5 subjects.

Table 4
Reliability of the method: Five subjects were examined by three examiners independently of each other. The individual measurements were each repeated 5 times in defined functional positions. All the measurements were evaluated centrally.

| | | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 |
|---|---|---|---|---|---|---|
| **Inclination** | **Mean** | 32.83 | 30.50 | 26.33 | 25.33 | 24.33 |
| | **Standard deviation** | 0.41 | 0.55 | 0.52 | 0.52 | 0.81 |
| **Reclination** | **Mean** | 15.67 | 12.50 | 18.50 | 15.50 | 17.83 |
| | **Standard deviation** | 1.37 | 1.05 | 1.64 | 0.55 | 0.75 |
| **Lateroflexion** | **Mean** | 24.67 | 20.67 | 16.67 | 16.50 | 15.33 |
| | **Standard deviation** | 1.21 | 1.03 | 0.52 | 0.84 | 0.52 |
| **Rotation** | **Mean** | 60.17 | 63.17 | 62.17 | 78.5 | 75.17 |
| | **Standard deviation** | 1.47 | 2.23 | 1.72 | 1.52 | 2.14 |

to the visualization aspect of conventional myelography. The same group presents 2D evaluations (diameter of subarachnoid space, myelon and neuroforamen) in functional studies [11]. Limitation to one plane, usually the sagittal plane, has been another limitation of functional MR examinations. Examinations in rotation have indeed been reported [11], but they are limited to a few stages of motion. Reports on reproducibility of the examinations are lacking.

Isolated examinations in lateroflexion have been attempted using open systems. Steppless, i. e. smooth movements which can be combined arbitrarily have not been described to date [10]. In the present study, a newly developed device was utilized. This device allows both passive (sagittal plane) and active (lateroflexion and rotation) movements which can be freely combined in all three planes. A sequence adapted to the specific requirements of the cervical spinal region was modified for the examinations, i. e. a TSE sequence with half-Fourier space sampling was selected instead of 3D gradient echo sequences. To acquire the degenerative calcifications which often occur in the region of the cervical spine, a 2D-FLASH sequence was preferred over the TSE sequences for evaluation of the sagittal functional images. A MEDIC-2D sequence with modified parameters was also used to evaluate the myelon, so that the entire cervical spine could be examined axially with adequate resolution and good signal-to-noise ratio in a measurement time of approx. 4 min. The results from the subjects examined show that the range of motion in the sagittal plane agrees with the values from previously published conventional functional examinations [12]. Here it is interesting that the total range of motion in healthy subjects shows very little variation (SDev: 2.8°), but the segmental mobility shows substantial fluctuations even in clinically healthy subjects (SDev: 2.4° to 5.5°). This applies not only to sagittal movement but similarly also for coronal movement (SDev: 0.9° to 1.2° for the total range of motion, and 1.3° to 4.3° for the segmental range of motion) and to the axial plane (SDev: 12.5° to 13.6° for the total range of motion and 1.5° to 10.4° for the segmental range of motion). Comparative reports on the axial range of motion are derived from functional CT examinations [12]. We do not yet have information about the segmental range of motion in the coronal plane, i. e., in lateroflexion. Our examinations are reproducible, as is clearly shown by a series of 5 subjects (SDev: 0.5° to 0.8° in inclination, 0.6° to 1.4° in reclination, 0.5° to 1.2° in lateroflexion, and 1.5° to 2.2° in rotation). In reproducibility examinations, defined functional positions were carried out 5 times by each of the three independent examiners, with the patient repositioned each time. The evaluation was performed independently by three experienced radiologists. Because of the good repetitive accuracy, it was possible to save time by repeating arbitrary positioning without a new topogram. In case the examination had to be interrupted briefly because of disturbances, for instance, it could be repeated easily after a brief pause. This is an especially important aspect in the case of time-consuming high-resolution examinations. The visualization results with VRT as 3D MR myelography show that high-resolution examinations are possible with a modified 3D-HASTE sequence. In this case, an isotropic matrix is possible down to a spatial resolution of 0.5 x 0.5 x 0.5 mm in the cervical spinal region. In the present study, to save time, we considered a voxel size of 1 x 1 x 1 mm adequate for functional examinations. The signal-to-noise ratio of the 3D-HASTE sequence used is very good. The intradural nerve roots can be differentiated well from the CSF and dura. The transition to the extradural segment, i. e. the true axilla section, can be visualized without artifacts. Our results show that it is entirely comparable with a high-resolution MEDIC-2D sequence. Due to the isotropic matrix, multiplanar reconstructions (MPR) are quite possible in all reconstruction planes as an alternative to 3D visualization. No artifacts due to CSF pulsation or vessel movement appeared. Despite the low bandwidth of the HASTE sequence, no chemical shift artifacts appeared, because of the frequency-selective presaturation of the fatty tissue surrounding the dura.

## Summary and Prospect

Our study shows that high-resolution MRI examinations comparable to conventional myelography are functionally possible by means of the auxiliary device used and the sequences specially modified for the particular area of examination. Since the individual segmental mobilities are quite different, in our opinion it is best to perform a rapid survey first so that the course of the subsequent examination can be planned better. Due to the high reproducibility of our method, a high-resolution, patient-friendly diagnostic imaging examination can then be planned with confidence. If necessary, the examination may be interrupted briefly at any time, without requiring a new topogram to plan the examination. Since the clinical utility of functional examinations has been proven adequately, the functional examination method should become increasingly available for routine use. The positioning aid used can be easily integrated in the examination table in a short amount of time. This would perhaps enable future cervical examinations to be performed exclusively using a variable positioning device. The coil combinations commonly used in the cervical spine region and other vertebral regions are integrated into the auxiliary device, enabling supplemental examination of the segments of the vertebral column caudally adjacent to the cervical spine without having to interrupt the examination. The last four figures show one such a step-by-step procedure in the case of cervical spinal trauma in a young competitive athlete. Although a previous trauma was known – and almost completely healed – at the time of the examination, the MR diagnosis closely corresponded to

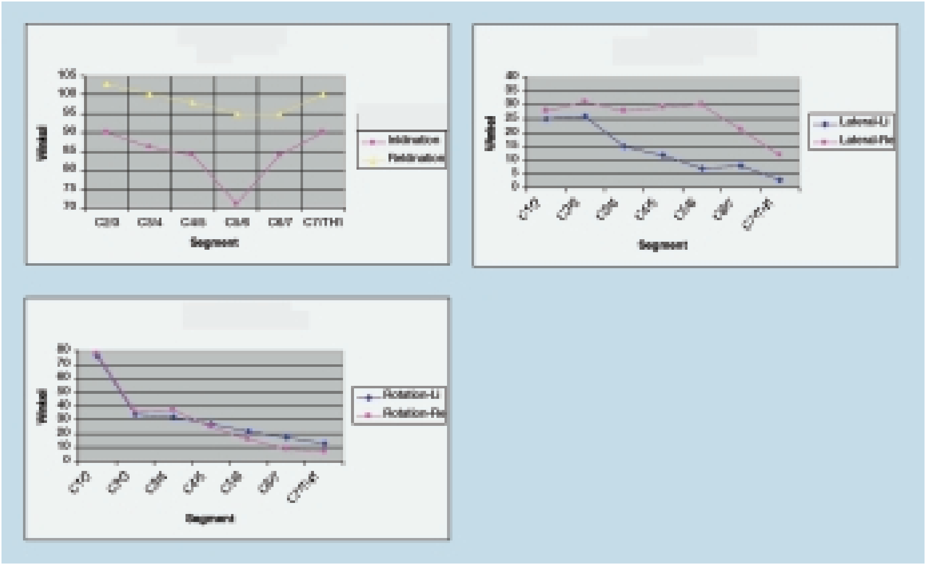

Fig. 6
Movement diagrams. Distinct hypermobility in inclination in segment C5/6 and in latero-flexion on the right side in both the segments C6/7 and C7/Th1.

Standard rotation both sides. Diagnosis of a 23-year-old gymnast following whiplash trauma to the cervical spine.

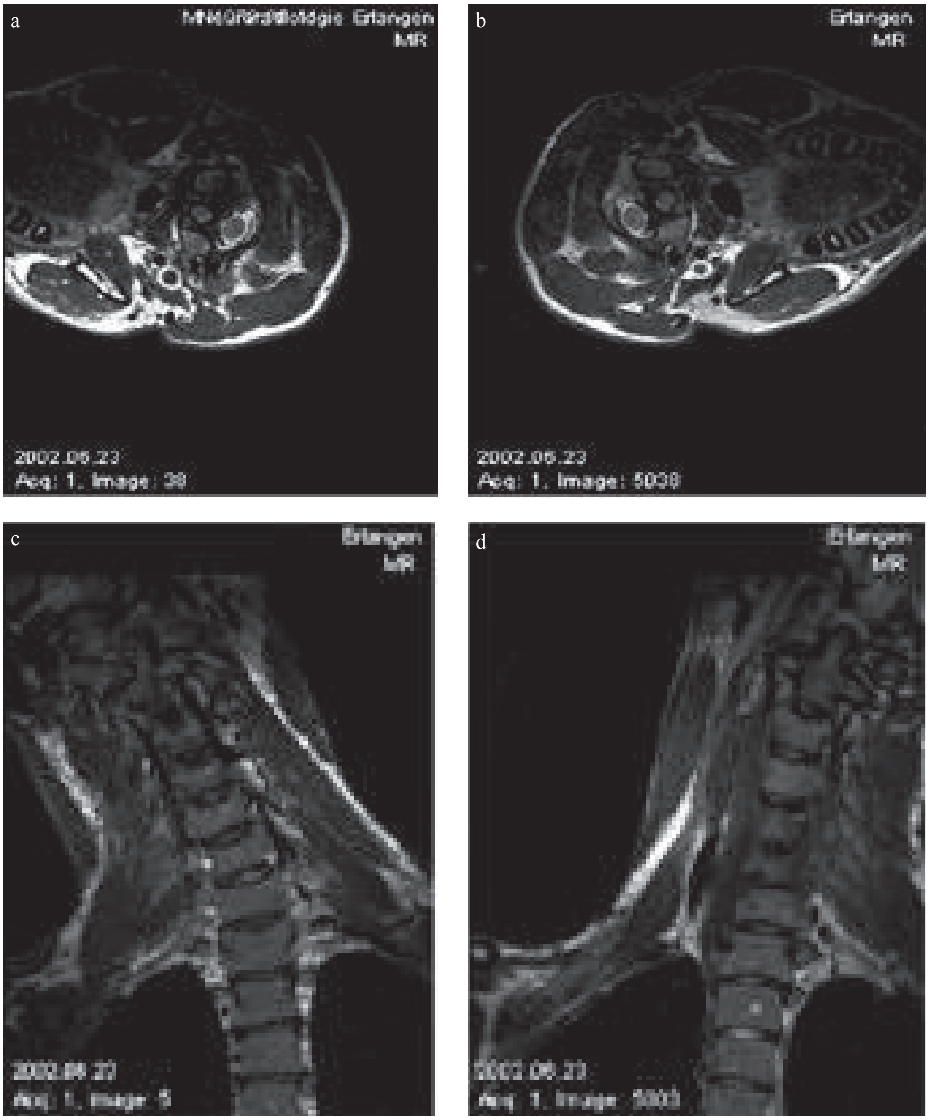


Fig. 7
Functional MRI.
A) and B) Rotation and
C) and D) lateroflexion.

Reduced mobility in the first five segments of the cervical spine on the right side following whiplash trauma.

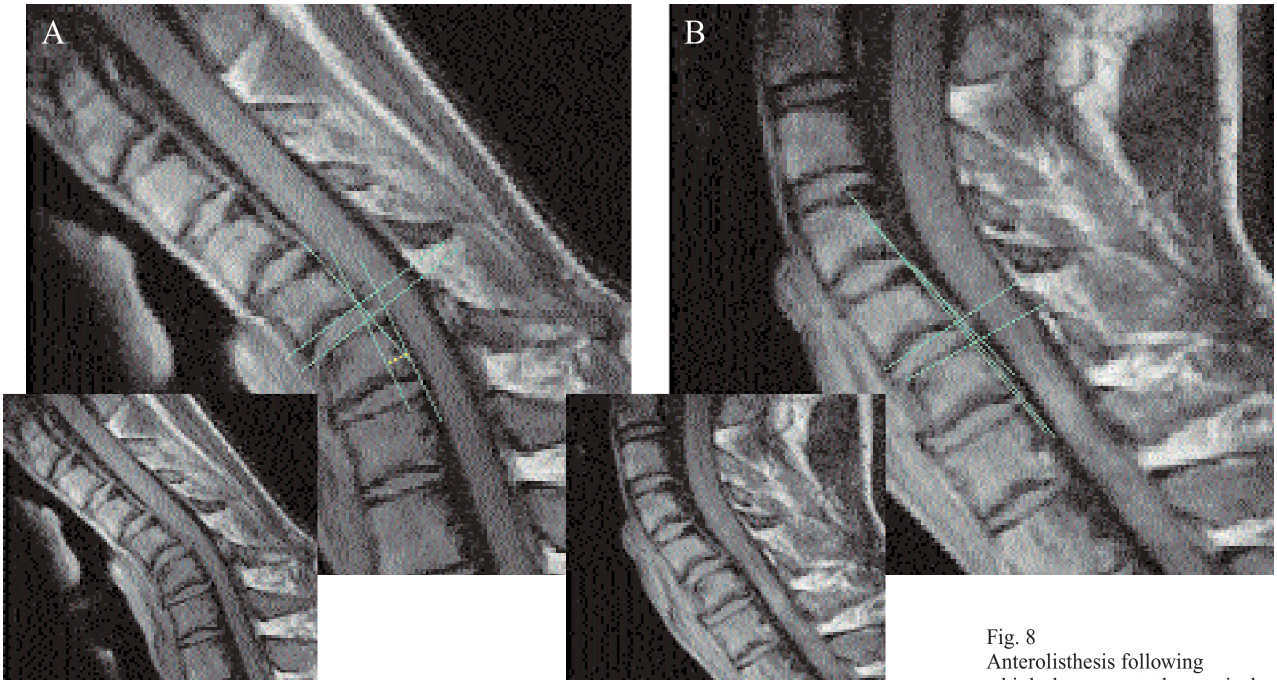


Fig. 8
Anterolisthesis following whiplash trauma to the cervical spine.

A) In inclination. 6 mm ventral shift C5/6 (according to Dupuis).
B) In reclination. Normal finding.
TSE: 3 mm, matrix 256 x 256; measurement time 90 s.

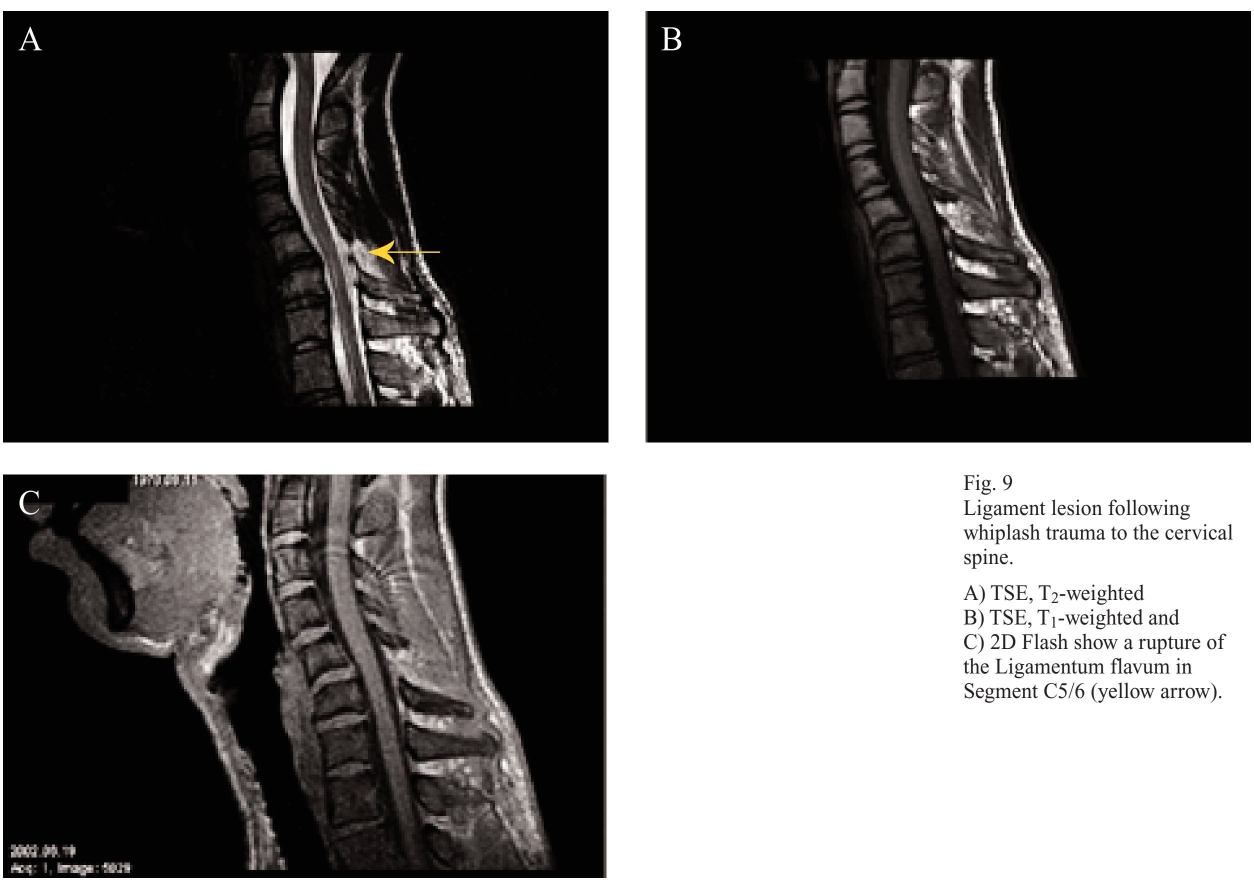


Fig. 9
Ligament lesion following whiplash trauma to the cervical spine.

A) TSE, $T_2$-weighted
B) TSE, $T_1$-weighted and
C) 2D Flash show a rupture of the Ligamentum flavum in Segment C5/6 (yellow arrow).

incidental findings obtained by an examination of test subjects.

Fig. 6 shows hypermobility, primarily in inclination. Similar, though less extensive, findings appear in the movement diagram for right lateroflexion. Fig. 7 shows a left-side motion deficit in lateroflexion in a rapid TSE with a reduced image matrix. The rotation appears normal. Fig. 8 demonstrates the results of a listhesis measurement according to Dupuis. The 2D-FLASH images show a ventral shift (anterolisthesis) of 6 mm in the inclination position which cannot be detected in the standard position. Fig. 9 confirms a rupture of the *Ligamentum flavum* in the C5/6 segment in the $T_2$-weighted TSE sequence.

## Abbreviations

| | |
|---|---|
| CP | = Circular Polarized |
| CSF | = Cerebrospinal Fluid |
| FLASH | = Fast Low Angle Shot |
| FoV | = Field of View |
| HASTE | = Half-Fourier Single Shot Turbo Spin Echo |
| MAP | = Multi Angle Projection |
| MEDIC | = Multi Echo Data Image Combination |
| MRI | = Magnetic Resonance Imaging |
| MRP | = Multiplanar Reconstruction |
| SDev | = Standard Deviation |
| SINOP | = Simultaneous In-Phase Oppose-Phase |
| TR | = Time Repetition |
| TSE | = Turbo Spin Echo |
| VRT | = Volume Rendering Technique |

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Author's address

PD K. E. W. Eberhardt
Hauptstrasse 56
D-97228 Rottendorf
Germany

Tel.: +49-(0)93023271
Fax: +49-(0)93023271
e-mail: eberhardt.rottendorf@t-online.de