Hyaluronan and synovial joint: function, distribution and healing

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ABSTRACT
Synovial fluid is a viscous solution found in the cavities of synovial joints. The principal role of synovial fluid is to reduce friction between the articular cartilages of synovial joints during movement. The presence of high molar mass hyaluronan (HA) in this fluid gives it the required viscosity for its function as lubricant solution. Inflammation oxidation stress enhances normal degradation of hyaluronan causing several diseases related to joints.

This review describes hyaluronan properties and distribution, applications and its function in synovial joints, with short review for using thiol compounds as antioxidants preventing HA degradations under inflammation conditions.

KEY WORDS: synovial joint fluid; hyaluronan; antioxidant; thiol compound

Introduction
The human skeleton consists of both fused and individual bones supported and supplemented by ligaments, tendons, and skeletal muscles. Articular ligaments and tendons are the main parts holding together the joint(s). In respect of movement, there are freely moveable, partially moveable, and immovable joints. Synovial joints (Figure 1), the freely moveable ones, allow for a large range of motion and encompass wrists, knees, ankles, shoulders, and hips (Kogan, 2010).

Structure of synovial joints
Cartilage
In a healthy synovial joint, heads of the bones are encased in a smooth (hyaline) cartilage layer. These tough slippery layers – e.g. those covering the bone ends in the knee joint – belong to mechanically highly stressed tissues in the human body. At walking, running, or sprinting the strokes frequency attain approximately 0.5, 2.5 or up to 10 Hz.
cartilage tissue (Servaty et al., 2000). Figure 2 sketches a section of the cartilage – a chondrocyte cell that permanently restructures/rebuilds its extracellular matrix. Three classes of proteins exist in articular cartilage: collagens (mostly type II collagen); proteoglycans (primarily aggrecan); and other noncollagenous proteins (including link protein, fibronectin, COMP – cartilage oligomeric matrix protein) and the smaller proteoglycans (biglycan, decorin, and fibromodulin). The interaction between highly negatively charged cartilage proteoglycans and type II collagen fibrils is responsible for the compressive and tensile strength of the tissue, which resists applied load in vivo.

Synovium/synovial membrane
Each synovial joint is surrounded by a fibrous, highly vascular capsule/envelope called synovium, whose internal surface layer is lined with a synovial membrane. Inside this membrane, type B synoviocytes (fibroblast-like cell lines) are localized/embedded. Their primary function is to continuously extrude high-molar-mass hyaluronans (HAs) into synovial fluid.

Synovial fluid
The synovial fluid (SF) of natural joints normally functions as a biological lubricant as well as a biochemical pool through which nutrients and regulatory cytokines traverse. SF contains molecules that provide low-friction and low-wear properties to articulating cartilage surfaces.

Molecules postulated to play a key role in lubrication alone or in combination, are proteoglycan 4 (PRG4) (Swann et al., 1985) present in SF at a concentration of 0.05–0.35 mg/ml (Schmid et al., 2001), hyaluronan (HA) (Ogston & Stanier, 1953) at 1–4 mg/ml (Mazzucco et al., 2004), and surface-active phospholipids (SAPL) (Schwarz & Hills, 1998) at 0.1 mg/ml (Mazzucco et al., 2004). Synoviocytes secrete PRG4 (Jay et al., 2000; Schumacher et al., 1999) and are the major source of SAPL (Dobbie et al., 1995; Hills & Crawford, 2003; Schwarz & Hills, 1996), as well as HA (Haubeck et al., 1995; Momberger et al., 2005) in SF. Other cells also secrete PRG4, including chondrocytes in the superficial layer of articular cartilage (Schmid et al., 2001b; Schumacher et al., 1994) and, to a much lesser extent, cells in the meniscus (Schumacher et al., 2005).

As a biochemical depot, SF is an ultra filtrate of blood plasma that is concentrated by virtue of its filtration through the synovial membrane. The synovium is a thin lining (~50 μm in humans) comprised of tissue macrophage A cells, fibroblast-like B cells (Athanasou & Quinn, 1991; Revell, 1989; Wilkinson et al., 1992), and fenestrated capillaries (Knight & Levick, 1984). It is backed

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**Figure 2.** Articular cartilage main components and structure (adapted from Chen et al., 2006).
by a thicker layer (~100 μm) of loose connective tissue called the subsynovium (SUB) that includes an extensive system of lymphatics for clearance of transported molecules. The cells in the synovium form a discontinuous layer separated by intercellular gaps of several microns in width (Knight & Levick, 1984; McDonald & Levick, 1988). The extracellular matrix in these gaps contains collagen types I, III, and V (Ashhurst et al., 1991; Rittig et al., 1992), hyaluronan (Worrall et al., 1991), chondroitin sulphate (Price et al., 1996; Worrall et al., 1994), biglycan and decorin proteoglycans (Coleman et al., 1998), and fibronectin (Poli et al., 2004). The synovial matrix provides the permeable pathway through which exchange of molecules occurs (Levick, 1994), but also offers sufficient outflow resistance (Coleman et al., 1998; Scott et al., 1998) to retain large solutes of SF within the joint cavity. Together, the appropriate reflection of secreted lubricants by the synovial membrane and the appropriate lubricant secretion by cells are necessary for development of a mechanically functional SF (Blewis et al., 2007).

In the joint, HA plays an important role in the protection of articular cartilage and the transport of nutrients to cartilage. In patients with rheumatoid arthritis (RA), (Figure 3) it has been reported that HA acts as an anti-inflammatory substance by inhibiting the adherence of immune complexes to neutrophils through the Fc receptor (Brandt, 1970), or by protecting the synovial tissues from the attachment of inflammatory mediators (Miyazaki et al., 1983, Mendichi & Soltes, 2002).

Reactive oxygen species (ROS) (O₂•−, H₂O₂, •OH) are generated in abundance by synovial neutrophils from RA patients, as compared with synovial neutrophils of osteo-arthritis (OA) patients and peripheral neutrophils of both RA and OA patients (Niwa et al., 1983).

McCord (1973) demonstrated that HA was susceptible to degradation by ROS in vitro, and that this could be protected by superoxide dismutase (SOD) and/or catalase, which suggests the possibility that there is pathologic oxidative damage to synovial fluid components in RA patients. Dahl et al. (1985) reported that there are reduced HA concentrations in synovial fluids from RA patients. It has also been reported that ROS scavengers inhibit the degradation of HA by ROS (Soltes, 2010; Blake et al., 1981; Betts & Cleland, 1982; Soltes et al., 2004).

These findings appear to support the hypothesis that ROS are responsible for the accelerated degradation of HA in the rheumatoid joint. In the study of Juranek and Soltes (2012) the oxygen radical scavenging activities of synovial fluids from both RA and OA patients were assessed, and the antioxidant activities of these synovial fluids were analyzed by separately examining HA, d-glucuronic acid, and N-acetyl-d-glucosamine.

Hyaluronan

In 1934, Karl Meyer and his colleague John Palmer isolated a previously unknown chemical substance from the vitreous body of cows’ eyes. They found that the substance contained two sugar molecules, one of which was uronic acid. For convenience, therefore, they proposed the name “hyaluronic acid”. The popular name is derived from “hyalos”, which is the Greek word for glass + uronic acid (Meyer & Palmer, 1934). At the time, they did not know that the substance which they had discovered would prove to be one of the most interesting and useful natural macromolecules. HA was first used commercially in 1942.

![NORMAL JOINT

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Cartilage</th>
<th>Tendon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>Joint Capsule</td>
<td>Synovial Fluid</td>
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<td>Bone</td>
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![JOINT AFFECTED BY RHEUMATOID ARTHRITIS

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<thead>
<tr>
<th>Bone Loss/Erosion</th>
<th>Cartilage Loss</th>
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<tr>
<td>Bone Loss (Generalized)</td>
<td></td>
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<tr>
<td>Inflamed Synovium</td>
<td>Swollen Joint Capsule</td>
</tr>
</tbody>
</table>

Figure 3. Normal, (healthy) and rheumatoid arthritis synovial joint.
when Endre Balazs applied for a patent to use it as a substitute for egg white in bakery products (Necas et al., 2008).

The term “hyaluronan” was introduced in 1986 to conform to the international nomenclature of polysaccharides and is attributed to Endre Balazs (Balazs et al., 1986) who coined it to encompass the different forms the molecule can take, e.g., the acid form, hyaluronic acid, and the salts, such as sodium hyaluronate, which forms at physiological pH (Laurent, 1989). HA was subsequently isolated from many other sources and the physicochemical structure properties and biological role of this polysaccharide were studied in numerous laboratories (Kreil, 1995). This work has been summarized in a Ciba Foundation Symposium (Laurent, 1989) and a recent review (Laurent & Fraser, 1992; Chabrecek et al., 1990; Orvisky et al., 1992).

Hyaluronan (Figure 4) is a unique biopolymer composed of repeating disaccharide units formed by N-acetyl-d-glucosamine and d-glucuronic acid. Both sugars are spatially related to glucose which in the β-configuration allows all of its bulky groups (the hydroxyls, the carboxylate moiety, and the anemic carbon on the adjacent sugar) to be in sterically favorable equatorial positions while all of the small hydrogen atoms occupy the less sterically favorable axial positions. Thus, the structure of the disaccharide is energetically very stable. HA is also unique in its size, reaching up to several million Daltons and is synthesized at the plasma membrane rather than in the Golgi, where sulfated glycosaminoglycans are added to protein cores (Itano & Kimata, 2002; Weigel et al., 1997; Kogan et al., 2007a).

In a physiological solution, the backbone of a HA molecule is stiffened by a combination of the chemical structure of the disaccharide, internal hydrogen bonds, and interactions with the solvent. The axial hydrogen atoms form a non-polar, relatively hydrophobic face while the equatorial side chains form a more polar, hydrophilic face, thereby creating a twisting ribbon structure. Solutions of hyaluronan manifest very unusual rheological properties and are exceedingly lubricious and very hydrophilic. In solution, the hyaluronan polymer chain takes on the form of an expanded, random coil. These chains entangle with each other at very low concentrations, which may contribute to the unusual rheological properties. At higher concentrations, solutions have an extremely high but shear-dependent viscosity. A 1% solution is like jelly, but when it is put under pressure it moves easily and can be administered through a small-bore needle. It has therefore been called a “pseudo-plastic” material. The extraordinary rheological properties of hyaluronan solutions make them ideal as lubricants. There is evidence that hyaluronan separates most tissue surfaces that slide along each other. The extremely lubricious properties of hyaluronan have been shown to reduce postoperative adhesion formation following abdominal and orthopedic surgery. As mentioned, the polymer in solution assumes a stiffened helical configuration, which can be attributed to hydrogen bonding between the hydroxyl groups along the chain. As a result, a coil structure is formed that traps approximately 1000 times its weight in water (Chabrecek et al., 1990; Cowman & Matsuoka, 2005; Schiller et al., 2011).

Properties of hyaluronan

Hyaluronan networks

The physico-chemical properties of hyaluronan were studied in detail from 1950 onwards (Comper & Laurent, 1978).

The molecules behave in solution as highly hydrated randomly kinked coils, which start to entangle at concentrations of less than 1 mg/mL. The entanglement point can be seen both by sedimentation analysis (Laurent et al., 1960) and viscosity (Morris et al., 1980). More recently Scott and his group have given evidence that the chains when entangling also interact with each other and form stretches of double helices so that the network becomes mechanically more firm (Scott et al., 1991).

Rheological properties

Solutions of hyaluronan are viscoelastic and the viscosity is markedly shearing dependent (Morris et al., 1980; Gibbs et al., 1968). Above the entanglement point the viscosity increases rapidly and exponentially with concentration (~c⁻³) (Morris et al., 1980) and a solution of 10 g/l may have a viscosity at low shear of ~10⁶ times the viscosity of the solvent. At high shear the viscosity may drop as much as ~10³ times (Gibbs et al., 1968). The elasticity of the system increases with increasing molecular weight and concentration of hyaluronan as expected for a molecular network. The rheological properties of hyaluronan have been connected with lubrication of joints and tissues and hyaluronan is commonly found in the body between surfaces that move along each other, for example cartilage surfaces and muscle bundles (Bothner & Wik, 1987).

Water homeostasis

A fixed polysaccharide network offers a high resistance to bulk flow of solvent (Comper & Laurent, 1978). This was demonstrated by Day (1950) who showed that hyaluronidase treatment removes a strong hindrance to water flow through a fascia. Thus HA and other polysaccharides prevent excessive fluid fluxes through tissue compartments. Furthermore, the osmotic pressure of a hyaluronan solution is non-ideal and increases exponentially with the concentration. In spite of the high molecular weight of the polymer the osmotic pressure of a 10 g/l hyaluronan solution is of the same order as an 10 g/l albumin solution. The exponential relationship makes hyaluronan a particularly potent osmotic buffer in tissues. It is, for example, used for treating postoperative bleeding, for raising blood pressure, and as a diluent for blood transfusion.

Figure 4. Structural formula of hyaluronan – the acid form.
to marked changes in osmotic pressure. Flow resistance together with osmotic buffering makes hyaluronan an ideal regulator of the water homeostasis in the body.

Network interactions with other macromolecules
The hyaluronan network retards the diffusion of other molecules (Comper & Laurent, 1978; Simkovic et al., 2000). It can be shown that it is the steric hindrance which restricts the movements and not the viscosity of the solution. The larger the molecule the more it will be hindered. In vivo hyaluronan will therefore act as a diffusion barrier and regulate the transport of other substances through the intercellular spaces. Furthermore, the network will exclude a certain volume of solvent for other molecules; the larger the molecule the less space will be available to it (Comper & Laurent, 1978). A solution of 10 g/l of hyaluronan will exclude about half of the solvent to serum albumin. Hyaluronan and other polysaccharides therefore take part in the partition of plasma proteins between the vascular and extravascular spaces. The excluded volume phenomenon will also affect the solubility of other macromolecules in the interstitium, change chemical equilibria and stabilize the structure of, for example, collagen fibers.

Medical applications of hyaluronic acid
The viscoelastic matrix of HA can act as a strong bio-compatible support material and is therefore commonly used as growth scaffold in surgery, wound healing and embryology. In addition, administration of purified high molecular weight HA into orthopaedic joints can restore the desirable rheological properties and alleviate some of the symptoms of osteoarthritis (Balazs & Denlinger, 1993; Balazs & Denlinger, 1989; Kogan et al., 2007). The success of the medical applications of HA has led to the production of several successful commercial products, which have been extensively reviewed previously.

Table 1 summarizes both the medical applications and the commonly used commercial preparations containing HA used within this field. HA has also been extensively studied in ophthalmic, nasal and parenteral drug delivery. In addition, more novel applications including pulmonary, implantation and gene delivery have also been suggested. Generally, HA is thought to act as either a mucoadhesive and retain the drug at its site of action/absorption or to modify the in vivo release/absorption rate of the therapeutic agent. A summary of the drug delivery applications of HA is shown in Table 2.

Table 1. Summary of the medical applications of hyaluronic acid (Brown & Jones, 2005).

<table>
<thead>
<tr>
<th>Disease state</th>
<th>Applications</th>
<th>Commercial products</th>
<th>Publications</th>
</tr>
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<tbody>
<tr>
<td>Osteoarthritis</td>
<td>Lubrication and mechanical support for the joints</td>
<td>Hyalgan® (Fidia, Italy), Artz® (Seikagaku, Japan), ORTHOVISC® (Amika, USA), Healon®, Opegan® and Opellead®</td>
<td>Hochburg, 2000; Altman, 2000; Dougados, 2000; Guidolin et al., 2001; Maheu et al., 2002; Barrett &amp; Siviero, 2002; Miltner et al., 2002; Tascioglu and Oner, 2003; Uthman et al., 2003; Kelly et al., 2003; Hamburger et al., 2003; Kirwan, 2001; Ghosh &amp; Guidolin, 2002; Mabuchi et al., 1999; Balazs, 2003; Fraser et al., 1993; Zhu &amp; Granick, 2003.</td>
</tr>
<tr>
<td>Surgery and wound healing</td>
<td>Implantation of artificial intraocular lens, viscoelastic gel</td>
<td>Bionect®, Connettivina® and Jossalind®</td>
<td>Ghosh &amp; Jossal, 2002; Risbert, 1997; Inoue &amp; Katakami, 1993; Miyazaki et al., 1996; Stiebel-Kalish et al., 1998; Tani et al., 2002; Vazquez et al., 2003; Soldati et al., 1999; Ortonne, 1996; Cantor et al., 1998; Turino &amp; Cantor, 1999.</td>
</tr>
<tr>
<td>Embryo implantation</td>
<td>Culture media for the use of in vitro fertilization</td>
<td>EmbryoGlue® (Vitrolife, USA)</td>
<td>Simon et al., 2003; Gardner et al., 1999; Vanso et al., 1999; Kemmann, 1998; Suchanek et al., 1994; Joly et al., 1992; Gardner, 2003; Lane et al., 2003; Figueiredo et al., 2002; Miyano et al., 1994; Kano et al., 1998; Abeysheera, 2002; Jakkne et al., 1997; Fumus et al., 1998; Jang et al., 2003.</td>
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</table>

Table 2. Summary of the drug delivery applications of hyaluronic acid.

<table>
<thead>
<tr>
<th>Route</th>
<th>Justification</th>
<th>Therapeutic agents</th>
<th>Publications</th>
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<tbody>
<tr>
<td>Ophthalmic</td>
<td>Increased ocular residence of drug, which can lead to increased bioavailability</td>
<td>Pilocarpine, tropicamide, timolol, gen-timycin, tobramycin, aracnedine polyester, (S) aceclidine</td>
<td>Jarvinen et al., 1995; Sasaki et al., 1996; Gurney et al., 1987; Camber et al., 1987; Cumber &amp; Edman, 1989; Saettone et al., 1994; Saettone et al., 1991; Bucolo et al., 1998; Bucolo &amp; Mangialfico, 1999; Herrero-Vanrell et al., 2000; Morera et al., 1991; Bernatelas et al., 1993; Gandolfi et al., 1992; Langer et al., 1997.</td>
</tr>
<tr>
<td>Nasal</td>
<td>Bioadhesion resulting in increased bioavailability</td>
<td>Xylometazoline, vasopressin, gentamycin</td>
<td>Morimoto et al., 1991; Lim et al., 2002.</td>
</tr>
<tr>
<td>Pulmonary</td>
<td>Absorption enhancer and dissolution rate modification</td>
<td>Insulin</td>
<td>Morimoto et al., 2001; Surendrakumar et al., 2003.</td>
</tr>
<tr>
<td>Implant</td>
<td>Dissolution rate modification</td>
<td>Insulin</td>
<td>Surini et al., 2003; Takayama et al., 1990.</td>
</tr>
<tr>
<td>Gene</td>
<td>Dissolution rate modification and protection</td>
<td>Plasmid DNA monoclonal antibodies</td>
<td>Yun et al., 2004; Kim et al., 2003.</td>
</tr>
</tbody>
</table>
Cosmetic uses of hyaluronic acid

HA has been extensively utilized in cosmetic products because of its viscoelastic properties and excellent biocompatibility. Application of HA containing cosmetic products to the skin is reported to moisturize and restore elasticity, thereby achieving an antiwrinkle effect, albeit so far no rigorous scientific proof exists to substantiate this claim. HA-based cosmetic formulations or sunscreens may also be capable of protecting the skin against ultraviolet irradiation due to the free radical scavenging properties of HA (Manuskiatti & Maibach, 1996).

HA, either in a stabilized form or in combination with other polymers, is used as a component of commercial dermal fillers (e.g. Hylaform®, Restylane® and Dermalive®) in cosmetic surgery. It is reported that injection of such products into the dermis, can reduce facial lines and wrinkles in the long term with fewer side-effects and better tolerability compared with the use of collagen (Duranti et al., 1998; Bergeret-Galley et al., 2001; Leyden et al., 2003). The main side-effect may be an allergic reaction, possibly due to impurities present in HA (Schartz, 1997; Glogau, 2000).

Biological function of hyaluronan

Naturally, hyaluronan has essential roles in body functions according to organ type in which it is distributed (Laurent et al., 1996).

Space filler

The specific functions of hyaluronan in joints are still essentially unknown. The simplest explanation for its presence would be that a flow of hyaluronan through the joint is needed to keep the joint cavity open and thereby allow extended movements of the joint. Hyaluronan is constantly secreted into the joint and removed by the synovium. The total amount of hyaluronan in the joint cavity is determined by these two processes. The half-life of the polysaccharide at steady-state is in the order of 0.5–1 day in rabbit and sheep (Brown et al., 1991; Fraser et al., 1993). The volume of the cavity is determined by the pressure conditions (hydrostatic and osmotic) in the cavity and its surroundings. Hyaluronan could, by its osmotic contributions and its formation of flow barriers in the limiting layers, be a regulator of the pressure and flow rate (McDonald & Leviek, 1995). It is interesting that in fetal development the formation of joint cavities is parallel with a local increase in hyaluronan (Edwards et al., 1994).

Lubrication

Hyaluronan has been regarded as an ideal lubricant in the joints due to its shear-dependent viscosity (Ogston & Stanier, 1953) but its role in lubrication has been refuted by others (Radin et al., 1970). However, there are now reasons to believe that the function of hyaluronan is to form a film between the cartilage surfaces. The load on the joints may press out water and low-molecular solutes from the hyaluronan layer into the cartilage matrix. As a result, the concentration of hyaluronan increases and a gel structure of micrometric thickness is formed which protects the cartilage surfaces from frictional damage (Hlavacek, 1993). This mechanism to form a protective layer is much less effective in arthritis when the synovial hyaluronan has both a lower concentration and a lower molecular weight than normal. Another change in the arthritic joint is the protein composition of the synovial fluid. Fraser et al. (1972) showed more than 40 years ago that addition of various serum proteins to hyaluronan substantially increased the viscosity and this has received a renewed interest in view of recently discovered hyaladherins (see above). TSG-6 and inter-α-trypsin inhibitor and other acute phase reactants such as haptoglobin are concentrated to arthritic synovial fluid (Hutadilok et al., 1988). It is not known to what extent these are affecting the rheology and lubricating properties.

Scavenger functions

Hyaluronan has also been assigned scavenger functions in the joints. It has been known since the 1940s that hyaluronan is degraded by various oxidizing systems and ionizing irradiation and we know today that the common denominator is a chain cleavage induced by free radicals, essentially hydroxy radicals (Myint et al., 1987). Through this reaction hyaluronan acts as a very efficient scavenger of free radicals. Whether this has any biological importance in protecting the joint against free radicals is unknown. The rapid turnover of hyaluronan in the joints has led to the suggestion that it also acts as a scavenger for cellular debris (Laurent et al., 1995). Cellular material could be caught in the hyaluronan network and removed at the same rate as the polysaccharide (Stankovska et al., 2007; Rapta, et al., 2009).

Regulation of cellular activities

As discussed above, more recently proposed functions of hyaluronan are based on its specific interactions with hyaladherins. One interesting aspect is the fact that hyaluronan influences angiogenesis but the effect is different depending on its concentration and molecular weight (Sattar et al., 1992). High molecular weight and high concentrations of the polymer inhibit the formation of capillaries, while oligosaccharides can induce angiogenesis. There are also reports of hyaluronan receptors on vascular endothelial cells by which hyaluronan could act on the cells (Edwards et al., 1995). The avascularity of the joint cavity could be a result of hyaluronan inhibition of angiogenesis.

Another interaction of some interest in the joint is the binding of hyaluronan to cell surface proteins. Lymphocytes and other cells may find their way to joints through this interaction. Injection of high doses of hyaluronan intra-articularly could attract cells expressing these proteins. Cells can also change their expression of hyaluronan-binding proteins in states of disease, whereby hyaluronan may influence immunological reactions and cellular traffic in the path of physiological processes in cells (Edwards et al., 1995). The observation often
reported that intra-articular injections of hyaluronan alleviate pain in joint disease (Adams, 1993) may indicate a direct or indirect interaction with pain receptors.

**Hyaluronan and synovial fluid**

In normal/healthy joint, the synovial fluid, which consists of an ultrafiltrate of blood plasma and glycoproteins contains HA macromolecules of molar mass ranging between 6–10 mega Daltons (Praest et al., 1997). SF serves also as a lubricating and shock absorbing boundary layer between moving parts of synovial joints. SF reduces friction and lubricating and shock absorbing boundary layer between moving parts of synovial joints. SF reduces friction and wear and tear of the synovial joint playing thus a vital role in the lubrication and protection of the joint tissues from damage during motion (Oates et al., 2002).

As SF of healthy humans exhibits no activity of hyaluronidase, it has been inferred that oxygen-derived free radicals are involved in a self-perpetuating process of HA catabolism within the joint (Grootveld et al., 1991; Stankovska et al., 2006; Rychly et al., 2006). This radical-mediated process is considered to account for ca. twelve-hour half-life of native HA macromolecules in SF.

Acceleration of degradation of high-molecular-weight HA occurring under inflammation and/or oxidative stress is accompanied by impairment and loss of its viscoelastic properties (Parsons et al., 2002; Soltes et al., 2005; Stankovska et al., 2005; Lath et al., 2005; Hrabarova et al., 2007; Valachova & Soltes, 2010; Valachova et al., 2013a).

Low-molecular weight HA was found to exert different biological activities compared to the native high-molecular-weight biopolymer. HA chains of 25–50 disaccharide units are inflammatory, immune-stimulatory, and highly angiogenic. HA fragments of this size appear to function as endogenous danger signals, reflecting tissues under stress (Noble, 2002; West et al., 1985; Soltes et al., 2007; Stern et al., 2007; Soltes & Kogan, 2009). Figure 5 describes the fragmentation mechanism of HA under free radical stress.

a. Initiation phase: the intact hyaluronan macromolecule entering the reaction with the HO• radical formed via the Fenton-like reaction: 
\[ \text{Cu}^2+ + \text{H}_2\text{O}_2 \rightarrow \text{Cu}^{2+} + \text{HO}^+ + \text{OH}^- \]

\( \text{H}_2\text{O}_2 \) has its origin due to the oxidative action of the Weissberger system (see Figure 6)

b. Formation of an alkyl radical (C-centered hyaluronan macroradical) initiated by the HO• radical attack.

c. Propagation phase: formation of a per oxy-type C-macroradical of hyaluronan in a process of oxygenation after entrapping a molecule of O_2.

d. Formation of a hyaluronan-derived hydroperoxide via the reaction with another hyaluronan macromolecule.

e. Formation of highly unstable alk ox y-type C-macroradical of hyaluronan on undergoing a redox reaction with a transition metal ion in a reduced state.

f. Termination phase: quick formation of alk ox y-type C-fragments and the fragments with a terminal C=O group due to the glycosidic bond scission of hyaluronan. Alkoxy-type C fragments may continue the propagation phase of the free-radical hyaluronan degradation reaction. Both fragments are represented by reduced molar masses (Kogan, 2011; Rychly et al., 2006; Hrabarova et al., 2012; Surovcikova et al., 2012; Valachova et al., 2013b; Banasova et al., 2012).

Several thiol compounds have attracted much attention from pharmacologists because of their reactivity toward endobiotics such as hydroxyl radical-derived species. Thiols play an important role as biological reducing (antioxidants) preserving the redox status of cells and protecting tissues against damage caused by the elevated reactive oxygen/nitrogen species (ROS/RNS) levels, by which oxidative stress might be indicated.

Soltes and his coworkers examined the effect of several thiol compounds on inhibition of the degradation kinetics of a high-molecular-weight HA in vitro. High molecular weight hyaluronan samples were exposed to free-radical chain degradation reactions induced by ascorbate in the presence of Cu(II) ions, the so called

![Figure 5. Schematic degradation of HA under free radical stress (Hrabarova et al., 2012).](image-url)
Weiissberger’s oxidative system. The concentrations of both reactants [ascorbate, Cu(II)] were comparable to those that may occur during an early stage of the acute phase of joint inflammation (see Figure 6) (Banasova et al., 2011; Valachova et al., 2011; Soltes et al., 2006a; Soltes et al., 2006b; Stankovska et al., 2004; Soltes et al., 2006c; Soltes et al., 2007; Valachova et al., 2008; 2009; 2010; 2011; 2013; Hrabarova et al., 2009, 2011; Rapta et al., 2009, 2010; Surovcikova-Machova et al., 2012; Banasova et al., 2011; Drafi et al., 2010; Fisher & Naughton, 2005).

Figure 7 illustrates the dynamic viscosity of hyaluronan solution in the presence and absence of bucillamine, d-penicillamine and l-cysteine as inhibitors for free radical degradation of HA. The study showed that bucillamine to be both a preventive and chain-breaking antioxidant. The first 60 min. Then, however, the inhibition activity is lost (Valachova et al., 2011; Valachova et al., 2011; Valachova et al., 2011; Valachova et al., 2011; Hrabarova et al., 2009, 2011; Soltes et al., 2006a; Stankovska et al., 2004; Soltes et al., 2006c; Soltes et al., 2007; Valachova et al., 2008; 2009; 2010; 2011; 2013; Hrabarova et al., 2009, 2011; Rapta et al., 2009, 2010; Surovcikova-Machova et al., 2012; Banasova et al., 2011; Drafi et al., 2010; Fisher & Naughton, 2005).

It was found that l-glutathione exhibited the most significant protective and chain-breaking antioxidative effect against hyaluronan degradation. Thiol antioxidative activity, in general, can be influenced by many factors such as various molecule geometry, type of functional groups, radical attack accessibility, redox potential, thiol concentration and pH, ionic strength of solution, as well as different ability to interact with transition metals (Hrabarova et al., 2012).

The effectiveness of antioxidant activity of 1,4-dithioerythritol expressed as the radical scavenging capacity was studied by a rotational viscometry method (Hrabarova et al., 2010). 1,4-dithioerythritol, widely accepted and used as an effective antioxidant in the field of enzyme and protein oxidation, is a new potential antioxidant standard exhibiting very good solubility in a variety of solvents. Figure 9 describes the effect of 1,4-dithioerythritol on Weissberger’s oxidative system containing 1.0 μM CuCl₂ + 100 μM ascorbic acid (Valachova et al., 2011).
degradation of HA solution under free radical stress (Hrabarova et al., 2010).

N-Acetyl-l-cysteine (NAC), another significant precursor of the GSH biosynthesis, has broadly been used as effective antioxidant in a form of nutritional supplement (Soloveva et al., 2007; Thibodeau et al., 2001). At low concentrations, it is a powerful protector of α1-antiproteinase against the enzyme inactivation by HOCl. NAC reacts with HO• radicals and slowly with H2O2; however, no reaction of this endobiotic with superoxide anion radical was detected (Aruoma et al., 1989).

Investigation of the antioxidative effect of N-Acetyl-l-cysteine. Unlike l-glutathione, N-acetyl-l-cysteine was found to have preferential tendency to reduce Cu(II) ions to Cu(I), forming N-acetyl-l-cysteinyl radical that may subsequently react with molecular O2 to give O2•− (Soloveva et al., 2007; Thibodeau et al., 2001). Contrary to l-cysteine, NAC (25 and 50 μM), when added at the beginning of the reaction, exhibited a clear antioxidative effect within ca. 60 and 80 min, respectively (Figure 10A). Subsequently, NAC exerted a modest pro-oxidative effect, more profound at 25-μM than at 100-μM concentration (Figure 10A).
Application of NAC 1 h after the onset of the reaction (Figure 10B) revealed its partial inhibitory effect against formation of the peroxyl-type radicals, independently from the concentration applied (Hrabarova et al., 2012).

An endogenous amine, cysteamine (CAM) is a cystine-depleting compound with antioxidative and anti-inflammatory properties; it is used for treatment of cystinosis – a metabolic disorder caused by deficiency of the lysosomal cystine carrier. CAM is widely distributed in organisms and considered to be a key regulator of essential metabolic pathways (Kessler et al., 2008).

Investigation of the antioxidative effect of cysteamine. Cysteamine (100 μM), when added before the onset of the reaction, exhibited an antioxidative effect very similar to that of GSH (Figure 8A and Figure 11A). Moreover, the same may be concluded when applied 1 h after the onset of the reaction (Figure 11B) at the two concentrations (50 and 100 μM), suggesting that CAM may be an excellent scavenger of peroxyl radicals generated during the peroxidative degradation of HA (Hrabarova et al., 2012).

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