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UPRIGHT, WEIGHT-BEARING, DYNAMIC-KINETIC MRI OF THE SPINE: *P*MRI/*K*MRI

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SUMMARY — The purpose of the study was to demonstrate the general utility of the first dedicated magnetic resonance imaging (MRI) unit enabling upright, weight-bearing positional evaluation of the spinal column (*p*MRI) during various dynamic-kinetic maneuvers (*k*MRI) in patients with degenerative conditions of the spine. This study consisted of a prospective analysis of cervical or lumbar imaging examinations. All studies were performed on a recently introduced whole body MRI system (IndomitableT^{M}, Fonar Corp, Melville, NY). The system operates at 0.6T using an electromagnet with a horizontal field, transverse to the longitudinal axis of the patient's body. Depending upon spinal level, all examinations were acquired with either a cervical or lumbar solenoidal radiofrequency receiver coil. This unit is configured with a top-open design, incorporating a patient-scanning table with tilt, translation and elevation functions. The unique motorized patient handling system developed for the scanner allows for vertical (upright, weight bearing) and horizontal (recumbent) positioning of all patients. The top-open construction also allows for dynamic-kinetic flexion and extension maneuvers of the spine. Patterns of bony and soft tissue change occurring among recumbent (rMRI) and upright neutral *p*ositions (pMRI), and dynamic-*k*inetic acquisitions (kMRI) were sought.

Depending on the specific underlying pathologic degenerative condition, significant alterations observed on pMRI and kMRI that were either more or less pronounced than on rMRI included: fluctuating anterior and posterior disc herniations, hypermobile spinal instability, central spinal canal and spinal neural foramen stenosis and general sagittal spinal contour changes. No patient suffered from the feelings of claustrophobia requiring termination of the examination.

To conclude, the potential relative beneficial aspects of upright, weight-bearing (*p*MRI), dynamic-kinetic (*k*MRI) spinal imaging on this system over that of recumbent MRI (*r*MRI) include: the revelation of occult disease dependent on true axial loading, the unmasking of kinetic-dependent disease, and the ability to scan the patient in the position of clinically relevant signs and symptoms. This imaging unit also demonstrated low claustrophobic potential and yielded relatively high-resolution images with little motion/chemical artifact.

Introduction

Magnetic resonance imaging (MRI) using commercial systems has until the present been limited to acquiring scans with patients in the recumbent position. It is a logical observation that the human condition is subject to the effects of gravity in positions other than that of recumbency. In addition, it is clear that patients experience signs and symptoms in positions other than the recumbent one. For this reason, a new fully open MRI unit was config-

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ured to allow upright, angled-intermediate, as well as recumbent imaging. This would at the same time allow partial or full weight bearing and simultaneous kinetic maneuvers of the patient's whole body or any body part. The objective was to enable imaging of the body in any position of normal stress, across the limits of range of motion, and importantly in the specific position of the patient's clinical syndrome. Under optimized conditions it was hoped that a specific imaging abnormality might be linked with the specific position or kinetic maneuver that reproduced the clinical syndrome. In this way, imaging findings could potentially be tied meaningfully to patient signs and symptoms. Furthermore, it was anticipated that radiologically occult but possibly clinically relevant weight bearing and/or kinetic dependent disease not visible on the recumbent examination would be unmasked by the positional-dynamic imaging technique.

Material and Methods

This study consisted of a prospective analysis of cervical or lumbar MRI examinations. All examinations were performed on a recently introduced full body MRI system (Indomitable^{TM}, Fonar Corporation, Melville, NY). The system operates at 0.6T using an electromagnet with a horizontal field, transverse to the axis of the patient's body. Depending upon spinal level, all examinations were acquired with either a cervical or lumbar solenoidal radiofrequency receiver coil. This MRI unit is configured with a top-open design, incorporating a patient-scanning table with tilt, translation and elevation functions. The unique MRI-compatible, motorized patient handling system developed for the scanner allows for vertical (upright, weight bearing) and horizontal (recumbent) positioning of all patients. The top-open construction also allows for dynamic-kinetic flexion and extension maneuvers of the spine.

Sagittal lumbar/cervical T1- (TR: 680, TE: 17, NEX: 3, ETL: 3) weighted fast spin echo imaging (T1FSEWI), sagittal lumbar/cervical T2- (4000, 140-160, 2, 13-15) weighted fast spin echo imaging (T2FSEWI), axial lumbar T1WI (600, 20, 2) or T1FSEWI (800, 17, 3, 3), axial cervical gradient recalled echo T2*-weighted (620-730, 22, 2) (T2*GREWI) were performed in all cervical/lumbar studies, respectively. In all cases, recumbent neutral, upright neutral, upright flexion, and upright extension imaging was performed. The patients were seated for the upright cervical examinations and for the neutral upright lumbar acquisitions, and were placed in the standing position for the lumbar kinetic studies.

Patterns of bony and soft tissue change occurring among recumbent neutral (rMRI) and upright neutral *p*ositions (pMRI), and dynamic-*k*inetic acquisitions (kMRI: upright flexion-extension) were sought. Specifically, degenerative spinal disease including focal intervertebral disc herniations, spinal stenosis involving the central spinal canal and spinal neural foramina, and hypermobile spinal instability were compared to other visibly normal segmental spinal levels among the rMRI, the pMRI and kMRI acquisitions. Focal disc herniations were defined as localized protrusions of intervertebral disc material that encompassed less that 25% of the total disc periphery in the axial plane; central spinal stenosis was defined as generalized narrowing of the central spinal canal in the axial and/or sagittal plane relative to that of other spinal levels; spinal neural foramen narrowing was defined as general narrowing of the neural foramina as determined from sagittal acquisitions relative to that of other segmental spinal levels; and hypermobile spinal instability was defined as relative mobility between adjacent spinal segments as compared to other spinal levels that in turn demonstrated virtually no intersegmental motion. Generally speaking, degenerative disc disease was defined as both intrinsic discal MRI signal loss as well as morphological alteration to include a reduction in superoinferior dimensional disc space height. Alterations in sagittal spinal curvature were also noted between the neutral rMRI and pMRI acquisitions. Finally, notation was made as to whether or not the patient was referred in part because of an inability to undergo a prior MRI due to subjective feelings of claustrophobia attempted in a "closed" MRI unit.

Results

The neutral upright imaging studies (neutral-pMRI) demonstrated the assumption by the patient of the true postural sagittal lumbar cervical or lumbar lordotic spinal curvature existing in the patient at the time of the MRI examination, a feature that was partially or completely lost on the neutral recumbent examination (rMRI). In other words, this relative spinal curvature postural sagittal spinal curvature correction phenomenon was manifested by a change from a straight or even reversed lordotic curvature or rMRI to a more lordotic one on pMRI. Increasing severity of focal posterior disc herniation on the neutral-pMRI compared to the rMRI was noted, and was yet

worse in degree on extension-kMRI; these posterior disc herniations were less severe on flexion-kMRI maneuvers as compared to all other acquisitions. Absolute de n*ovo* appearance of disc herniation on neutral-pMRI was identified on extension-kMRI acquisitions in some cases as compared to rMRI. Increasing severity of central spinal canal stenosis was identified on neutral-pMRI and on extension-kMRI acquisitions, as compared to rMRI, and was overall most severe on extension and least severe on flexion-kMRI acquisitions. Similarly, increasing severity of spinal neural foramen stenosis was identified on neutral-pMRI and on extension-kMRI acquisitions, as compared to rMRI, and was overall most severe on extension and least severe on flexion-kMRI acquisitions. Increasing central spinal canal narrowing with spinal cord compression on extension-kMRI was identified in some cervical examinations as compared to recumbent rMRI, neutral-pMRI and flexion-kMRI maneuvers. No examination was uninterpretable based on patient motion during any portion of the MRI acquisitions. No patient was unable to complete the entire examination due to subjective feelings of claustrophobia.

Discussion

Conventional recumbent MRI, or *r*MRI, is obviously inadequate theoretically for a complete and thorough evaluation of the spinal column and its contents. The human condition includes both weight bearing body positioning, or pMRI, as well as complex kinetic maneuvers, or *k*MRI. The present MRI unit was intended to address these considerations. Both occult weight bearing disease (e.g., focal intervertebral disc herniations, spinal stenosis), and kinetic dependent disease (e.g., disc herniations, spinal stenosis, hypermobile instability) of a degenerative nature were unmasked by the p/kMRI technique. In addition, a true assessment of the patient's sagittal spinal lordotic curvature was possible on neutral upright pMRI, thereby enabling better evaluation of whether the loss of curvature was due to patient positioning (i.e., rMRI) or as a probable result of somatic perispinal muscular guarding or spasm.

Simply upright standing, or upright pMRI showed a phenomenon here termed "telescoping" whereby the levels of generalized intersegmental spinal degeneration showed a collapse of the spine into itself. Consequent redundancy of the discal, ligamentous and meningeal tissues of the spine resulted in increased degrees of central canal and lateral recess spinal stenosis, while craniocaudal shortening of the spine associated with telescoping caused increased degrees of neural foramen stenosis. On occasion, the degree of frank posterior disc herniation was seen to enlarge with upright pMRI. This latter finding would seem to be an important observation, obviously improving the qualitative nature of the analysis in relevant cases of disc herniation.

Upright extension kMRI tended to show greater degrees of central canal and neural foramen stenosis, while flexion kMRI revealed a lessening or complete resolution of the same central canal and neural foramen narrowing. These phenomena were only observed at levels of disc degeneration (i.e., both disc desiccation and disc space narrowing). In exceptional cases, de novo posterior disc herniations were revealed only on upright extension kMRI. When present in the cervical spine, such cases invariably showed compression of the underlying spinal cord. Overall, this was felt to be one of the most important observations noted in this study. Interestingly, some of the posterior disc herniations became less severe when upright flexion kMRI was performed. This would seem to be worthy of preoperative note to those surgeons that operate on the spine in positions of flexion.

It was noted that all cases of fluctuating intervertebral disc herniation had MRI signal loss compatible with desiccation as well as intervertebral disc space height reduction. These disc findings were also invariably true in cases of sagittal plane hypermobile spinal instability. It was possible to judge even minor degrees of translational hypermobile spinal instability (e.g., mobile antero- or retrolisthesis) grossly as well as by using region of interest measurements. The kMRI technique obviously does not suffer from the effects of magnification error potentially inherent in conventional radiographic dynamic flexion-extension studies traditionally used in these circumstances.

Also noted at levels of disc degeneration was a sagittal plane hypermobile "rocking" of the vertebrae in relationship to each other. Observation of the opposed adjacent vertebral endplates in such cases showed them to move in relationship to each other to a much greater degree than is observed at levels with normal intervertebral discs as judged by MRI. This is here termed as "dysfunctional intersegmental motion" (DIM). The significance of DIM is the theoretical possibility that such pathologic vertebral motion may engender generalized accelerated intersegmental degeneration due to the effects of micro-autotrauma over long periods of time. The self-protect-

ing spinal mechanisms inherent in the normal intervertebral discs and spinal ligaments are lacking is such cases, perhaps initiating a progressive degenerative cascade of autotramatizing hypermobility.

The postoperative spine may be best analyzed by p/kMRI in those patients who have undergone surgical intersegmental fusion procedures. In the absence of ferromagnetic fusion implants, the MRI unit was capable of identical evaluation as compared to the preoperative spine. Cases of stabile intersegmental fusion, for example, showed no evidence of intersegmental motion, thereby confirming postoperative intersegmental stability.

Spinal cord motion is another dynamic factor that may be amenable to analysis in cases where there is clinically suspected congenital or postoperative spinal cord tethering. In test cases, for example, the conus medullaris was seen to freely move anteriorly and posteriorly on flexion and extension kMRI, respectively.

Provocative p/kMRI is an experimental technique that may be of major practical relevance in the future. By comparing images where the patient is pain or symptom free, with a specific position in which the patient experiences the pain or symptom for which the examination is being performed, the imaging specialist may profitably link the medical images with the clinical syndrome. In successful cases, provocative p/kMRI may for the first time be able to become a truly specific diagnostic method in cases of spinal disease.

The images of the cervical and lumbar spine suffered very little from motion artifacts from either CSF or body origin; no study was degraded to the point of being uninterpretable. Patient motion was not a problem, this being overcome by simply placing the scan table at 5 degrees posterior tilt enabling the patient to "rest" against the table during the MRI acquisitions. In addition, it was found to be unnecessary to stand the patient for upright p/kMRI of the cervical and thoracic spines; at present, only one sagittal sequence is felt to be necessary for evaluation of the lumbar spine, in order to analyze the lumbosacral spine for true postural curvature and for considering issues of spi*nal balance*. The remainder of the lumbosacral spine p/k MRI examination may be performed in the sitting position.

The chemical shift artifact was minor on all images, this being directly related to field strength; this effect would be expected to be less than one-half that experienced at 1.5 T. In addition, the degree of motion artifact from such sources as the heart or CSF motion was typically minor, even without 'flow compensation' overlay techniques that were not used; this source of artifacts is also related to field strength, commonly being worse on high-field MRI units.

Other currently relevant overlay techniques are possible on this p/kMRI unit. Included among these are fat suppression imaging (STIR: short tau inversion recovery) coupled with fast spin echo acquisitions. This is felt to be very useful in the evaluation of spinal inflammation and spinal neoplasia.

Finally, in the patient with a possible critical stenosis of the spine, long time period acquisition sequences are of concern in the patient who may have greater degrees of spinal cord or cauda equina compression in upright flexion-extension p/kMRI. For this purpose, very fast acquisition sequences have been implemented in order to screen for such critical abnormalities before going forward with longer time period imaging studies (e.g., ~4-5 minutes). Driven equilibrium fast spin echo acquisitions offer excellent quality imaging in a fraction of the time (e.g., ~15 seconds) required of traditional sequences, and allow safe imaging of almost any patient with p/kMRI. These fast high-resolution techniques may in the future be the major if not only method of imaging the spine using p/kMRI.

Conclusion

To conclude, the potential relative beneficial aspects of upright, weight-bearing (*p*MRI), dynamic-kinetic (*k*MRI) spinal imaging on this system over that of recumbent MRI (*r*MRI) include: clarification of true sagittal upright neutral spinal curvature unaffected by patient positioning, revelation of occult degenerative spinal disease dependent on true axial loading (i.e., weight-bearing), unmasking of kinetic-dependent degenerative spinal disease (i.e., flexion-extension), and the potential ability to scan the patient in the position of clinically relevant pain. This MRI unit also demonstrated low claustrophobic potential and yielded high-resolution images with little motion/chemical artifact.

Based on initial experience with this unit, it is felt that mid-field MRI may prove to be the optimal field strength for routine, anatomic MR imaging of the spinal column in degenerative as well as other spinal disease categories. In addition, the evidence thus far indicates that p/kMRI may prove to be efficacious to incorporate as a part of the diagnosis-treatment paradigm in patients with spinal, radicular and referred pain syndromes originating from spinal pathology.

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Sažetak

DINAMIČKO-KINETIČKA MRI KRALJEŠNICE PRI USPRAVNOM POLOŽAJU I UZ OPTEREĆENJE: *p*MRI/*k*MRI

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Cilj ispitivanja bio je pokazati opću korisnost prvoga uređaja za prikazivanje magnetskom rezonancijom (MRI) koji omogućuje pozicijsku procjenu kralješnice u uspravnom položaju i pri opterećenju (*p*MRI) za vrijeme različitih dinamičko-kinetičkih zahvata (*k*MRI) u bolesnika s degenerativnim promjenama kralješnice. Istraživanje je obuhvatilo prospektivnu analizu oslikavanja cervikalnog i lumbalnog područja. Sva su istraživanja izvedena na nedavno uvedenom MRI uređaju za cijelo tijelo (Indomitable™, Fonar Corp, Melville, NY). Sustav radi pri 0,6 T, uporabom elektromagneta s horizontalnim poljem, poprečnim na uzdužnu os bolesnikova tijela. Ovisno o spinalnoj razini, svi su pregledi obavljeni s cervikalnom ili lumbalnom prijemnom solenoidnom zavojnicom radiofrekvencije. Uređaj je na vrhu otvoren, a sastoji se od stola za skeniranje koji se može naginjati, pomicati i podizati. Jedinstveni motorom pokretani sustav za namještanje bolesnika, konstruiran za potrebe skenera, omogućuje okomit (uspravan, uz opterećenje) i vodoravan (ležeći) položaj svih bolesnika. Izvedba s otvorom na gornjem dijelu omogućuje dinamičko-kinetičke fleksijske i ekstenzijske zahvate na kralješnici. Traženi su uzorci promjena koštanog i mekog tkiva u ležećem položaju (rMRI) i uspravnoj neutralnoj poziciji (pMRI), te dinamičko-kinetičkim akvizicijama (kMRI).

Ovisno o specifičnom patološkom degenerativnom stanju, na pMRI i kMRI su uočene značajne promjene koje su bile više ili manje izražene u odnosu na rMRI, obuhvaćale su fluktuirajuće prednje ili stražnje hernijacije diska, hipermobilnu spinalnu nestabilnost, stenozu centralnog spinalnog kanala i spinalnog neuralnog foramena te opće promjene sagitalne spinalne konture. Nijedan bolesnik nije imao osjećaj klaustrofobije zbog koje bi se pretraga morala prekinuti. Potencijalni relativni aspekti korisnosti MRI kralješnice u uspravnom položaju i uz opterećenje (*p*MRI) te dinamičko-kinetičkog (*k*MRI) prikazivanja na ovom sustavu u odnosu na MRI u ležećem položaju (rMRI) obuhvaćaju: otkrivanje prikrivenih bolesti ovisno o stvarnom aksijalnom opterećenju, razjašnjenje bolesti ovisnih o kinetici, te mogućnost skeniranja bolesnika u položaju pri kojemu su uočljivi klinički važni znakovi i simptomi. Opisani uređaj ima mali klaustrofobični potencijal te daje slike relativno visoke rezolucije, s malo artefakata vezanih uz pokrete i kemikalije.