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Collagen: An Overview

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Collagen is a versatile material with biological properties that make it useful for the fabrication of implantable devices in medicine and dentistry. In this article we review collagen biosynthesis, structure, and types, as well as the properties that make it compatible with human tissues. (Implant Dent 2002;11: 280–285)

Key Words: collagen synthesis, collagen types, collagen structure, fibrillar collagen, review, tropocollagen, basement membrane

Collagen is the most abundant protein (by weight) in animals, accounting for 30% of all proteins in mammals. Collagen assembles into different supramolecular structures and has exceptional functional diversity. Collagen is the major protein of connective tissue, tendons, ligaments, and the cornea, and it forms the matrix of bones and teeth.

Collagen is a protein with three polypeptide chains. Each chain has 1000 amino acids and contains at least one stretch of the repeating amino acid sequence Gly-X-Y (where X and Y can be any amino acid but are usually proline and hydroxyproline, respectively; see Fig. 1).[1]

Molecular Structure

The basic unit of collagen, tropocollagen, is a rigid rod-shaped molecule approximately 3000 Å in length and 15 Å in diameter.[2] Collagens have two different types of structural domains: triple helical and globular.[3] Most collagens consist of two α-1 chains and one α-2 chain. An individual α-chain is a left-handed helix with approximately 3.3 residues per turn. The α-chains are twisted together to form a right-handed superhelical structure. Hydrogen bonds form between residues of the different chains.[4]

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The characteristic structure of both chains is a repeating unit of three amino acids; one third of all the amino acids in each collagen chain is glycine (Gly). Proline (Pro) and hydroxyproline (Hyp) follow each other frequently, and about 10% of the molecule has the sequence Gly-Pro-Hyp.

Procollagen is the precursor of tropocollagen. The procollagen molecule has three pro-α chains arranged in a triple-stranded conformation and differs from tropocollagen in that it contains six extraglobular tails. The N-terminal propeptide contains intrachain (but not interchain) disulfide links, whereas the polypeptides from the C-terminal region are linked to each other by disulfide bridges. The nonhelical regions of procollagen are partially cleaved by procollagen peptidases.[5]

Collagen Types

There are 20 collagens identified to date, type I being the most abundant structural protein found in vertebrates (Table 1). The different collagen types are designated with Roman numerals I to XIX. These numerals were assigned following the order in which they were discovered.

Most authors have classified collagens based on their supramolecular structures in two main classes: the fibrillar collagens and the nonfibrillar collagens.[6,7] In addition, type XIII and type VI collagens are described below, but they have not yet been classified.

Fibrillar Collagens

This group contains the type I, II, III, V, and XI collagens. Those collagens form highly organized fibers and fibrils and provide the structural support for the body in the skeleton, skin, blood vessels, nerves, intestines, and the fibrous capsules of organs.[6] Fibrils are frequently organized into bundles or lamellae, and the size and higher-order arrangement of fibrils gives rise to tissue-specific, biomechanical, and other biological properties.[8]

Type I collagen is composed of three chains, two identical α-1(I) chains and one different chain, referred to as α-2(I). Type I collagen is abundant in bone, tendon, skin, ligaments, arteries, uterus, and cornea, and comprises between 80% and 99% of the total collagen.[3] Type I collagen is very important as demonstrated by studies of mutations, where the effect of deletions, insertions, and single amino acid substitutions have resulted in osteogenesis imperfecta, Ehlers-Danlos syndromes, and many degenerative diseases. Type I collagen is among the most important stress-carrying protein structures in mammals. For the fibril to carry out this function, kinks occur in the gap region of the fibrils during packaging because of the low levels of proline and hydroxyproline, resulting in a reduced

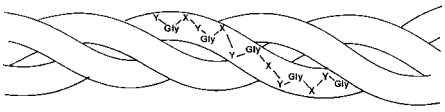

Fig. 1. Collagen triple helix with its repeating unit of three amino acids. Each chain has 1000 amino acids and contains at least one region of the repeating amino acid sequence Gly-X-Y. Gly is the amino acid glycine; X and Y can be any amino acid, but are usually proline and hydroxyproline, respectively.

packing density compared with the overlap region.[9]

Type II collagen is the major collagen type present in cartilaginous tissues, although it is also present in significant amounts in other connective tissues such as the nucleolus pulposus of the intervertebral disk and the vitreous humor.[10] Type II collagen contains three identical α chains that have chromatographic and electrophoretic characteristics similar to the α-1 chains of type I collagen. These chains are designated α-1(II). Cartilage collagen has a relatively high hydroxylysine and glycosylated hydroxylysine content, and it is synthesized during the chondrogenic stages of mesoderm development.[3]

Type III collagen is composed of three identical α-1(III) chains. This collagen has a high content of hydroxyproline and is low in hydroxylysine. It is a normal constituent of skin (10–20% of the total collagen) and is found in many other connective tissues. It is associated with type I collagen in lung, heart valves, heart muscle, uterus, nerves, liver, placenta, umbilical cord, blood vessels, spleen, gingiva, kidney, lymph nodes, sclera, and other eye structures, as well as normal bone. Type III collagen is correlated with tissue extensibility and may contribute to elasticity, a unique biological property associated with this collagen isoform.[10]

Type V collagen is more soluble than other collagens. This collagen is abundant in vascular tissues and typically is found in the interior, but not the exterior, of the fibril. Its amino acid composition is similar to that of interstitial collagens except for a high ratio of hydroxylysine to lysine and a low content of alanine. The hydroxylysine is only partially glycosylated with glusosygalactose or galactosyl groups.[3] The chain composition of type V collagen is variable: the most common structure is two α-1(V) chains and one α-2(V) chain, but homotrimers of α-1(V) have also been detected as well as the heterotrimers α-1(V), α-2(V), and α-3(V).[12] In addition, the structure of the globular domains of type V collagen is significantly larger than in the other collagen types.[10]

Type XI collagen is found in cartilaginous tissues. The predominant form of type XI collagen is α-1(XI) α-2(XI) α-3(XI). The function of type XI collagen has not been elucidated; however, it is suspected that it regulates the diameter or growth of type II collagen fibrils.[13]

It is known that most collagen fibrils are composed of two or more different collagen types. This has been demonstrated for types I and III, types I and V, and types II and XI.[1] Electron microscopic studies of collagen fibrils show a quarter-stagger arrangement of the individual collagen molecules, ie, each tropocollagen molecule overlaps four other tropocollagen molecules.[6] Recent x-ray diffraction studies show collagen as a crystal structure based on a quasi-hexagonal packing; however, the structure of the collagen fibril is not completely elucidated.[14,15]

Nonfibrillar Collagens

Nonfibrillar collagens are classified according to their molecular characteristics, supramolecular structures, and types of extracellular networks in basement membrane collagens, short-chain collagens, and fibril-associated collagens.[7]

A. Basement membrane collagens. The major components of basement membranes are type IV collagen, laminins, and heparan sulfate proteoglycans. Type VII collagen is also included in this category because of its association with basement membranes.

Type IV collagen consists mostly of two α-1 chains and one α-2 chain. The α-chains are not proteolytically processed and have high hydroxylysine and glycosylated hydroxylysine content. There are three domains: a central triple-helix that is approximately 25% longer than the fibrillar collagens and that it is interrupted at several positions by short nontriple he-

Table 1. Collagen Types*

	α Chains	Tissue Distribution
I	α1(I), α2(I)	Most connective tissues, eg, bone, tendon, skin, lung, cornea, sclera, vascular system
II	α1(II)	Cartilage, vitreous humour, embryonic cornea
III	α1(III)	Extensible connective tissues, eg, skin, lung, vascular system
IV	α1(IV), α2(IV), α3(IV), α4(IV), α5(IV)	Basement membranes
V	α1(V), α2(V), α3(V)	Tissues containing collagen I, quantitatively minor component
VI	α1(VI), α2(VI), α3(VI)	Most connective tissues, including cartilage
VII	α1(VII)	Basement-membrane-associated anchoring fibrils
VIII	α1(VIII), α2(VIII)	Product of endothelial and various tumor cell lines
IX	α1(IX), α2(IX), α3(IX)	Tissues containing collagen II, quantitatively minor component
X	α1(X)	Hypertrophic zone of cartilage
XI	α1(XI), α2(XI), α3(XI)	Tissues containing collagen II, quantitatively minor component
XII	α1(XII)	Tissues containing collagen I, quantitatively minor component
XIII	α1(XIII)	Quantitatively minor collagen, eg, found in skin and intestine
XIV	α1(XIV)	Tissues containing collagen I, quantitatively minor component

* Modified from Hulmes, et al.[8]

lical sequences. These interruptions are sites of increased molecular flexibility.[16] The C-terminal globular domain is a large domain and consists of two homologous internal domains. These domains on two adjacent molecules become covalently linked by disulfide exchange to form a dimer. The N-terminal domain represents an additional triple-helical region, separated from the main triple helix by a kink. These domains of two adjacent molecules also associate, in interactions that are stabilized by disulfide and covalent cross-links, forming a tetramer. When these interactions are present, type IV collagen forms a flexible three-dimensional network.[6,7]

Type VII collagen is found beneath stratified squamous epithelia, in close proximity to the basement membrane. It links the basement membrane to anchoring plaques in the underlying extracellular matrix. Type VII collagen has a long triple-helical region with a small globular region at one end that is removed during assembly and a tridentate structure at the other end. This type of collagen also presents nonhelical interruptions. Type VII collagen functions to strengthen the dermal epidermal junction.[1]

B. Short chain collagens. This group involves type VIII and X collagens, which have similar structure and assembly but different distribution and function.

Type VIII collagen has been found in the Descemet's membrane of the eye, vascular endothelial cells, and some tumor-derived cells. The type VIII collagen molecule has a triple helical region of 135 nm in length, with a globular region at the C-terminus and a smaller globular region at the N-terminus. The entire triple-helical domain is encoded by one single exon. The triple helices have interruptions in the same positions in α-1(VIII) and α-2(VIII) chains. The function of type VIII collagen is as yet unknown.[6,7]

Type X collagen is a homotrimeric disulfide-bonded collagen and is the product of hypertrophic chondrocytes. It is the most specialized of the collagens, having a function related to cartilage mineralization. Its molecular structure is similar to that of type VIII collagen, especially in the triple-helical and C-terminal globular regions. Its triple helical domain has eight interruptions in the gly-X-Y repeat structure. The entire triple helical domain is encoded by one single exon. The function of type X collagen has been suggested to play a role in the formation of a framework during replacement of cartilage by bone and guiding endothelial cells during angiogenesis.[7]

C. Fibril-associated collagens. This subgroup, fibril-associated collagens with interrupted triple-helices (FACIT), comprises type IX, XII, and XIV collagens. These collagens attach to the surface of pre-existing fibrils.

Type IX collagen is expressed in cartilages (1–10% of total collagens). It is a heterotrimer, contains three short triple helical domains with interchain disulfide bonds, and has a large globular region at the N-terminus of cartilage α-1(I). The function of type IX collagen remains unknown although it may have a role in mediating the interaction between type II collagen and proteoglycans in cartilage. Type IX molecules have been localized on the surface of cartilage type II collagen fibrils in a periodic distribution.[17] The interaction between type IX and type II collagens is stabilized by covalent intermolecular cross-links.[13,18]

Type XII collagen is found in dense collagen I-containing connective tissues such as tendons and ligaments.[19,20] The molecule is a homotrimer of three α-1(XII) chains, where each chain has two triple-helical domains. Because of the similarity with type IX collagen, an analogous function has been suggested: lateral association with type I collagen on the surfaces of fibrils.[6] Type XIV collagen is found in skin and tendon. Further studies are necessary to determine whether structural homology exists with type XII collagen.

Type XIII Collagen

Type XIII collagen has been characterized at the cDNA and genomic levels[21] and has a complex pattern of alternative splicing. This type of collagen has both triple-helical and noncollagenous domains. The function of type XIII collagen is unknown.

Type VI Collagen

This collagen is distributed throughout the connective tissues but does not form banded collagen fibrils.[11,22] This collagen is a heterotrimer of α-1, α-2, and α-3 chains with a short triple-helix. The three chains are mostly noncollagenous. Type VI collagen is extensively glycosylated. One of the features of this type of collagen is the large number of arg-gly-asp sequences throughout the triple helix.[23] Type VI collagen is assembled by forming antiparallel dimers, and then the dimers associate by lateral aggregation to form tetramers.[1] Tetramers are stabilized by an intermolecular disulfide bond network that appears to form intracellularly.

Collagen Synthesis

Intracellular Events

The first step in the process of collagen synthesis is the formation of collagen specific messenger-RNA.[6] After gene transcription, the gene is spliced yielding a functional mRNA that contains about 3000 bases. Specific mRNA are transported to the cytoplasm and translated on membrane-bound polysomes to the rough endoplasmic reticulum (rER).[3] As the collagen polypeptides are synthesized in the rER, important cotranslational events accompany this process. Prolyl and lysyl hydroxylases mediate the hydroxylation of proline and lysine. Glycosylations occur that are catalyzed by galactosyltransferase and glusosyltransferase.[7] Accompanying these enzymatic events, association of pro-α chains in the correct chain registration and triple-helix assembly occurs. During alignment, cysteine residues are juxtaposed for the formation of disulfide bridges that will link the individual pro-α chains at the C-terminal end.

The procollagen molecules travel from the rER toward the Golgi apparatus through the microsomal lumen. In the Golgi, procollagen molecules are packed into secretory vesicles and translocated to the surface of the cell, where they are secreted into the extracellular environment by exocytosis.[7]

Extracellular Events

Once in the extracellular matrix, the newly synthesized procollagen

molecules interact with processing enzymes and undergo fibril formation and cross-linking.[23,24] The enzymes are procollagen N-proteinases (removal of N-propeptides), procollagen C-proteinase (removal of C-propeptides), and lysyl oxidase (initiation of cross-linking). Lysyl oxidase, an extracellular amine oxidase, initiates cross-linking of collagens by oxidative deamination of certain lysine and hydroxylysine residues located in the short N- and C-terminal nonhelical regions (telopeptides) that remain after the removal of the procollagen propeptides.[25] Bifunctional cross-links undergo further intra and intermolecular reactions to form a variety of mature, trifunctional cross-links. Cross-link diversity accounts for some of the major differences between skeletal and nonskeletal connective tissues.[23]

Biological Properties of Collagen

Collagen has a number of biochemical and biophysical properties, which makes it an important biomaterial. These properties include: solubility, strength, mediation of intracellular interactions, controllable stability, biodegradability, and low immunogenicity.

Collagen is biosynthesized in a manner that allows a soluble collagen to be secreted by the cells and subsequently be modified to produce various structural patterns.[26] A greater part of native collagen is insoluble, but most of the insoluble collagen is solubilized with proteolytic enzymes without destroying the basic, rigid triple-helical structure.

A physical-mechanical property of collagen is the high tensile strength and minimal extensibility that depend on the amount of insoluble collagen present (number of cross-links) and the interaction with glycoproteins and proteoglycans. Therefore, collagen has the capability of transmitting tensile and compressive forces of great magnitude.[27]

Collagen is a natural substrate for the support and growth of a variety of cells and tissues in the body. It works as a framework in conjunction with other extracellular molecules such as glycosaminoglycans and fibronectin. In addition, it is thought that collagen may promote wound healing because of other chemotactic properties, acting as nucleation centers that form fibrillar structures.[28]

The chemical properties of collagen depend on the presence of covalent cross-links, which give collagen a controllable stability. There are two types of cross-links: the intramolecular cross-links and the intermolecular cross-links.[29] Cross-links can be introduced into soluble collagen *in vitro* by physical or chemical reagents, giving it structure and stability.

Collagen is biodegradable, being degraded *in vitro* by collagenases that produce cleavage under physiological conditions of pH and temperature.[30] This process is a biological mechanism that, concomitantly with its biosynthesis, controls growth, morphogenesis, and repair of collagen.[29] When collagen is transplanted into tissues, it degrades leaving no permanent foreign residue. This property can be reduced or even suppressed by cross-linking.[31]

Collagen has low immunogenicity, particularly when in a purified, undenatured form.[32] The primary antigenic loci of collagen are located at both the C- and N-terminal regions of the molecule in the nonhelical structures called telopeptides. The weak antigenicity of collagen has been related to its ability to resist digestion by the usual proteolytic enzymes[33] and to the ability of its helical structure to mask potential antigenic determinants.[34]

Conclusion

Solubility, high tensile strength, controllable stability, biodegradability, and low immunogenicity are some of the advantages that make collagen suitable for use as a biomaterial in many medical and dental applications.

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Abstract Translations [German, Spanish, Portuguese, Japanese]

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ZUSSAMENFASSUNG: Kollagen findet aufgrund seiner biologischen Eigenschaften in der Medizintechnik vielseitigen Einsatz. Unter anderem eignet sich der Stoff ideal zur Herstellung von Implantaten in der Allgemein- und Zahnmedizin. Der vorliegende Artikel liefert einen thematischen Überblick über die Kollagen-Biosynthese, die Struktur des Materials, die verschiedenen Kollagen-Sorten und die das Kollagen mit menschlichem Gewebe kompatibel machenden Stoffeigenschaften.

SCHLÜSSELWÖRTER: Kollagen-Synthese, Kollagen-Sorten, Kollagen-Struktur, feinfaseriges Kollagen, Übersicht, Tropakollagen, Basismembran

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ABSTRACTO: El colágeno es un material versátil con propiedades biológicas que lo vuelven útil para la fabricación de dispositivos implantables en medicina y odontología. En este artículo se explica la biosíntesis, estructura y tipos de colágeno, así como las propiedades que lo vuelven compatible con los tejidos humanos.

PALABRAS CLAVES: Síntesis del colágeno, tipos de colágeno, estructura del colágeno, colágeno fibrilar, evaluación, tropocolágeno, membrana de base.

SINOPSE: o colágeno é um material versátil com propriedades biológicas que o tornam útil na fabricação de dispositivos de implantação em medicina e odontologia. Neste artigo, revisamos a biosíntese, a estrutura e os tipos de colágeno, bem como as propriedades que fazem com que seja compatível com tecidos humanos.

PALAVRAS-CHAVES: síntese de colágeno, tipos de colágeno, estrutura do colágeno, colágeno fibrilar, revisão, tropocolágeno e membrana basal.

コラーゲン：その概観

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概要：コラーゲンは用途の広い生体物質で、医科・歯科の両部門でインプラント可能なディバイスの形成に有用である。この論文は、コラーゲンの生体内合成、構造、種類、その人体組織との適応性を高める特性について論じる。

キーワード：コラーゲン合成、コラーゲンの種類、コラーゲンの構造、線維性コラーゲン、再調査、トロポコラーゲン、基底膜

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