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Gd-DTPA-Enhanced 3D MR Imaging of Cervical Degenerative Disk Disease: Initial Experience

Jeffrey S. Ross,¹ Paul M. Ruggieri,¹ Jean A. Tkach,¹ Thomas J. Masaryk,¹ Lata Paranandi,² John J. Dillinger,¹ and Michael T. Modic¹

Purpose: To assess whether a single enhanced T1-weighted gradient echo volume sequence, with the appropriate reformatted images, could be equivalent to a more conventional 2D set of MR sequences for the evaluation of cervical extradural degenerative disk disease (bony canal and foraminal stenosis; disk herniation). **Materials and Methods:** Sixty-one patients evaluated for extradural degenerative disease by MR were imaged with a "standard" MR examination (Sagittal T1-weighted spin echo, axial low flip angle gradient echo), were then given 0.1 mmol/kg Gd-DTPA intravenously, and reimaged with either a 3D FLASH (fast low angle shot), TR 40/TE 7/1 excitation), 40° flip angle, acquired as 64, 2-mm sagittal partitions, or a 3D turbo FLASH (MP RAGE-magnetization prepared rapid acquisition gradient echo) (10/4/1), 10° flip angle acquired as 128, 2-mm coronal partitions. The volume sequences were reconstructed in the axial plane, and right and left 45° oblique coronal planes. The two sets of examinations (standard vs volume) were prospectively interpreted by two neuroradiologists for quality of examination, and location, type, and severity of extradural degenerative disease in a random, blinded, independent fashion. **Results:** There was no significant difference between the standard examination and the 3D MP RAGE for central extradural disease. The 3D FLASH examination was significantly worse than the standard examination in identification of central extradural disease, with an average of 21 herniations not identified, or underestimated in size. Neither the 3D FLASH, nor the 3D MP RAGE examinations showed any significant improvement compared to the routine 2D examination for the location and severity of foraminal disease. **Conclusion:** If extradural degenerative disk disease is being evaluated, then a single enhanced 3D T1-weighted imaging sequence taking 6 minutes can be equivalent to a routine set of mixed 2D spin echo and low flip angle gradient echo sequences.

Index terms: Spine, intervertebral disks; Degenerative spinal cord disease; Magnetic resonance, comparative studies; Spine, magnetic resonance

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The ability of magnetic resonance (MR) imaging to evaluate cervical spine degenerative disease as effectively as computed tomography (CT) myelography has been demonstrated in several studies (1, 2). However, MR imaging of the cervical spine has several well known problem areas which include: accurate identification of foraminal

disease due to long echo times, thick slices (3-4 mm), and the failure to optimally view the course of the existing nerve roots (3). Although overall examination times have decreased with gradient echo imaging, the length of examinations continues to be problematic. One potential solution to these problems is found in gradient echo volume imaging, which would allow short echo times with thin contiguous slices, and the ability to reformat the data in any desired viewing plane. Our anecdotal experience with noncontrast-enhanced T1-weighted gradient echo volume imaging of the cervical spine for degenerative disease suggested that foraminal tissue contrast was inadequate with these sequences. We reasoned that enhancement with Gd-DTPA would increase the foraminal and epidural tissue contrast, and thus the con-

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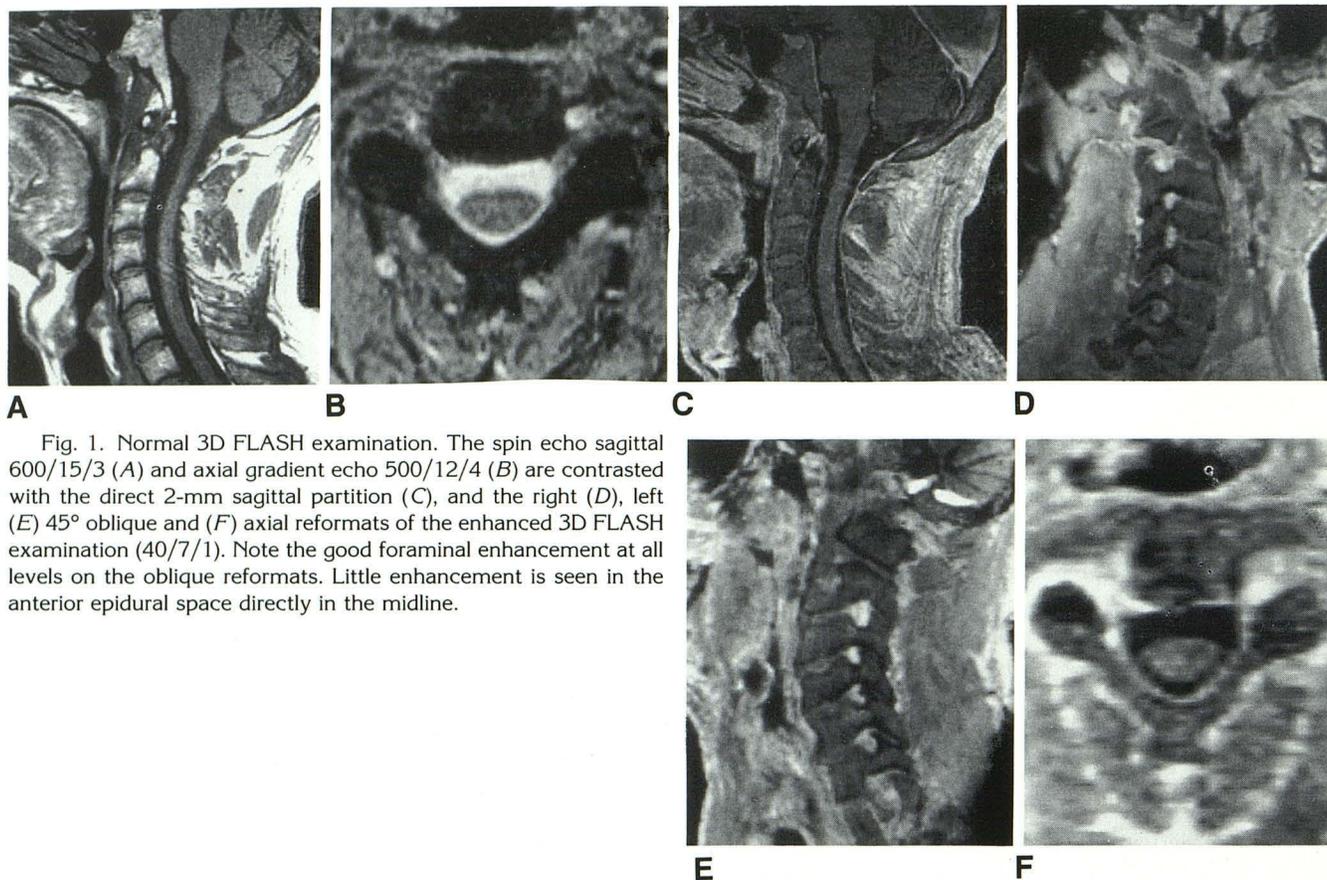


Fig. 1. Normal 3D FLASH examination. The spin echo sagittal 600/15/3 (A) and axial gradient echo 500/12/4 (B) are contrasted with the direct 2-mm sagittal partition (C), and the right (D), left (E) 45° oblique and (F) axial reformats of the enhanced 3D FLASH examination (40/7/1). Note the good foraminal enhancement at all levels on the oblique reformats. Little enhancement is seen in the anterior epidural space directly in the midline.

TABLE 1: Central extradural disease, readers 1/2: standard sequence set versus 3D MP RAGE

Routine Frequency	3D MP RAGE				Total
	0	1	2	3	
0	143/116	1/2	2/0	0/0	146/118
1	6/7	14/27	3/3	1/0	24/37
2	1/0	3/3	13/22	4/0	21/25
3	0/0	2/0	1/4	9/5	12/9
Total	150/123	20/32	19/29	14/5	203/189

Note.—Codes: 0 = normal, 1 = mild, 2 = moderate, 3 = severe disease; McNemar's test statistic = 6.04/6.78.

spicuity of extradural degenerative disease by enhancement of the epidural and foraminal venous plexus, in a manner analogous to the use of iodinated contrast material with CT (4, 5). We combined T1-weighted volume imaging with contrast enhancement to achieve the good anatomic detail and good signal-to-noise present in T1-weighted gradient echo imaging, with the good tissue contrast within the epidural and foraminal spaces provided by contrast enhancement. Our hypothesis was that a single enhanced T1-weighted gradient echo volume sequence, with

the appropriate reformatted images, would be superior to a more conventional set of two-dimensional (2D) MR sequences for the evaluation of cervical extradural degenerative disease (particularly in the evaluation of lateral disease because of the foraminal plexus enhancement and the ability to reformat the data for oblique imaging of the neural foramina) (6).

Materials and Methods

This prospective study involved 61 sequential patients being evaluated for cervical extradural degenerative disease by MR. "Extradural degenerative disease" was defined as canal or foraminal bony stenosis and/or disk bulge/herniation. There were 25 males, and 36 females, with an average age of 50.5 years. Patients symptoms were either radiculopathy or a mixture of radiculopathy/myelopathy. Patients referred solely for myelopathy, intrinsic cord disease, or disk space infection were not evaluated with the protocol outline below, since T2-weighted spin echo sequences would have been required.

All examinations were performed on a 1.5 T superconducting unit (Siemens Magnetom SP). Each patient received a "standard" (routine) MR examination, was then given 0.1 mmol/kg Gd-DTPA (Berlex Laboratories, Inc,

TABLE 2: Central extradural disease, readers 1/2: standard sequence set versus 3D FLASH

Routine Frequency	3D FLASH				Total
	0	1	2	3	
0	155/145	0/0	3/0	0/0	158/145
1	8/6	3/39	10/8	0/0	21/53
2	3/7	3/4	21/25	0/0	27/36
3	8/2	0/0	0/1	3/1	11/4
Total	174/160	6/43	34/34	3/1	217/238

Note.—Codes: 0 = normal, 1 = mild, 2 = moderate, 3 = severe disease; McNemar's test statistic = 19.77/16.33 (significant at the 0.05 level).

Wayne, NJ) intravenously, and reimaged with a "volume" gradient echo MR sequence. The standard examination consisted of: 1) sagittal 2D T1-weighted spin echo sequence (TR 600/TE 15/3 excitations), 3-mm slice thickness, 192 × 256 matrix, 5.76 minutes imaging time, and 2) 2D low flip angle gradient echo sequence (500/12/4), 10° flip angle, 3-mm slice thickness, 192 × 256 matrix, 6.4 minutes examination time. The *enhanced three-dimensional* (3D) gradient echo examinations were either: 1) FLASH (fast low angle shot), (40/7/1), 40° flip angle, acquired as 64, 2-mm sagittal partitions, 256 × 256 matrix, 10:67 minutes examination time, or 2) 3D turbo FLASH (MP RAGE-magnetization prepared, rapid acquisition gradient echo), (10/4/1), 10° flip angle, acquired as 128, 1.5-mm coronal partitions, 130 × 256 matrix, TI 350, T1 recovery time of 1 second, 6:07 minutes examination time (7). The volume sequences were reconstructed on the standard SP console in 1-mm increments in the 1) axial plane at the level of the disk spaces, 2) right and left 45° oblique coronal planes set perpendicular to the exciting course of the cervical nerve roots, and 3) for the 3D MP RAGE, in the sagittal plane from foramen to foramen. The volume examinations were reformatted by a technologist at the SP console to match the day-to-day image production of the standard sequence set.

The two sets of examinations (standard vs volume) were independently interpreted by two neuroradiologists (J.S.R. and P.M.R.: "reader 1" and "reader 2") for quality of examination and location, type, and severity of extradural degenerative disease in a random, blinded fashion. Quality of the examination was graded on a 0–5 scale (0 = uninterpretable, 1 = poor, 2 = average, 3 = good, 4 = excellent) based on a qualitative assessment of tissue contrast and enhancement, dural extradural interface conspicuity, signal/noise, and presence of artifacts. Location of disease was determined as either "central" (canal) or "lateral" (foraminal) in a forced choice method. Type of disease was determined to be either osteophyte, "disk," or both. The term "disk" included annular bulge, and frank disk herniation. Herniations were not subcategorized into protrusion or extrusion, but rather defined by size (severity). Severity of disease was graded on a 0–3 scale (0 = normal, 1 = mild, 2 = moderate, 3 = severe) corresponding to approximately 1%–33%, 34%–66%, and 67%–100%

compromise of the canal and foramina, respectively. Eight patients were imaged with both of the volume sequences. Thus, the total number of examinations was: 3D FLASH, n = 33; 3D MP RAGE, n = 36.

Data was subjected to McNemar's test, a nonparametric test for the agreement of two categorical factors that are paired. When this test is used for square tables larger than 2 × 2, the test is whether the upper right corner of the table is symmetrical with the lower left corner. For these data sets, a number greater than 12 is considered significantly different ($P < .05$).

Results

There was no significant difference in quality of examination between the standard 2D sequence set and the 3D MP RAGE for reader 1 or 2. The 3D FLASH examinations were significantly worse in quality compared to the standard 2D set at the $P < .05$ level for reader 2, and near significance for reader 1 (McNemar's test 18.28 vs 19 for significance) (Fig. 1).

Comparisons of both readers of the standard versus 3D FLASH, and standard versus 3D MP RAGE for central disease are shown in Tables 1 and 2. If all the frequencies fell along the diagonal of the tables from top left to bottom right, then there would be perfect agreement between factors. There was no significant difference between the standard examination and the 3D MP RAGE for central extradural disease (Figs. 2 and 3). Nevertheless, cases occurred where the 3D MP RAGE sequence underestimated the severity of central extradural disease (Fig. 4). The 3D FLASH examination was significantly worse than the standard examination in identification of central extradural disease, with an average of 21 instances of herniations not identified, or underestimated in size (Fig. 5).

Comparisons of both readers of the standard versus 3D FLASH, and standard versus 3D MP RAGE for lateral disease are shown in Tables 3 and 4. Neither the 3D FLASH nor the 3D MP RAGE examinations showed any significant difference compared to the routine examination for the location and severity of lateral extradural disease (Figs. 2B, 2D, 2E, 2F, 4C, 4E, and 4F). The degree of epidural and foraminal enhancement was qualitatively similar for both the 3D FLASH and the 3D MP RAGE.

Discussion

Three-dimensional MR imaging differs from the more conventional 2D imaging in that a large

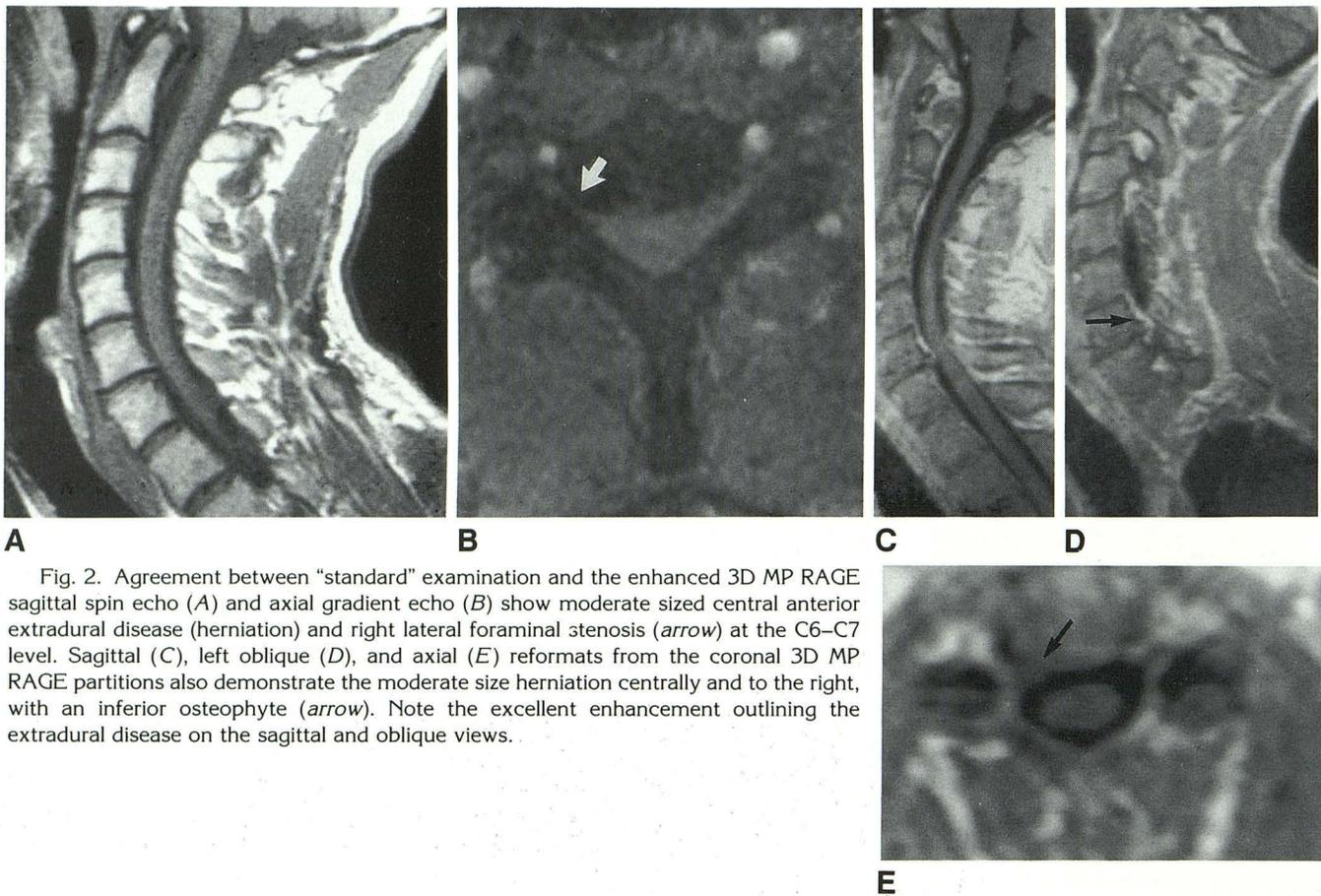


Fig. 2. Agreement between "standard" examination and the enhanced 3D MP RAGE sagittal spin echo (A) and axial gradient echo (B) show moderate sized central anterior extradural disease (herniation) and right lateral foraminal stenosis (*arrow*) at the C6-C7 level. Sagittal (C), left oblique (D), and axial (E) reformats from the coronal 3D MP RAGE partitions also demonstrate the moderate size herniation centrally and to the right, with an inferior osteophyte (*arrow*). Note the excellent enhancement outlining the extradural disease on the sagittal and oblique views.

volume of interest is defined by the initial radio frequency (RF) pulse in the former, as opposed to a thin slice in the latter. This volume is then divided into thin contiguous partitions by the application of an additional direction of phase encoding along the slice select direction. In-plane phase- and frequency-encoding gradients are used as in 2D imaging. With phase encoding used in two different directions, the imaging time of 3D compared to 2D will be proportionally increased by the number of partitions selected. This potentially lengthy imaging time necessitates the short TR's of gradient echo imaging. One advantage of 3D imaging is a theoretical increase in signal-to-noise compared to 2D imaging by the square root of the number of partitions, since there is reexcitation of the volume for each partition, (each N_y is collected N_z times, similar to increasing the number of acquisitions in 2D imaging) (8, 9). Also with the 3D technique, thin contiguous slices are obtained from the volume. Contiguous slices are obtained with minimal cross talk in 3D imaging when slice thickness is less than 3 mm (9). Since the partition selection is

achieved by phase encoding (as opposed to being a function of RF pulse bandwidth and gradient amplitude in 2D imaging), the actual slice thickness in 3D imaging is more accurate than in 2D (10). These thin contiguous slices may then be postprocessed and reformatted in any desired imaging plane.

The T1-weighted 3D images in this study were produced by two different gradient echo techniques. The FLASH technique destroys the residual transverse magnetization by a spoiler gradient applied after the data is collected. Since the transverse magnetization is irreversibly dephased prior to each RF pulse, only the longitudinal magnetization reaches a steady state. This steady state signal is dependent upon T1, but not T2. The 40° flip angle employed allows T1-weighting with good signal to noise (8).

Even more recently, snapshot imaging has become available in a 3D sequence, called 3D turbo FLASH, 3D T1 MP RAGE (7, 11, 12). This technique uses very short TRs (10 msec or less) and low flip angles (10°). Because of the very short TR, a 128-partition volume sequence can

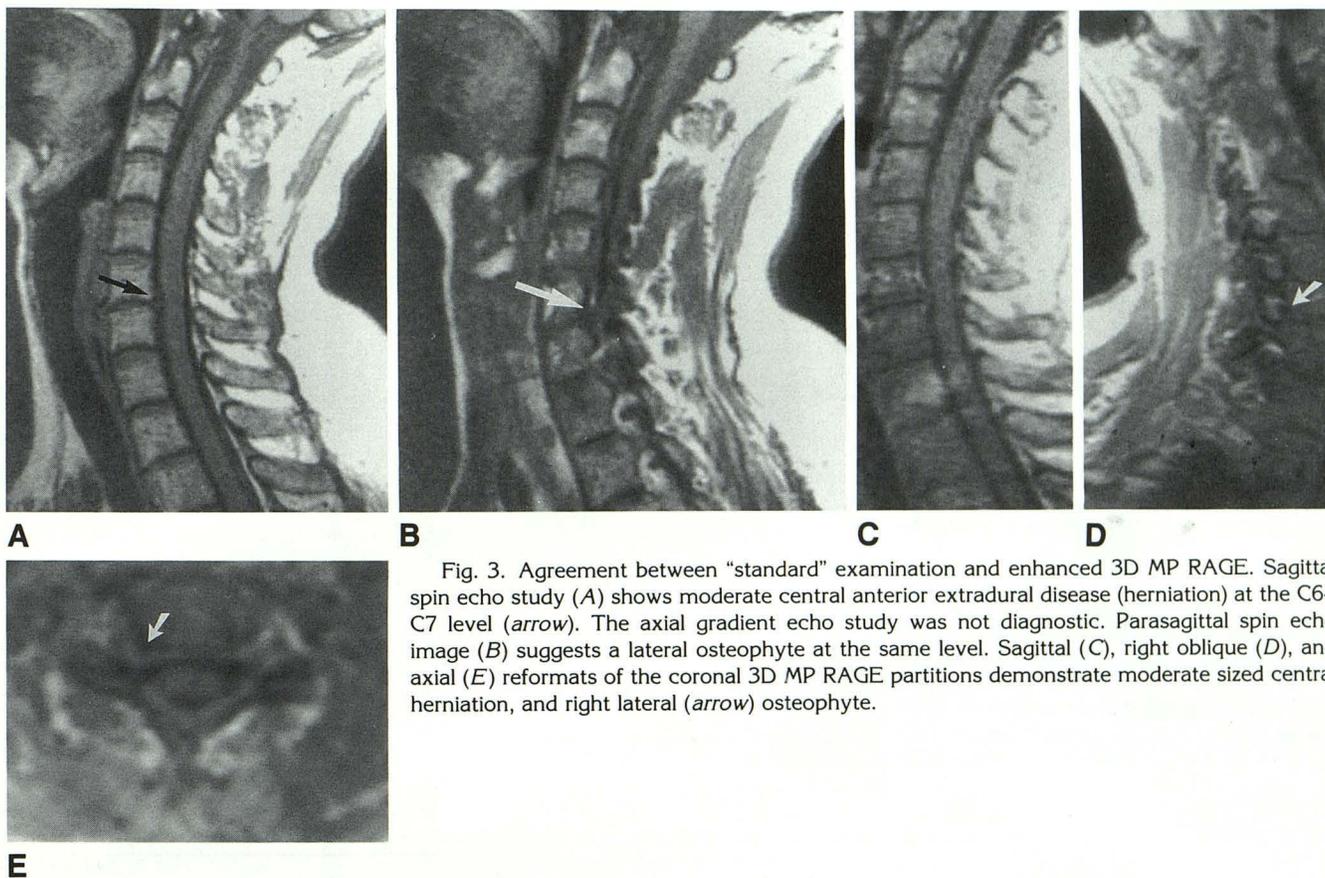


Fig. 3. Agreement between "standard" examination and enhanced 3D MP RAGE. Sagittal spin echo study (A) shows moderate central anterior extradural disease (herniation) at the C6-C7 level (arrow). The axial gradient echo study was not diagnostic. Parasagittal spin echo image (B) suggests a lateral osteophyte at the same level. Sagittal (C), right oblique (D), and axial (E) reformats of the coronal 3D MP RAGE partitions demonstrate moderate sized central herniation, and right lateral (arrow) osteophyte.

be completed in approximately 6 minutes. With the very short TR, image contrast and signal-to-noise would be a problem since very little time is available between excitations for T1 relaxation. To solve this problem, a small excitation flip angle is used. Since contrast is now inherently spin density weighted, a preparation period is often included. The purpose of this preparation period is to impart T1 or T2 weighting (ie, "prepare") to the longitudinal magnetization, prior to the standard image acquisition (Fig. 6). For 3D imaging, this preparation is applied prior to the collection of a full slice select phase-encoding cycle and, therefore, one per Ky line. For example, T1 contrast is produced by inverting the spins initially with a 180° RF pulse, and then waiting a few hundred milliseconds for the T1 relaxation past the null signal point (the TI time), the same method used in inversion recovery spin echo imaging. The rapid gradient echo sequence then samples the signal. Following the acquisition of each complete slice select phase encoding loop, there is "dead time" or recovery time, which allows the full recovery of magnetization prior to the next RF preparation pulse. Thus, the se-

quence structure can be thought of in three parts: a preparation period, acquisition of one complete slice select phase encoding loop with a rapid gradient echo, and a recovery period. The current sequence utilizes a nonselective pulse, necessitating the acquisition of the partitions in the coronal plane to minimize aliasing artifact from the shoulders. Spoiling is achieved solely by failure to rewind phase encoding over each TR interval and the natural T2 processes. The latter is limited for a short TR. As a consequence of the small excitation flip angles, no additional spoiling mechanisms (ie, variable gradients) are required. Despite the use of reformatted sagittal images for the 3D MP RAGE sequence (versus the directly acquired sagittal partitions in the 3D FLASH sequence) the 3D MP RAGE was superior to the FLASH sequence for identification of central disease, a diagnosis heavily influenced by the quality of the sagittal images.

While low flip angle 2D gradient echo imaging is currently the standard for use in the cervical spine, 3D low flip angle (bright cerebrospinal fluid (CSF)) imaging has shown good results with axial partitions (13-16). Low flip angle imaging has

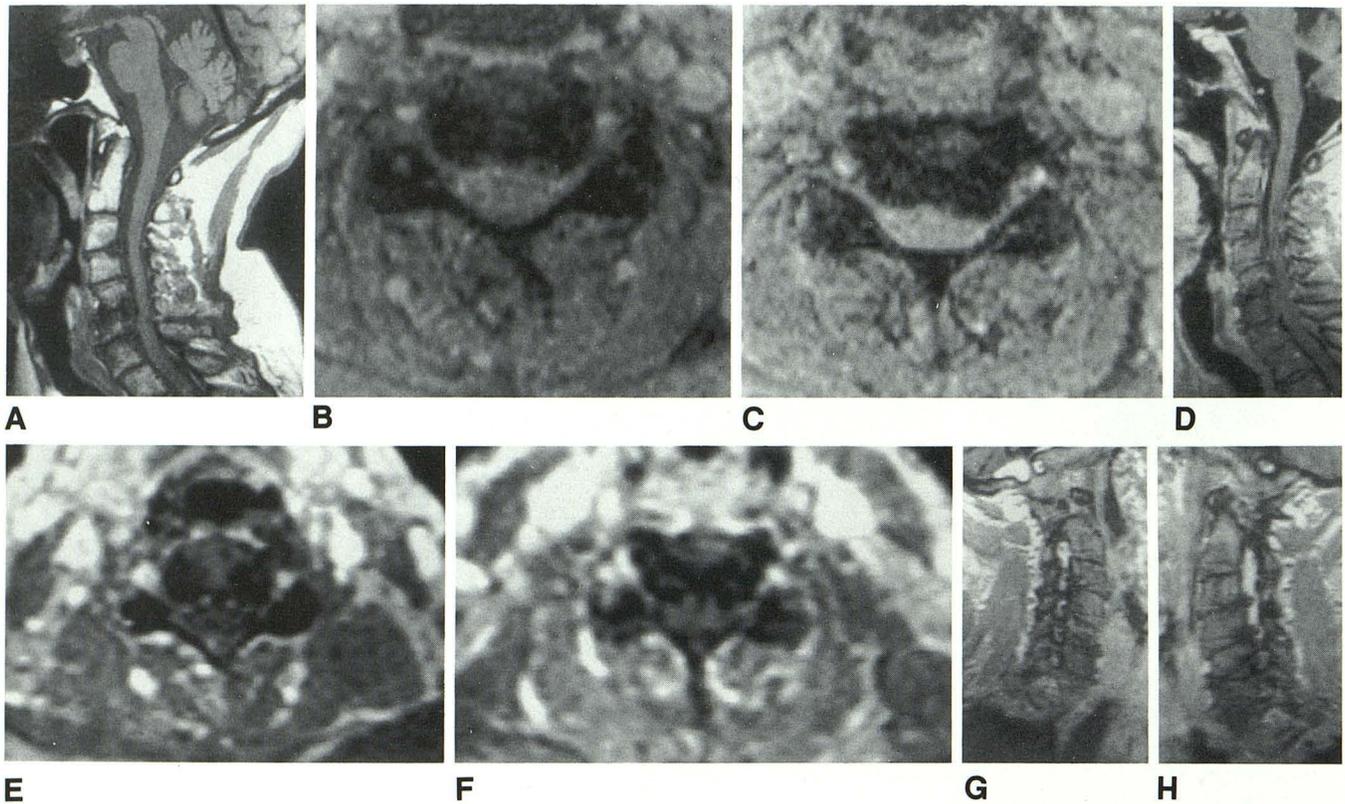
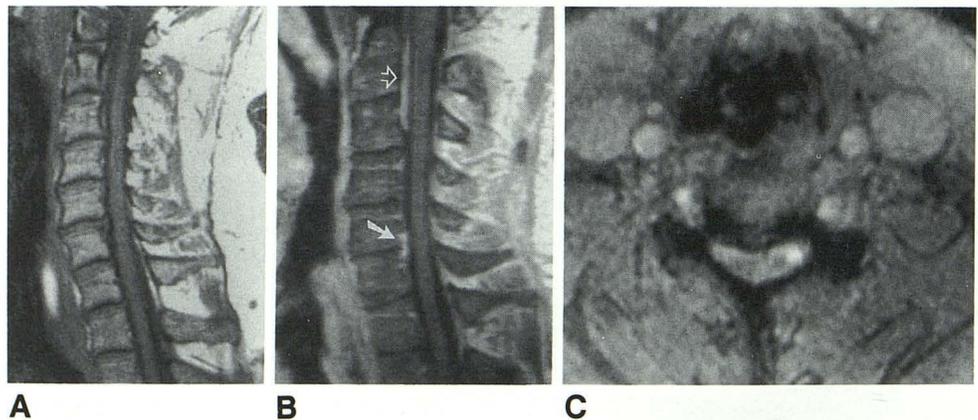


Fig. 4. Disagreement between "standard" examination and the enhanced 3D MP RAGE for severity of central extradural disease. Sagittal spin echo and axial gradient echo sections (A) (B: C4-C5 level; C: C5-C6 level) show moderate disease at C3-C4, and severe disease at C4-C5, C5-C6. Axial sections show moderate bilateral foraminal stenosis. Sagittal (D), axial (E) at C4-C5, axial (F) at C5-C6, right oblique (E) and left (F) oblique reformats of the coronal 3D MP RAGE partitions demonstrate no definite disease (other than a subluxation) at C3-C4, with moderate disease at C4-C5, C5-C6. Cord deformity seen at C5-C6 on the SE study is not easily identified on the 3D MP RAGE study due to the similar signal intensity of the cord and disk/vertebral body. There is enhancement of type I degenerative changes at the C3-C4, C5-C6, and C6-C7 levels that may contribute to obscuration of the central disease by increasing the signal within the vertebral bodies to that of cord. The oblique study corresponds to the standard examination, and demonstrate moderate sized osteophytes at multiple levels bilaterally.

Fig. 5. Failure of the 3D FLASH study to identify central disease. Sagittal spin echo study (A) shows moderate sized disk herniation at the C5-C6 level. Sagittal reformat of the 3D FLASH study (B) shows enhancement at the posterior margin of the disk (arrow), but no definite disk herniation. Note the epidural plexus enhancement at the C2 and C3 levels (open arrow). Axial 2D GE examination (C) confirms the presence of the central herniation.



achieved wide acceptance due to its ability to define low signal intensity extradural defects and foraminal disease, contrasted with the high signal intensity of the CSF. However, these low flip angle gradient echo sequences are not ideal, due

to their low signal-to-noise. We chose T1-weighted volume imaging with contrast enhancement in an attempt to combine the best of both worlds, good anatomic detail with good signal-to-noise present in T1-weighted gradient echo im-

TABLE 3: Lateral extradural disease, readers 1/2: standard sequence set versus 3D MP RAGE

Routine Frequency	3D MP RAGE				Total
	0	1	2	3	
0	142/106	4/2	0/2	1/0	147/110
1	1/7	4/25	2/5	1/1	8/38
2	2/0	2/3	11/4	2/2	17/9
3	0/0	0/0	0/3	2/2	2/5
Total	145/113	10/30	13/14	6/5	174/162

Note.—Codes: 0 = normal, 1 = mild, 2 = moderate, 3 = severe disease; McNemar's test statistic = 7.80/6.48.

TABLE 4: Lateral extradural disease, readers 1/2: standard sequence set versus 3D FLASH

Routine Frequency	3D FLASH				Total
	0	1	2	3	
0	155/140	4/8	3/1	0/0	162/149
1	0/5	1/29	6/6	0/0	7/40
2	3/0	1/3	7/6	3/3	14/12
3	0/0	0/0	0/1	3/2	3/3
Total	158/145	6/40	16/14	6/5	186/204

Note.—Codes: 0 = normal, 1 = mild, 2 = moderate, 3 = severe disease; McNemar's test statistic = 10.57/3.69.

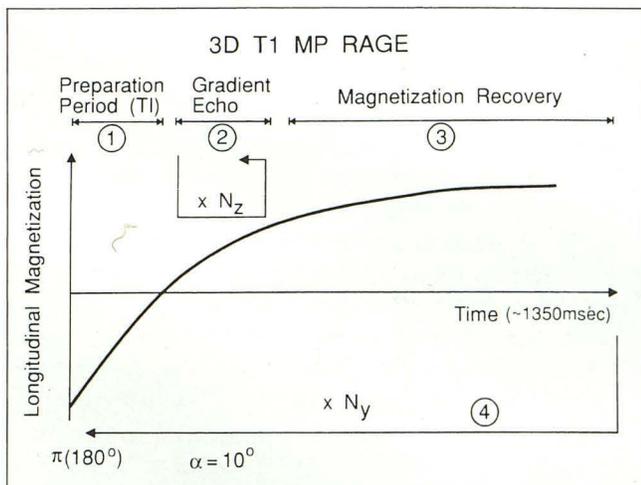


Fig. 6. Schematic representation of the 3D T1 MP RAGE sequence. The sequence consists of a preparation period composed of a 180° (π) inverting pulse and a T1 recovery time T_1 (1), a rapid gradient echo examination with a small flip angle (α) (2) which is repeated the number of slice select phase encoding steps (N_z), and a recovery period (3), allowing recovery of longitudinal magnetization. These three steps are then repeated N_y times (number of in-plane phase encoding steps) (4).

aging, and good tissue contrast within the epidural and foraminal spaces provided by contrast enhancement. This enhancement of the epidural and foraminal plexus with Gd-DTPA is analogous

to the use of iodinated contrast enhancement with CT, where the enhancing plexus, dura, ganglia and fibrovascular tissue will outline nonenhancing herniations (3, 4).

We have shown that the 3D FLASH sequence is inferior to the 3D MP RAGE sequence (and the standard 2D sequence set) for cervical extradural degenerative disease in two categories, both overall image quality and the ability to define central degenerative disease. There are a couple of possibilities why the enhanced 3D FLASH sequence was inferior in identifying central degenerative disease: 1) Imaging time was relatively long, which no doubt contributed to the generally poor image quality of the 3D FLASH versus 3D MP RAGE (due to the increased motion sensitivity of these volume sequences with the additional direction of phase encoding). However, motion artifact should also degrade the lateral disease detection as well, which was not seen. 2) More likely is the fact that epidural venous plexus enhancement is the least abundant at the disk space level, related to the natural thinning of the plexiform sinuses in these regions (17). This lack of midline enhancement, coupled with the low signal intensity of extradural degenerative disease and the CSF, would not allow detection of the degenerative disease. However, the general degree of venous plexus enhancement was qualitatively similar for both types of volume sequences. 3) The third possibility is that vertebral body enhancement secondary to degenerative type I changes (Fig. 4), and posterior disk margins enhancement due to granulation tissue (Fig. 5) could alter the tissue contrast between vertebral body, CSF, and cord sufficiently to mask the extradural disease (5, 18). The 3D FLASH sequence did consistently produce lower signal intensity vertebral bodies relative to the MP RAGE sequence. If insufficient plexus enhancement was present at the disk space, the more similar signal intensities of the CSF and vertebral bodies with the 3D FLASH sequence may have contributed to the poor detection of central disease. The 3D FLASH sequence was not shown to be any different from the 2D standard set for foraminal disease identification (although it approached significance for reader 1 (Table 4)). The inherent high contrast within the foramen due to Gd-DTPA enhancement may play a role in improving foraminal disease detection versus central disease.

Additionally, we found that a single enhanced T1-weighted gradient echo imaging sequence (MP RAGE) can be equivalent to a routine set of

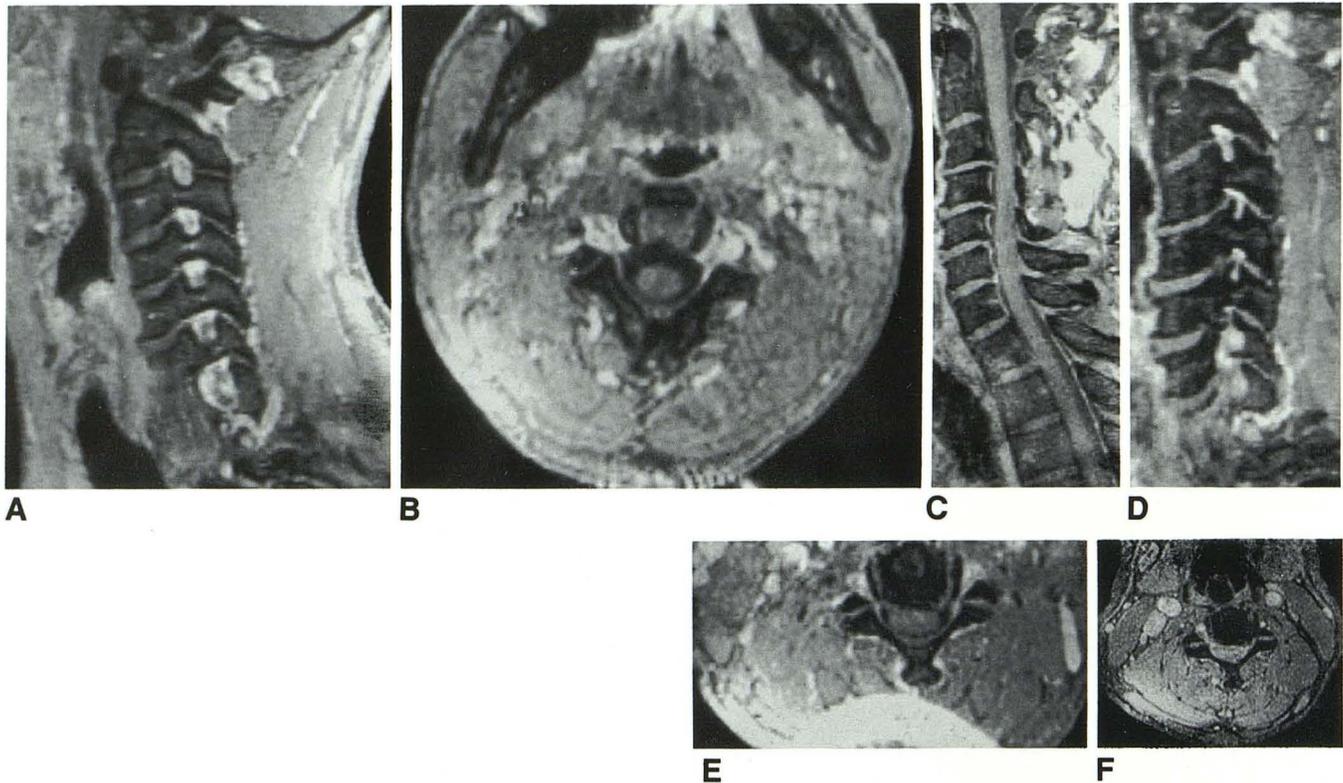


Fig. 7. Current technique. Oblique (A) and axial (B) reformats of the current 3D fast FLASH sequence (13/6/1), no preparation pulse, 50 msec wait time, shows improved resolution due to thinner partitions (1.2 mm) and a 192×256 in-plane matrix (imaging time, 5:31). Sagittal (C), oblique (D), and axial (E) reformats (C4–C5 level) in a patient with spondylosis shows the canal and foraminal stenosis at C3–C4 through C6–C7. Axial (F) 2-mm partition from a 3D gradient echo sequence (35/7/1), 5° flip angle, shows the central and foraminal disease in a similar fashion to E.

mixed spin echo and gradient echo sequences in the evaluation of degenerative disease of the cervical spine in one-half of the imaging time. The MP RAGE sequence was superior to the 3D FLASH in image quality and ability to define central degenerative disease. This sequence was equivalent to 3D FLASH for identifying foraminal disease. Based on the comparisons of these two volume sequences with the standard 2D sequence set, 3D FLASH (40/7/1) with a 40° flip angle is not a suitable technique for 3D T1-weighted cervical spine imaging.

The use of a single MR sequence serving as a screen for cervical degenerative disease is attractive, since it could minimize patient discomfort, motion, and the time spent within the magnet. Although the 3D MP RAGE sequence does appear equivalent to a set of 2D sequences, we have failed to demonstrate a clear superiority of the MR RAGE sequence for lateral (foraminal) disease, despite the use of reformatting perpendicular to the course of the exiting nerve roots. The cause of this failure is also unknown, but could relate to inadequate spatial resolution, failure to

optimize the sequence for examination of extradural tissues (especially true of the MP RAGE sequence, were not only is flip angle important, but also inversion and recovery times), or simply insufficient patient numbers to see a significant result given the 80%–88% accuracy of the MR techniques to begin with (1, 2). Our current technique attempts to overcome some of these limitations by employing a 192×256 matrix, 1.2-mm partition thickness, no preparation pulse, and a 50 msec recovery time (Fig. 7). With this sequence, some T1 contrast is sacrificed by the elimination of the preparation pulse and the shortening of the wait time. However, this allows the overall examination time to remain approximately the same with an increased in-plane matrix. The larger matrix and thinner partitions allow improved resolution of the reformatted images, especially in the axial plane.

Problems remain in the routine implementation of these volume sequences with the large amount of data that is generated. Those problems which are inherent in 2D MR imaging also plague 3D imaging. Truncation artifact is present in the in-

plane directions, but also in the slice encoding direction due to finite sampling (19, 20). Motion and ghosting artifacts are present along not only the in-plane phase encoding direction as in 2D imaging, but also along the slice select phase-encoding direction. Motion artifact presented the most commonly encountered problem affecting the routine implementation of 3D techniques used in this study. The overall superior image quality of the 3D MP RAGE sequence in part related simply to the shorter imaging time, with less patient motion. While magnetic susceptibility artifact may overestimate foraminal stenosis on gradient echo images (21), this problem is lessened by minimizing the echo time. We do not consider this a significant problem in this study due to the 4 and 7 msec TE's used, being considerably shorter than that previously reported (16). In addition, T2* dephasing is reduced in 3D versus 2D gradient echo imaging, because 3D imaging samples more points of the slice select echo as a consequence of the phase encoding in the slice select direction (22). Magnetic susceptibility was also decreased by decreasing the slice thickness (voxel size), which lessens the magnetic field gradient across the voxel (23).

RF profiles associated with selective (FLASH) and nonselective 3D sequences (MP RAGE) are not perfect. Their effect on image quality and actual voxel size differ from that in 2D imaging. Although the individual partition thickness is preserved in 3D, the imperfect slice profile results in excitation of material outside the volume of interest with subsequent aliasing of the information in the slice select direction (16). The amount of slice select aliasing for a fixed volume decreases as the number of partitions is increased. The imperfect slice profile also causes nonuniform distribution of flip angle, and thus nonuniform contrast and signal-to-noise ratio from partition to partition. While this may have no noticeable effect on any one partition, it would be particularly noticeable on reformations. This potential problem was not a significant cause of image degradation. This nonuniformity is reduced by the use of a short nonselective RF pulse as in the MP RAGE sequence. Another potential source of image nonuniformity in the reformatted images is nonuniform spoiling across the 3D volume. This is not considered a problem in the MP RAGE sequence due to the non-zero recovery time that effectively spoils any residual coherent magnetization. Reformatting times for the oblique and orthogonal planes, while currently not prohibitive,

nevertheless need to be considerably shortened and displayed in a more user-friendly manner to realistically accommodate the day-to-day throughput of cervical spine studies.

This study has demonstrated a "proof of concept": That enhanced T1-weighted volume gradient echo imaging is an alternative to be considered in the approach to routine imaging of cervical degenerative disk disease. Instead of a volume sequence replacing one sequence in a series of sequences in a protocol, volume imaging may be the only sequence required. It was not our purpose to compare MR to a "gold standard" such as CT myelography. Rather, our goal was to determine whether a single 3D examination taking approximately 6 minutes (current sequence 5:31) could detect an equivalent or more extradural degenerative disease than a routine set of sequences taking 12.2 minutes, regardless of their possible inadequacies compared to CT myelography. Questions that remain to be addressed include the best sequence for a screening study, the advisability of using contrast enhancement as part of a routine study for degenerative disease, and the ability of the gradient echo sequences to identify ancillary or incidental findings (such as vertebral body or marrow involvement by degenerative changes/neoplasms or intrinsic cord damage secondary to cervical spondylosis). One compromise would be a two-sequence set consisting of a sagittal T1-weighted spin echo study, followed by the enhanced MP RAGE sequence. The spin echo study would allow less ambiguous diagnosis of altered marrow states in the vertebral bodies, and may improve "central" degenerative disease detection (which is not currently as easily defined by MP RAGE). Patients presenting with a question of intrinsic cord abnormality are not presently suitable for this technique, since the ability of 3D MP RAGE to define intrinsic cord disease is unknown.

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