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Natural history of the aging spine

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Abstract The unrelenting changes associated with aging progressively affects all structures of the spinal units. The degenerative process starts early during the first decade of life at the disc level. Discal degeneration is associated with biochemical changes followed by macroscopic alterations including tears and fissures, which may lead to discal herniation, the main cause of radiculopathy in the young adult. Moreover, nociceptive nerve fibers have been demonstrated in degenerated discs. They may be a source of nociception and of pure low-back pain. Facet joint changes are usually secondary to discal degeneration. They include subluxation, cartilage alteration and osteophytosis. Facet hypertrophy and laxity, associated with discal degeneration, and enlargement of the ligamen-

tum flavum progressively create narrowing of the spinal canal as well as degenerative instabilities such as spondylolisthesis and scoliosis, which are the main causes of neurogenic claudication and radiculopathy in old persons. Vertebral bodies are the static elements of the spinal unit. With advancing age, osteoporosis weakens the bony structures and facilitates bone remodeling and rotatory deformities. Finally, aging of bone, discs, facets, ligaments, and muscles may ultimately lead to rotatory scoliosis, destabilization, and rupture of equilibrium.

Keywords Lumbar disc degeneration · Age-related intervertebral changes · Disc herniation · Stenosis · Low-back pain

Introduction

The spine is a flexible, multisegmented column. Its functional role is to maintain stability and an upright position as well as providing mobility at the segmental level. The spine comprises a static, changeless element – the vertebral bodies – and an elastic mobile component – the three-joint complex, consisting of the intervertebral disc and the two posterior facet joints. Spine motion, stability, equilibrium and control of position are assumed by the antagonist action of the powerful flexor and extensor muscle groups.

Changes with age and pathology may modify these structures. Because most of the research work has been devoted to the lumbar spine, the present paper will focus

more on this anatomic section of the spine. Aging is a normal process to all structures. As emphasized by Garfin and Herkowitz [9], aging is difficult to distinguish from degenerative changes.

As for every human tissue, aging of the structural components of the spine may be related to a predetermined genetic cell viability and/or to exposure of the tissues to heavy mechanical forces throughout life. Whatever the mechanism, aging will lead to degenerative changes starting with subtle biochemical alterations followed by micro-structural and finally gross structural changes of the spinal unit. The degenerative cycle with its biomechanical consequences will progressively modify the functional anatomy and generate various pain syndromes, rupture of equilibrium and destabilization. Aging affects all the structures of the spine. This review paper will summarize the

age-related changes of the various components of the spinal unit in turn.

Aging of the disc

Historically, primary degeneration of the disc has been considered as the initiating event resulting in secondary deterioration of the facets, ligaments, and muscles. The physiology of the intervertebral disc has been recently reviewed [22]. Disc degeneration depends on the failure of cellular activity in charge of producing a normal extracellular matrix. In a normal disc, an equilibrium exists between synthesis and degradation of the matrix elements. Loss of aggrecan and water, and a decrease in collagen organization and of disc height are the early modifications of aging. Simultaneously, the level of the proteases responsible for the enzymatic degradation process increases [2, 3, 19]. Rupture of metabolic equilibrium observed with aging is multifactorial, including a predisposed genetic condition [22].

Decrease of nutrient supply of the cells is an important factor in degeneration. The main nutritional pathway of the disc is through the adjacent vertebral end plate [11]. This source of nutrition is at great risk in the aging disc, as the permeability of the end plate diminishes with advancing age. Detrimental effect of a decreased blood supply from the end plate results in tissue breakdown, starting in the nucleus. A recent study has shown that this process may begin early in the second decade of life [3]. The cells of the disc are also sensitive to mechanical signals. They can be negatively affected by mechanical stresses and stimulation undergone throughout life, leading to qualitative and quantitative modulation of the matrix proteinases [17].

The biochemical modifications of the disc are further accompanied by gross anatomic and macroscopic changes. As aging progresses, the boundary between nucleus and annulus becomes less distinct, with an increase of collagen in the nucleus. Concentric fissuring and radial tears may appear during the third and fourth decade of life, with substantial individual differences: elderly persons may have a "young disc" and vice versa. Significant temporospatial variations of histologic and macroscopic changes are also observed across levels and regions [23]. The degenerative changes can be assessed by magnetic resonance imaging, exhibiting variations of signal intensity, with the ultimate loss of disc height and dark signal. Loss of disc height and turgor, secondary to the biochemical events summarized above, have serious biomechanical consequences. Loss of proteoglycans and fluid, lowering of osmotic pressure in the nucleus, as well as alterations of the collagen network, affect the normal absorption and dissipation of the movement forces applied to the normal viscoelastic hydrostatic nature of the disc. Mechanical changes with age and degeneration have been recently reviewed [15]. Loss of mechanical competence and flattening of the

disc may generate diffuse bulging, which should be differentiated from focal bulges or true herniations, characterized macroscopically by nuclear migration through radial fissures of the disc. Disc herniation requires pre-existing age-related degenerative changes.

Aging and degeneration are also associated with dramatic changes in vascularization and innervation of the disc. A normal healthy adult disc is avascular, apart from a sparse vascularization at the outer part of the annulus. Presence of blood vessels has been demonstrated in degenerated disc and in herniated disc tissue [2, 10]. Penetration of blood vessels through the rim lesions is promoted by angiogenesis factors [10]. Inflammatory cells as well as macrophages also invade the degenerated disc. Production of various cytokines and proteases by endogenous cells and by the vascular cells of the invading vessels has been demonstrated [18]. Metallo-proteinase (MMP) expression increases with advancing age, thus enhancing the destruction pathway. Correlation of MMPs expression with formation of tears and clefts in the annulus has also been demonstrated [23]. Presence of nerve fibers relevant to pain sensation is a prerequisite for a tissue to be a source of nociception. Recent studies [2, 8, 10, 20] have shown the presence of nociceptive nerve fibers in the annulus and inner nucleus of the degenerated disc. Most nerve fibers identified by immunochemistry accompany blood vessels, suggesting a role of vaso-regulation. However, another set of neural elements, independent of vessels, expressing substance P and with a morphology of nociceptive nerve terminals, have been found in the nucleus of painful discs assessed by provocative discography of patients undergoing anterior surgery for chronic low-back pain [8]. This important finding strongly suggests the role of the nerve terminals of the degenerated disc in the pathogenesis of low-back pain. An innervated disc may be a source of nociception.

In summary, among the various structures of the spine, the process of aging starts in the disc at the beginning of the second decade of life. Failure of the normal cell activity depends on various factors: genetic, nutritional, and mechanical. The initial event is not yet known, but when the degenerative cycle is started, a complex interplay of biochemical and biomechanical factors create a vicious circle, which progressively enhances the degenerative process.

Aging of the facet joint

The facet joints are the only synovial joints in the spine, with hyaline cartilage overlying subchondral bone. Kirkaldy Willis and associates have described a three-joint complex consisting of the intervertebral disc and the two facet joints [7, 9]. In a normal healthy spinal unit, the disc is the major anterior load-bearing structure. The facet joints provide a posterior load-bearing helper, stabilizing the motion segment in flexion and extension and also pro-

tecting the disc from excessive torsion. It is generally accepted that degenerative changes of the facets are secondary to disc degeneration. The mechanical consequences of disc degeneration, including loss of disc height and segmental instability, increase the loads on the facets and generate subluxation of the joints and cartilage alteration. Osteoarthritis of the facets is similar to that of all diarthrodial joints. Cartilage degradation leads to the formation of focal and then diffuse erosions, with sclerosis of the subchondral bone. Facet hypertrophy, apophyseal malalignment and osteophyte formation may narrow the spinal canal and create central and/or lateral stenosis. Destabilization of the three-joint complex may lead to degenerative instabilities including degenerative spondylolisthesis and scoliosis. Nociceptive nerve endings have been identified in the facet joint capsules. They may therefore be a source of back pain. Whether so-called "facet joint syndrome" really exists and, if so, how frequently it occurs, remain matters of controversy.

Aging of ligaments and muscles

The ligaments surrounding the spine contribute to its intrinsic stability. They also restrain extremes of motion in all planes. All spinal ligaments have a high content of collagen. Ligamentum flavum, which connects the adjacent vertebrae, has a high percentage of elastin, allowing contraction during flexion and elongation during extension [7]. As part of the aging process, ligaments undergo chemical and macroscopic changes, including a rise in the concentration of elastin, which decreases tensile properties, resulting in ligamentous weakening affecting the stabilizing function of the longitudinal ligaments [13]. In addition, aging and degeneration of the ligamentum flavum leads to increased thickness and bulging, often disclosed during surgery for spinal stenosis.

The trunk and pelvic muscles have a major role in both motion and stabilization of the spine. Their support stabilizes and modifies the load in static and dynamic situations. The postural dorsal and abdominal muscles are constantly active in a standing position. During motion, equilibrium and control of stability are assumed by the antagonist action of the extensor dorsal muscles and abdominal flexors [21]. Aging may induce a "degenerative myopathy," compromising the spine dynamics, and generating a rupture of equilibrium. Camptocormia is a good example of destabilization caused by muscular insufficiency. In this case, fat tissue invades the erector spinal muscles inducing a kyphotic attitude of the lumbar spine.

Aging of the bone

As mentioned earlier, the bony components constitute the static elements of the spinal unit. However, aging of the

bony structures, especially osteoporosis, may induce major changes. They will be discussed extensively in the following papers. They include sclerosis and bone formation of the end plate, lowering of the blood supply of the disc, and formation of osteophytes, which increase the surface area of load bearing [7]. Moreover, repetitive torsional loads may progressively induce bone remodeling and rotatory deformities of the posterior elements. These changes generate stenosis and slipping at the intervertebral level, as described by Farfan [6].

Clinical relevance

The biochemical, macroscopic, and biomechanical changes observed with aging, briefly summarized above, are indistinguishable from those disclosed in degenerated discs of symptomatic subjects. Pain and disability are the clinical expression of the aging spine. The role of the clinician is to relate the degenerative changes identified on the imaging studies to the clinical symptoms, and to differentiate the organic pain syndromes from non-organic spinal pain. It is recognized that a degenerated spinal unit may be totally asymptomatic and remain so.

Discal degeneration is generally considered as the primary source of pure low-back pain. The nociceptive nerve fibers identified in the inner annulus and nucleus can be sensitized by the cytokines and neuropeptides present in the degenerated disc [8, 18, 20]. However, other sources of nociception can be found in the spinal unit, including muscles, ligaments, and facets. Nociception coming from these various tissues is difficult to distinguish from discogenic pain. Moreover, recognition of the "painful disc" in multilevel disc degeneration is not easy. Therefore, the exact source of the pain is difficult to identify and often remains unknown at the individual level [4]. It should be remembered that pain is not only nociception: sensitization of the central nervous system may be responsible for chronic low-back pain [5]. Radicular pain is the other possible expression of the degenerative spine. A direct link between discal degeneration and radiculopathy was established many years ago by Mixter and Barr. The biologic activity of the herniated discal tissue has been identified more recently [12]. Discal herniation is not the only cause of nerve root irritation in the degenerated spinal unit. With advancing age, bony overgrowth in the central canal or the lateral recess can compress the nerve roots. The bony encroachment may or may not produce symptoms. The natural history of lumbar spinal stenosis has been recently reviewed [1]. As already mentioned, diffuse annular bulging, buckling of the ligamentum flavum, hypertrophy, and osteophytes of the facets may create midline compression and central stenosis. Lateral bony compression of the nerve root may result from subarticular entrapment, pedicular kinking or foraminal encroachment. Discal degeneration, osteoarthritis of the facets, and bony remodeling may be

responsible for degenerative instabilities such as spondylolisthesis, which aggravates the midline and lateral bony compression. These bony constraints are directly related to the changes of the aging spine. Central stenosis with or without slipping is the major cause of neurogenic claudication [16].

Aging of bone, of the segmental mobile spinal unit (disc, facets), and of the muscles may also lead to degenerative rotatory scoliosis, with the possible evolution towards a progressive disorganization of the spine, destabilization, and rupture of equilibrium [13, 14]. As the popu-

lation ages, stenosis and deformities are more common. As already mentioned, there are substantial differences between individuals: old persons may have a "young" spine. Many factors of degradation of the spinal unit remain unknown. The role of a genetic predisposition appears crucial, but the physical environment is also an important influential factor. Proper nutrition, adequate physical exercise and avoidance of smoking and of inappropriate physical loads are at the present time the only means of prevention at our disposal.

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