BIOCHEMISTRY

Versatile Collagens in Invertebrates

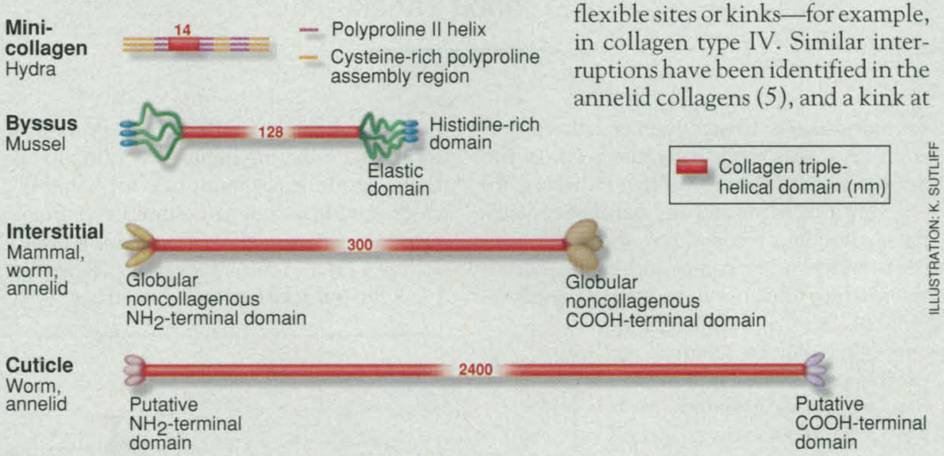
Jürgen Engel

Collagens, the most abundant proteins in our body, are the essential stuctural element of connective tissues such as skin, bone, and tendons. Many mammalian collagens (*1*)—the fibril-forming interstitial collagens (type I, II, III, and V) and basement membrane collagen (type IV), for example—can be traced back to early organisms like mussels, worms, and sponges (*2, 3*). In addition, invertebrates also contain other, unrelated collagens that serve specialized functions and have unusual domain organizations (see the figure). These include mini-collagens from hydra (*4*) and the longest known collagens, from annelids (*5*). A particularly fascinating example is the collagen from mussel byssus threads, described in this issue on page 1830 (*6*).

All collagens contain a triple-helical domain with the characteristic sequence repeat $(\text{Gly-X-Y})_n$, in which X and Y can be any amino acid but X is often proline and Y is often hydroxyproline. Three equal or different chains are connected through this domain, and all other domains in the molecule occur as oligomers of three. The collagen triple helix serves as a rodlike element with little flexibility and elasticity but with a high mechanical strength. Triple helices frequently show lateral self-association, and this is particularly prominent for interstitial collagens, which form fibrils by quarter-staggered association (*1*). When calculated on the basis of a translation repeat of 0.29 nm per residue, the total length of the triple helices is in good agreement with electron microscopic observation.

The collagen from the 2- to 4-cm-long byssus threads, by which mussels attach to supports, has a tendonlike function. Its triple helix is relatively long (128 nm), probably to support lateral association in a fibrillar structure, but not as long as the mammalian tendon collagen type I (300 nm). Triple-helical domains in mini-collagens of hydra are much shorter (on the order of 14 nm) (*4*). These collagens form highly cross-linked networks in the walls of nematocysts, as long helices are not required. On the other hand, the plywood arrangement of very long fibers in the cuticles of annelids seems to require the longest triple helices (2400 nm) (*5*).

The high diversity within the family of collagens and their great functional versatility originate from the combinatorial assembly of other domains with the collagen triple helix. For example, two specialized domains in byssus collagen (*6*) provide elasticity. The sequence of this region exhibits similarities with sequence regions in the protein elastin, without, however, showing homology. Other domains that up to now were detected only in the byssus collagen (*6*) are histidine rich. The authors speculate that these terminal domains may support Zn^{2+}-mediated cross-linking in the elastic parts of the byssus threads.



Collagens specialized for duty. Diverse functional domains are added to a central triple-helical core to create collagens that serve different purposes.

ILLUSTRATION: K. SUTLIFF

Mammalian interstitial collagens have terminal globular noncollagenous extensions (amino and carboxyl propeptides) (*1*), which are removed by specific amino and carboxyl propeptidases during fibril formation. The interstitial collagens of invertebrates such as annelids (*5*) also contain globular extensions, but the sequence and functional data are still incomplete. This also holds true for the cuticle collagens (*5*).

Very unusual domains flank the collagen triple helix in mini-collagens from hydra (*4*) and reef-building corals (*7*). Uninterrupted stretches of 14 to 23 proline residues are forced into a polyproline II helical conformation by sterical restrictions of proline residues. These regions are adjacent to cysteine- and proline-rich stretches, which most likely have the same conformation. The position of cysteines is well suited for inter- and intramolecular cross-linking in the disulfide bond–stabilized inner wall of nematocyst capsula. The tensile strength of these walls has been estimated to be near that of steel (*8*). As mentioned, proline (and hydroxyproline) have a high potential to stabilize the polyproline II helix, but glycine residues also favor this type of helix. Glycines, because they lack side chains, can closely approach a neighboring chain, thereby stabilizing bundles of polyproline II helices by hydrogen bonds (in which the amino group of glycine is the donor). Collagen triple helices are a special type of such a bundle in which Gly repeats in every third position in each of the chains. These proline- and hydroxyproline-rich helices are stabilized by trimer formation with all the glycines in the interior of the triple helix (*1*). Interruptions in the regular Gly-X-Y repeat are very frequent in some mammalian collagens (*1*) and may lead to flexible sites or kinks—for example, in collagen type IV. Similar interruptions have been identified in the annelid collagens (*5*), and a kink at a site of "a missing glycine" was proposed for the byssus collagen (*6*). There are ways to stabilize polyproline II helices in the presence of higher proportions of glycine. This was demonstrated by early structural studies with peptides of the type $(\text{Gly-Gly-Pro})_n$ (*9*) and for polyglycine. It is therefore possible that a polyproline II helix type of conformation may exist in the elastic regions of byssus collagen. They contain about 10% proline and are very rich in glycine, and in more than 80% of their sequence Gly repeats in every third position.

Most of the information on invertebrate collagens has been obtained from cDNA sequencing. Therefore, only limited knowledge exists about glycosylation and other posttranslational modifications and processing of the molecules by enzymatic cleavage. For the

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byssus collagen (6), short pepsin-solubilized peptides were sequenced by Edman degradation, and thus the presence of hydroxyproline in Y positions was demonstrated. Similar information exists for the annelid collagens but not for the mini-collagens. The byssus collagen contains many potential sites for O-glycosylation (for example, at Ser and Thr), but no information on their use exists. For an annelid cuticle collagen, a glycosylation of threonines in the Y position was demonstrated (10), and these residues may substitute for the normally occurring hydroxyprolines. By analogy with the mammalian collagens it may be assumed that some noncollagenous domains of invertebrate collagens may be removed by enzymatic processing, but this information has to be provided by future work.

References

1. J. F. Bateman *et al.*, in *Extracellular Matrix*, W. D. Comper, Ed. (Harwood, Amsterdam, 1996), vol. 2, pp. 22–67.
2. J. M. Kramer, *FASEB J.* **8**, 329 (1994).
3. R. Garrone *et al.*, *CR Seances Soc. Biol. Fr.* **187**, 114 (1993).
4. E. M. Kurz *et al.*, *J. Cell Biol.* **115**, 1159 (1991).
5. F. Gaill *et al.*, *J. Mol. Biol.* **221**, 209 (1991); F. Gaill *et al.*, *ibid.* **246**, 284 (1995).
6. K. J. Coyne *et al.*, *Science* **277**, 1830 (1997).
7. W. Wang *et al.*, *Gene* **152**, 195 (1995).
8. T. W. Holstein *et al.*, *Science* **265**, 402 (1994).
9. W. Traub and Y. Yonath, *J. Mol. Biol.* **16**, 404 (1966).
10. K. Mann *et al.*, *ibid.* **261**, 255 (1996).

OPTICAL MATERIALS

Light-Induced Anisotropy in Amorphous Chalcogenides

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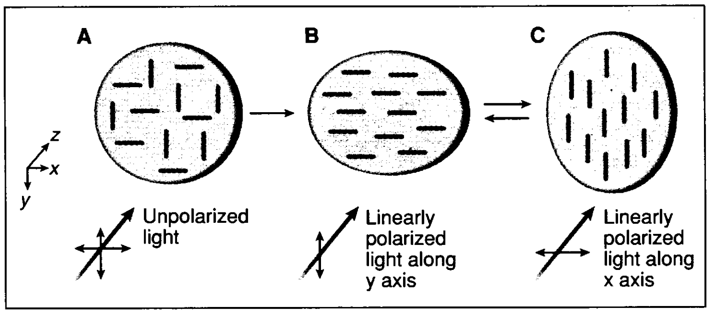
Are all glasses isotropic? In general, the answer is yes because isotropic structure is one of the definitions of a glassy material. However, for one very interesting and unusual class of materials—the chalcogenides, a group of sulfur, selenium, and tellurium compounds—the molecular structure turns out to be strongly anisotropic. This is because chalcogen atoms like sulfur or selenium are twofold coordinated in a random network of covalent bonds. Exposure of these materials to linearly or circularly polarized light produces a net anisotropy of the dielectric tensor, which results in optical anisotropy called dichroism and birefringence (see figure). In this way, polarization-dependent optical absorption and refraction can be induced in originally isotropic chalcogenide glasses (1). But now on page 1800 of this issue, Krecmer *et al.* (2) report an anisotropic mechanical effect induced by polarized light: Contraction occurs along the direction of the electric field vector of the inducing light, whereas dilatation occurs perpendicular to that direction. The result provides not only insight into the underlying physics of anisotropic effects but also a technological potential for amorphous chalcogenides.



Scalar and vector effects in chalcogenide glasses. In a simplified two-dimensional model, (**A**) all transition dipoles are randomly distributed after the exposure to unpolarized light (*z*-axis incidence), although isotropic photodarkening and photoexpansion occur (scalar effects). (**B**) Subsequent exposure to linearly polarized light along the *y* axis causes selective conversion of the transition dipoles directed along the *y* axis into the *x* axis, producing optical and mechanical anisotropy (vector effects): directional change in optical absorption (dichroism) and refractive index (birefringence). At the same time, directional compressive stress induces nanocontraction and nanodilatation along the *y* and *x* axes, respectively. (**C**) A change of the polarization direction of the inducing light from the *y* to the *x* direction rotates every anisotropy by a right angle.

The optical axis of the induced anisotropy switches from one to the other in response to a change of the polarization direction of the inducing light. According to the results of the experiment of Krecmer *et al.*, which was carried out with a multilayer atomic force microscope (AFM) microcantilever including a layer of thin amorphous AsSe film, the light-induced optical anisotropy is always accompanied by a mechanical anisotropy in terms of directional compressive stress. Actually, the microcantilever bends upward or downward depending on the polarization direction of the inducing light; there is a direct correlation between optical and mechanical anisotropy. Technologically, this experiment presents the possibility of a new kind of positioning device for nanotechnology, which can be controlled solely by polarized light.

Noncrystalline chalcogenide semiconductors—including melt-quenched glasses and amorphous thin-film structures of Se, As_2S_3, or AsSe—exhibit a variety of optical and structural changes when exposed to light or other radiation that excites electron-hole pairs (3). Before the initial report on optical anisotropy by Zhdanov *et al.* (1), other well-known light-induced phenomena, such as photostructural changes accompanying photodarkening, have been observed by many groups, although anisotropy was not seen. Optical anisotropic changes are, therefore, often called vector effects in order to distinguish them from photostructural changes and photodarkening, which are called scalar effects. Vector and scalar effects often take place in the same material under the same excitation but are completely different in nature (4). All of these light-induced effects are metastable and can be reversed by thermal annealing below the glass transition temperature, at which materials become supercooled liquid; the effects are unique to the amorphous phase and do not occur in its crystalline counterpart.

Why are chalcogenide glasses so sensitive to band-gap light? And what is the microscopic origin of light-induced anisotropy? The most characteristic feature common to chalcogenide glasses is the electronic structure originated in *p*-like lone pair (LP) electrons of chalcogen atoms. Selenium has four outer *p* electrons, two of which form two covalent bonds with *p* electrons from the neighboring two atoms and the remaining two of which are localized on the chalcogen atom as LP electrons. The LP electrons are energetically higher than bonding-state electrons and therefore occupy the top of the valence band. The presence of those high-energy LP electrons and the resultant low coordination number of the chalcogen atoms yields optical and

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