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Kinematic Cervical Spine MRI in Low-Impact Trauma Assessment - Review and Application in Clinical Practice

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Abstract

Kinematic magnetic resonance imaging can be implemented as a non-invasive adjunct examination for injuries in the cervical spine in the clinical assessment of ligamentous, disk, and soft tissue injuries, as a basis for determining medical versus surgical management, and also establishing the degree of functional clinical impairment. This article discusses the clinical indications and application of kinematic cervical spine MRI method in the diagnosis and management of cervical spine injuries. The spectrum and grading classification of cervical spine injuries using kinematic MRI is also discussed.

Keywords

MRI; Cervical Spine; Kinematic; Spinal injury; Spinal imaging

Introduction

Positional Magnetic Resonance Imaging studies are considered investigational. The use of such imaging technologies in clinical practice is largely derived from anecdotal evidence of MRI studies performed in recumbent (supine) and non-recumbent (sitting or standing) positions. The primary methodology for using kinematic MRI applications in the cervical spine is due to the frequency of such injuries. Low impact trauma resulting in acceleration and deceleration injuries accounts for most injuries in the cervical spine. Automobile accidents and sports-related injuries account for a majority of such injuries. More than 3 million cases of cervical spine injury related to motor vehicle accidents are reported annually, with varying degrees of soft tissue and ligamentous injuries [1,2]. Cervical spine injuries also occur in most contact sports, including football, hockey, rugby, and wrestling, as well as in several noncontact sports, such as skiing, track and field, diving, surfing, power lifting, and equestrian events. Cervical spine injuries are estimated to occur in 10 to 15% of all football players, most commonly in linemen and defensive players. Serious injuries with neurologic sequelae remain infrequent, and most of these injuries are self-limited. Injuries occur in all levels of play, from the high school to the professional level [3-5].

Injury models and clinical findings

The normal architecture of the cervical spine is a smooth C-shaped configuration, or normal lordosis. The angulation which occurs with normal cervical lordosis provides an optimal biomechanical configuration for controlled motion and dissipation of forces to the supporting muscles, ligaments, and soft tissues. During mild flexion of approximately 30 degrees angulation that occurs during normal physiologic movement, the naturally occurring normal cervical lordosis is straightened, allowing the forces of the axial load to be transmitted to the bony structures and intravertebral disks [6]. Complete angular motion of the cervical spine following full flexion and extension is approximately 110 degrees in normal subjects [7].

Low-impact collisions result in acceleration and deceleration of the head and neck, also known as whiplash. Traditional teaching viewed acceleration as producing extension forces and deceleration as producing flexion forces in the cervical spine [8]. Experimental biomechanical studies have further refined whiplash as a biphasic injury mechanism [9,10]. In the first phase, the cervical spine forms an S-shaped curve, with hyperflexion in the upper cervical spinal segments, and simultaneous hyperextension in the lower cervical spinal segments. During the second phase, both the upper and lower cervical spinal segments become fully extended according to a path of least resistance. The biphasic injury mechanism best explains the clinical findings observed following whiplash injury. The cervical spine appears most susceptible to injury during the hyperflexion stage, which increases biomechanical stress to the posterior cervical complex of the C4/C5, C5/C6, and C6/C7 spinal segments, corresponding anatomically to the posterior longitudinal ligament, joint capsule, interspinous ligaments, supraspinous ligaments, and ligamenta flava. Statistically, the C5/C6 disk is the most common source of cervical, axial, and referred arm pain [11]. Surprisingly, approximately 60% of whiplash injuries are occult to MRI, and include occult soft tissue, intervertebral disk, and ligamentous injuries, accounting for approximately 90% of injuries missed by MRI [12].

A spectrum of clinical findings can be encountered in cervical spinal injuries, including acute cervical sprain/strain, intravertebral disk injury, increased cervical spinal stenosis, nerve root injuries, and cervical spondylolisthesis, with or without fracture. A sprain is defined as an injury to the paraspinal musculotendinous unit. A strain is defined as an injury of the paraspinous muscle itself. Pain is typically localized and associated with restricted cervical range of motion, without radiculopathy or clinical signs of nerve impingement [13]. Acute disk herniations are less common, but typically present with transient neurologic deficits, varying from radiculopathy to anterior cord syndrome. A defined or localized sensory deficit can be associated with loss of pain and temperature sensation, but with preserved posterior column function, such as vibratory, proprioceptive, and light touch sensations [14]. Nerve root and brachial plexus injuries are often referred to as stringers or burners, associated with transient loss of function with searing or burning pain down the arm following injury [15].

The most important consideration in clinical evaluation of the cervical spine is stability. Spondylolisthesis, with or without fracture, requires immediate immobilization and stabilization [16]. Cervical instability is defined as angular motion greater than 11 degrees, or

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translation of greater than 3 mm for contiguous spinal segments [17]. However, in common practice, it is difficult to distinguish true instability because no clear distinction exists between maximum physiologic flexion and partial subluxations due to partial tears of the posterior longitudinal ligament. Catastrophic injuries of the cervical spine resulting from fracture-dislocations are readily apparent on cervical spine radiographs. However, such injuries are much less common than low-impact injuries, which account for a majority of cervical spine injuries [18]. Most patients with uncomplicated whiplash injuries improve symptomatically within 8 weeks but can persist as long as 3 months post-injury when associated with severe ligamentous, disk, or facet injuries [19].

Recumbent MRI technologies

Most of the early researches performed on biomechanical motion MRI studies in the cervical spine are based on flexion and extension MRI studies performed in a 0.2T open MRI system [10]. Giuliano et al. studied 100 consecutive uninjured normal asymptomatic adults and 100 adult accident victims following rear low-impact motor vehicle accidents were evaluated using rapid T2-weighted MRI in conjunction with a 0.2T open MRI imaging system [10]. Injured subjects were evaluated during the sub acute period, at 12 to 14 weeks after injury, following clinically resolved muscle spasm. Imaging findings were compared between normal and injured subjects. The normal subjects showed a stepwise segmental motion pattern that started at C1-C2 and transmitted to the lower cervical segments. Normal range of motion was quantified as 50 degrees and 60 degrees extention. Asymptomatic disk herniations were observed in 2% or normal test subjects. In the subacute post-traumatic subjects, there was a loss of the normal segmental motion pattern, with hypolordosis in 98% of patients. Range of motion in injured patients was 25 degrees flexion and 35 degrees extension. Disk herniations were observed in 28% of patients. Biomechanical changes in the herniated disks were associated with mildly increased spinal stenosis following flexion [20].

Morishita et al. performed kinematic MRI studies in 587 lumbar and 459 cervical spines of symptomatic patients in axially loaded, upright neutral (0°), flexion (40°), and extension (-20°) positions. In normal cervical spines, most of the total angular mobility was attributed to C4/5 and C5/6, but mobility was significantly reduced in these segments in patients with pre-existing disk degeneration. Cervical segmental mobility was observed to be significantly reduced in segments with cord compression, compared to those with no cord compression. The degree of such herniation increased significantly in flexion and extension images, compared to neutral images [21].

Non-recumbent MRI Technologies

Most of the active research in non-recumbent kinematic MRI evaluations was performed in the lumbar spine. The largest quantitative comparison of positional non-recumbent MRI in neutral, flexion, and extension positions was reported by Zou et al. [22]. The study included 553 patients with symptomatic back pain with and without radiculopathy who were referred for kinetic/positional MRI in a 0.6T system. Disk herniations were evaluated in three positions (neutral, flexion, and extension) and quantified by MRI analysis software. Increased spinal stenosis in extension and flexion, in comparison with neutral, was seen in 16% and 12% of disks, respectively, with 'missed' disk herniation rates of 19.5% for extension and 15.3% for flexion MRI [22].

Another study by Weishaupt et al. reported finding 13 instances of nerve root deviation in the seated extension position in a 0.5T positional MRI compared with 10 instances in the supine position in a 1.0 T conventional MRI in a group of 30 patients with chronic low back pain. The morphology of disks observed in the supine position changed in 5% of patients in non-recumbent flexion and in 9% of case in non-recumbent extension [23]. Similarly, Vitaz et al. reported changes in spinal cord compression, angulation, and alignment that occurred during physiologic movement in 20 patients with cervical spine disorders [24].

Ferriero-Perez et al. compared recumbent and non-recumbent positions in 89 patients combined cervical and lumbar MRI patients with disk herniation or spondylolisthesis using a 0.6T upright MRI system. Occult disk herniations and spondylolisthesis were observed in 76% of patients in the non-recumbent position compared to 16% in the recumbent position [25]. Madsen et al. further compared non-recumbent and recumbent MRI studies with axial loading in patients with lumbar spinal stenosis in a 0.6T MRI system. Results showed cross-sectional diameter changes between the two positions, suggesting that the standing position could be simulated while recumbent by axial loading and lordosis [26].

Other imaging applications

Radiographs are typically the preliminary study of choice, and include the anteroposterior (AP) and lateral flexion/extension views. The most common finding is straightening of the cervical spine, with either loss or reversal of the normal lordotic curve, also known as hypolordosis. Videofluoroscopy also has been used to evaluate increased, decreased, or abnormal segmental spinal motion in the cervical spine. However, its use has been controversial because of the inability to distinguish physiologic spinal movements associated with normal flexion from subtle, partial subluxations caused by partial tears of the posterior longitudinal ligament [27].

Indications for Kinematic MRI

MRI is clinically indicated in the setting of persistent arm pain, neurologic deficits, and clinical signs of nerve root compression. MRI offers the best noninvasive and detailed evaluation of the intravertebral disks, soft tissue structures, and spinal cord, but is considered unreliable in the detection of subtle annular disk tears [28]. Hyperflexion injuries can evade radiologic detection [27]. For these reasons, kinematic MRI provides the most optimal means of detecting subtle hyperflexion injuries and annular disk tears, in addition to evaluating segmental spinal motion and cervical lordosis patterns. Kinematic MRI, in contradistinction to other imaging methods, such as lateral flexion/extension radiographs and videofluoroscopy, can provide more accurate assessment of spinal canal stenosis [10].

Recommended kinematic MRI protocol

Giuliano et al. provide the most comprehensive imaging protocol for kinematic MRI evaluations of the cervical spine in the recumbent position [10,20]. Recumbent evaluations are particularly well suited to the injured patient. The recumbent position circumvents many of the technical issues associated with non-recumbent MRI applications, particularly with motion artifact due to poor stabilization in an upright or sitting position [24].

Kinematic MRI evaluations can be performed in any suitable MR

imaging system, including both low-field and high-field systems. All patients should ideally be screened by qualified emergency physicians to assess for clinical signs of cervical instability. Preliminary cervical spine radiographs are useful to exclude fracture and spondylolisthesis. Clinical criteria for kinematic MRI evaluations include the persistence of signs and symptoms during the subacute period, including localized neck pain and radiculopathy, despite clinically resolved muscle spasm. The kinematic MRI evaluation is typically coordinated with manipulative therapy and rehabilitation programs. Informed consent should be obtained and documented in the medical record, although there are no known contraindications to using kinematic MRI in the subacute trauma setting. A general advisory is recommended in patients with the potential for spinal cord injury and such patients should be carefully screened and excluded from study. These include patients with cord impingement from a large disk herniation; both symptomatic and asymptomatic patients with cord compression from ventral osteophytic spurs of advanced cervical spondylosis; severe congenital spinal stenosis; and pre-existing acquired versus congenital syringomyelia, with or without Chiari malformations [10,20].

Coil selection must consider the ability to accommodate the full range of possible segmental spinal motion, or an angular motion of approximately 110 degrees following full flexion and extension in normal subjects. Traditionally, general purpose coils were used for this purpose and the 11-inch coil has been successfully used in test subjects. However, modern high-field MRI systems now offer improved special resolution and much reduced imaging times using phased array and quadrature spine coils. MRI scan protocols are variable depending on the functional capabilities of the MRI system. Generally, the kinematic MRI protocol should be performed as an additional sequence following the static cervical MRI examination according to parameters recommended by the American College of Radiology accreditation standards [10,20].

The sagittal T2 fast-spin-echo (FSE) scan sequence is the most optimal imaging parameter and provides the most accurate and reliable diagnostic information in distinguishing soft tissue contrast between aqueous structures, such as nucleus pulposus and cerebral spinal fluid, from ligamentous structures. A well hydrated intravertebral disk and cerebrospinal fluid should demonstrate characteristic signal hyperintensity on T2 FSE scans, whereas the compact fibers of the posterior longitudinal ligament and discoligamentous complex show band like signal hypointensity on the sagittal T2 FSE scan sequence. Tissue contrast is generally achievable on T2 FSE scans on both low-field and high-field scan systems. FSE scans are recommended over fast inversion-recovery fast-spin echo T2 sequences (also known as STIR, FSEIR, or FLAIR) based on superior acquisition speed and resolution. Volumetric T2 FSE scans are now technically feasible in many high-field MRI systems and provide the best imaging results, provided that coil configurations are compatible with this technique [10,20].

A suggested representative scan protocol in a high-field MRI system (HDe 1.5T; GE Medical Systems, Milwaukee, Wis., USA) should include the sagittal T2 FRFSE scan sequence with scan parameters of: TR 1050, TE 110, ETL 23, NEX 2, slice thickness of 6 mm, skip of 1.0 mm, scan field-of-view of 26×26 cm, matrix of 320×224, resulting in a signal-to-noise ratio of 100% and in-plane resolution of 0.88 mm^2. This is well within ACR specifications of 1 mm^2 with adequate discrimination of annular disk tears and the posterior longitudinal ligament. This scan prescription produces 5 high quality scans in only 25 sec. The anterior saturation band is an option on most imaging systems which must be removed in order to eliminate inadvertent clipping or collimation of the spinal structures during spinal movements.

Suggested positioning of the patient is in the recumbent position (supine), with the neck positioned in the center of a head-holder. For the best possible image quality, the neck should be positioned in the center of the coil, with careful padding of the sides of the neck with foam or Velcro, in order to facilitate movements only in the flexed and extended positions, rather than side-to-side. A small foam dowel positioned at the base of the neck also adds neck support for smooth, coordinated spinal movements. All spinal movements are initiated only by the patient rather than by the imaging technologist, so as to simulate normal physiologic motion. Two scan prescriptions are obtained, one with patient-initiated full-flexion and a second, in full extension. Images are evaluated frame-by frame for cervical lordosis and segmental spinal motion of the spinous processes and posterior elements. The intravertebral disks, spinal cord, and degree of spinal stenosis are also assessed. Angular range-of-motion can be quantified using software available on most modern imaging systems.

Kinematic MRI Image interpretation

The kinematic MRI interpretation method is derived from the work of Giuliano et al. [10,20]. Normal, non-injured patients demonstrate normal cervical lordosis, with a normal segmental motion pattern characterized by a characteristic stepwise segmental motion initiating at C1-C2 and transmitting to the lower cervical spinal segments in a coordinated and orderly pattern. Hypolordosis with normal segmental motion is generally observed in 4 to 7% of cases, representing a normal variant. Movement of the spinous processes is fan-like and unrestricted, with most significant motion observed from C4 to C7 [10]. Measurements of angular motion of the cervical spine on kinematic MRI are adapted from existing methods of measuring angular motion on lateral bending views of the cervical spine [29]. Intersecting lines bisecting the middle third of the vertebral bodies in the upper and lower cervical spine is used to define the degree of angular motion. Normal angular range of motion is 45 to 60 degrees in flexion and 50 to 70 degrees in extension. Small asymptomatic bulging disks can be observed in 2% of patients [10].

Kinematic MRI evaluations in injured subjects generally support a spectrum of stable injury to the posterior cervical complex, including the joint capsule, interspinous/supraspinous ligaments, and ventral annulus fibrosus, with an intact posterior longitudinal ligament. The posterior longitudinal ligament is exceptionally durable, as confirmed in both biomechanical and autopsy studies. A distinct imaging pattern is seen on kinematic MRI in injured subjects. Hypolordosis is invariably present, with notable segmental motion restriction characterized by absence of the normal fan-like movements of the spinous processes of C4 through C7, sometimes fixed in a more horizontal configuration. Flexion appears disproportionally restricted compared to extension, with exacerbation of symptoms, including headache, arm pain, and arm numbness. Quantitative angular motion restriction is highly variable. Another phenomenon observed are morphologic changes in the injured disk, with flexion accentuating annular disk tears, disk bulges, and herniations to produce visible extradural impression on the subarachnoid space. Spinal stenosis is noted to be increased in

these subjects, sometimes with cord compression. Symptomatic disk protrusions can be observed in up to 28% of injured subjects [20].

Therapeutic assessment based on Kinematic MRI Data

Considering the overwhelming number of cervical spinal injuries, there are few studies correlating the results of imaging studies with therapeautic outcomes. The most recognized clinical scoring assessment for cervical spinal injuries is the Quebec Taskforce on Whiplash-Associated Disorders [30]. This clinical grading system (Table 1) classifies the severity of injury based on a 0 to 4 scoring scale; with a score of 0, no subjective neck complaints and absence of clinical signs and symptoms; a score l, complaints of stiffness and tenderness in the absence of other physical signs; a score of 2, neck complaints, with objective decreased range of motion and point tenderness; a score of 3, neck complaints with neurologic deficits of weakness, sensory and reflex changes; and a score of 4, neck complaints, with fracture and/or dislocation [30].

The only published prospective study regarding therapeutic kinematic MRI applications is derived from Giuliano et al., which describe a systematized grading system, known by the acronym STIP, or Soft Tissue Injury Protocol [20]. STIP scoring is an imaging grading system which classifies the degree of functional impairment based on an 8 point scale derived from the following clinical criteria, each with individual subscores ranging from 0 to 2 points: hypolordosis, motion restriction, disk herniation, and spinal stenosis (Table 1). STIP establishes five classes of clinical impairment, ranging from normal (no impairment) to severe impairment (Table 2) [20]. Class 1 is the normal patient, demonstrating normal cervical lordosis and a normal segmental motion pattern, without disk herniation or spinal stenosis. Class 2 represents pure ligamentous injury, characterized by hypolordosis and segmental motion restriction, without disk herniation or spinal stenosis (Figure 1). Segmental motion restriction and fixation can be observed in flexion, extension, or both. Class 3 represents the classic discoligamentous injury, characterized by the presence of disk protrusion and spinal stenosis, in addition to evidence of ligamentous injury, such as hypolordosis and segmental motion restriction. No cord compression is observed (Figure 2). Class 4 is defined by the presence of increased spinal stenosis with cord compression following flexion maneuvers (Figure 3). The presence of cord compression in the prototypical Class 4 injury and obligates the treating clinician to consult surgical intervention. The Class 5 injury is frank cord compression caused by a large cervical disk herniation

detected on static MRI scans in the neutral position. A Class 5 injury represents a contraindication to the kinematic MRI procedure due to the potential for cord injury [20].

The initial data reported by Giuliano et al. suggests that scoring whiplash injuries has important therapeutic implications. This appears consistent with anecdotal evidence that suggests that early rehabilitation is believed to augment chronic pain and disability [31]. The main goal of treatment is to restore normal range of motion aimed at improving strength, flexibility, posture, and body mechanics. There is growing clinical and epidemiologic evidence supporting the use of early manipulative therapy in place of the standard program of immobilization and application of a soft collar [32]. In the Giuliano et al. study using the STIP scoring method, comprised of 100 motor vehicle accident patients with symptomatic flexion and extension cervical spinal injuries, 94% of patients were determined to have nonsurgical injuries [20]. Class 1 and 2 injuries indicated mild impairment and were found in 68% of patients, who were considered to have reached maximum medical improvement at 12 weeks after injury. A Class 3 injury indicated moderate impairment and was found 26% of patients, who required an additional 12 weeks of rehabilitative and medical treatment to achieve maximum medical improvement. Class 4 and 5 injuries indicated severe impairment; these were identified in 6% of patients and required surgical intervention; of these surgical patients, 83% achieved maximum medical improvement at 36 weeks following injury [20]. In comparing kinematic MRI versus non-imaging evaluations, there is wide disparity of clinical outcomes in the literature, which reports 20 to 70% of patients remaining symptomatic at 6 months post injury [33]. Maximum medical improvement of all whiplash injuries is generally achieved within 2 years [34].

Conclusions

While still considered investigational, kinematic MRI studies of the cervical spine represent a newer, mechanized method of assessment of soft tissue injuries to complement subjective data obtained from routine clinical examinations. Kinematic MRI evaluations can be performed in any suitable MRI system, provided that the technology can achieve in-plane resolution of 1 mm^2 or less. To conclude, kinematic MRI examinations are particularly useful compared to conventional MRI studies performed in the neutral position in detecting occult disk herniations and spondylolisthesis, an indicator of potential spinal instability. However, ongoing research is needed in order to establish the benefits of recumbent versus

Table 1: STIP scoring criteria.

Subcategory	0-Points	1-Points	2-Points
Hypolordosis	Not present	Present, with normal motion	Present, with motion restriction
Motion Restriction	Not Present	Restriction, in flexion only	Restriction, in both flexion and extension
Disk Herniation	Not present	Single disk	Multiple disks
Spinal Stenosis	Not present	Stenosis, increased with motion	Cord compression, with motion

**Table 2:** STIP classification system for cervical spine trauma.

Classification	Point Score	Impairment Rating
Class 1	0 to 1	Normal; asymptomatic hypolordosis, with normal segmental motion and fixation
Class 2	2 to 3	Mild impairment; hypolordosis, with segmental motion and restriction
Class 3	4 to 6	Moderate impairment; hypolordosis, segmental motion restriction, disk herniation, and spinal stenosis; no cord compression present
Class 4	7 to 8	Severe impairment; Class 3 features with disc herniation causing cord compression with motion
Class 5	No score	No rating; cord compression is present from a disk herniation in the neutral position
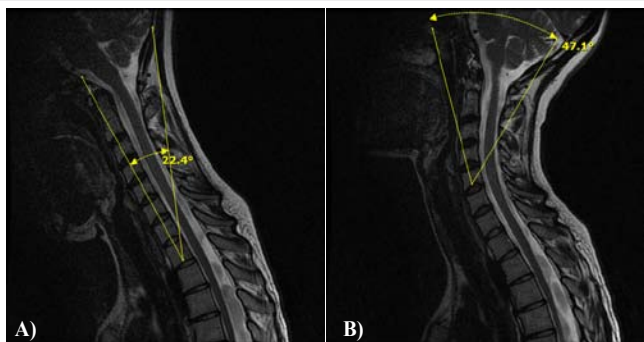
Figure 1: STIP Class 2 patient with hypolordosis and segmental motion restriction, in the flexed position (left) and extended position (right), 12 weeks post injury. Note that flexion is more significantly restricted than extension, with total angular motion of 70°. Normal angular motion is 110°.
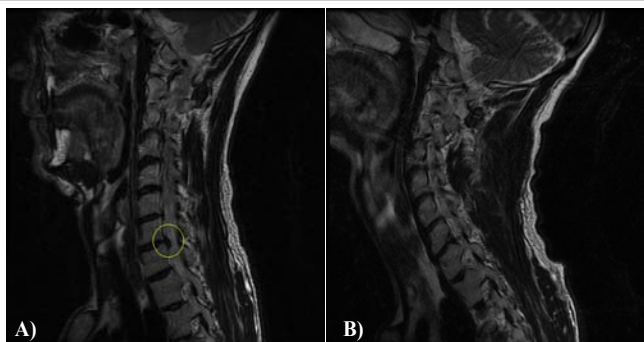
Figure 2: STIP Class 3 patient showing central disk herniation (circle) elicited following flexion (left) compared to extension (right), 12 weeks post injury.
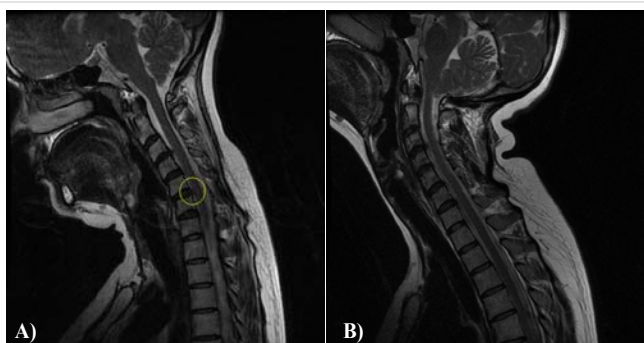
Figure 3: STIP Class 4 patient with morphologic changes in the herniated disk following flexion (left) and extension (right), with cord impingement following flexion (circle), 12 weeks post injury.

non-recumbent cervical kinematic MRI applications, based on the relatively few published studies.

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