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Invertebrate Data Predict an Early Emergence of Vertebrate Fibrillar Collagen Clades and an Anti-incest Model* §

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Fibrillar collagens are involved in the formation of striated fibrils and are present from the first multicellular animals, sponges, to humans. Recently, a new evolutionary model for fibrillar collagens has been suggested (Boot-Handford, R. P., Tuckwell, D. S., Plumb, D. A., Farrington Rock, C., and Poulsom, R. (2003) J. Biol. Chem. 278, 31067–31077). In this model, a rare genomic event leads to the formation of the founder vertebrate fibrillar collagen gene prior to the early vertebrate genome duplications and the radiation of the vertebrate fibrillar collagen clades (A, B, and C). Here, we present the modular structure of the fibrillar collagen chains present in different invertebrates from the protostome Anopheles gambiae to the chordate Ciona intestinalis. From their modular structure and the use of a triple helix instead of C-propeptide sequences in phylogenetic analyses, we were able to show that the divergence of A and B clades arose early during evolution because α-chains related to these clades are present in protostomes. Moreover, the event leading to the divergence of B and C clades from a founder gene arose before the appearance of vertebrates; altogether these data contradict the Boot-Handford model. Moreover, they indicate that all the key steps required for the formation of fibrils of variable structure and functionality arose step by step during invertebrate evolution.

Fibrillar collagens are present from sponges to humans and are the primary component of striated fibrils (1, 2). A fibrillar procollagen molecule is made of three identical or different pro-α-chains. Each pro-α-chain contains a central triple helix made of ~338 Gly-Xaa-Yaa triplets flanked by non-collagenous telopeptide regions, which in turn are flanked by the N- and C-propeptides. The C-propeptide is known to contain the most telopeptide regions, which in turn are flanked by the N- and C-propeptides. The C-propeptide is involved in α-chain recognition and in the registration of the major triple helical domain, an important step preceding elongation of the triple helix from the carboxyl to the amino terminus. In vertebrates, a short region of the C-propeptide appears to be involved in chain recognition (3). Recently, Boot-Handford and Tuckwell (4) indicated that most of this recognition sequence is absent in all invertebrate fibrillar chains characterized to date. During the extracellular maturation of procollagen molecules, the propeptides are generally removed by specific proteinases. The resultant collagen molecules participate in fibril formation.

In humans, fibrillar collagens are subdivided quantitatively into major (types I-III) and minor (types V/XI) collagens. According to the collagen types incorporated into the fibrils and their ratio, the partial processing of the N-propeptide, and interactions with other extracellular matrix components, the shape and functional properties of the fibrils can vary. The importance of quantitatively minor collagens in the regulation of fibril diameter has been pointed out in several studies (5–7). From the model of Linsenmayer et al. (6), the retention of the type V N-propeptide at the surface of types IV heterotypic fibrils is one of the key elements regulating the diameter of these fibrils.

From phylogenetic studies and the exon/intron organization, it has been shown that vertebrate fibrillar collagens can be divided into two clades (8–10): the A clade, including types I-III and the pro-α2(V) chain, and the B clade, including the pro-α1(V), pro-α3(V), and type XI chains. Moreover, the α-chains of the A and B clades possess a vWc1 and a TSPN module in their N-propeptide, respectively, in addition to a minor triple helix. It should be noted that the A clade pro-α2(I) chain presents a short N-propeptide reduced to the minor triple helix.

Recently, COL24A1 and COL27A1 have been characterized (11–13). These two genes encode collagen chains belonging to a new fibrillar collagen group, the C clade. They contain a C-propeptide, a major triple helix, and an N-propeptide including a TSPN module but not a minor triple helix. Moreover, the major triple helix is shorter than that of classical fibrillar collagens and presents several imperfections in the Gly-Xaa-Yaa triplet repeat. It has been suggested that vertebrate fibrillar collagens share a single common ancestor that arose at the very dawn of the vertebrate world and prior to the genome duplication events (4, 12). From invertebrate data, these authors have argued that this ancestor possesses a vWc module in its N-propeptide, a major triple helix, and a C-propeptide lacking most of the elongated chain selection sequence. The founder vertebrate fibrillar would have acquired this sequence and the characteristics of A clade members. Duplication of this gene

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The abbreviations used are: vWc, von Willebrand factor-type C; TSPN, thrombospondin amino-terminal-like domain; contig, group of overlapping clones; EST, expressed sequence tag.
and the swapping of the exon encoding the vWc module for that encoding a TSPN domain would permit the formation of the B clade. The most recent clade, the C, would then have arisen from the B clade after the deletion of the elongated chain selection sequence. This model is clearly distinct from our previous studies indicating that some invertebrate collagens are more closely related to B clade than A clade collagens (14–16). Moreover, it is difficult to understand how a sequence can be gained from invertebrate to vertebrates and then be lost during the divergence of the C clade from the B clade. One explanation for this conundrum is that almost all the invertebrate fibrillar chains described to date are quantitatively major ones and that, like their vertebrate counterparts, they possess a vWC module in their N-propeptide. However, we have recently shown that sea urchin also possesses a quantitatively minor fibrillar collagen chain (17).

In this study, we present evidence arguing against the Boot-Handford et al. model (4, 12) and indicating that the A and B/C clades arose early during evolution. These data suggest that the diversity of the vertebrate fibrillar collagens and subsequently fibril diversity are due not to a rare genomic event but instead to a step-by-step evolutionary process from the most primitive animal to humans, which corresponds to the maximum parsimony hypothesis.

**EXPERIMENTAL PROCEDURES**

**Genomic Cloning and Reverse Transcription-PCR of Paracentrotus lividus Sequences Encoding Fibrillar Collagens**—A search of sea urchin genes encoding fibrillar collagen α chains was conducted at the Human Genome Sequencing Center Web site (Baylor College of Medicine, Houston, TX) using the C-propeptide sequence from the Strongylocentrotus purpuratus 1α chain (18). The URL of this center is www.hgsc.bcm.tmc.edu. From this analysis, we were able to discover two regions of the S. purpuratus genome encoding the C-terminal part of the classical C-propeptide distinct from the three previously characterized sea urchin fibrillar collagen chains (17–19). The two sequence files corresponded to Contig18666 and Contig42144 and encoded part of the fibrillar collagen terms 6α and 7α, respectively, in this study. To characterize the ortholog genes in the sea urchin P. lividus, we first amplified by PCR (30 cycles) the most 3′-exon of these two genes using 500 ng of genomic DNA and the Taq Expand polymerase kit (Roche Applied Science). The oligonucleotides used for this amplification (6α sense primer GCATCGTCCAACTGACGTTC, 6α antisense primer GAGTCGTTCATATTCTTCTAGCACG) permitted a 1034-bp exon/intron organization of human fibrillar collagen genes was obtained in the figures are given in Table I.

**RESULTS**

**Diversity of Fibrillar Collagens in Sea Urchin**

Three sea urchin fibrillar collagen chains (1α, 2α, and 5α) have previously been characterized (17–19). They can be divided quantitatively into major (1α and 2α) and minor (5α) collagen chains (17). Blast searching of the S. purpuratus genome resources using a sequence encoding the 1α C-propeptide allowed us to identify two genomic sequences encoding the C-terminal part of the C-propeptides unrelated to those of the three known sea urchin fibrillar collagens. Using these sequences, we have been able to determine the last Gly-Xaa-Yaa triplets and the complete C-propeptide sequences of two fibrillar-like α chains (6α and 7α) in the sea urchin P. lividus (see “Experimental Procedures”). The unique feature of these two C-propeptides is their unusual length (344 and 308 residues for 6α and 7α, respectively), with the additional sequence located between the end of the triple helix and the most amino-terminal cysteine residue (number 1) of the C-propeptide (data not shown).

**B Cede Fibrillar Collagen Is Present in Protostomes**

To investigate vertebrate fibrillar collagen chains, we used C-propeptide sequences from human pro-α1(I), pro-α1(V), and
pro-α(XXVII) chains to analyze the genome of three invertebrates. Two of them are the protostomes A. gambiae and A. mellifera, whereas the third is an invertebrate chordate, the ascidian C. intestinalis. For the two protostomes and the ascidian, two and four fibrillar chains were deduced respectively from genomic data. The schematic structures of the A. gambiae and C. intestinalis chains in addition to other invertebrate chains and members of the three vertebrate clades are presented in Fig. 1.

In the protostome A. gambiae, the two genes encoding the fibrillar α chains have been named AgFa1 and AgFa2 (Table I). As shown in Fig. 1, the modular structures of the AgFa1 and AgFa2 chains are similar to those of vertebrate A and B clades, respectively. Hence, AgFa1 encodes an N-propeptide including a vWc module, whereas AgFa2 encodes an N-propeptide including a TSPN module and a minor triple helix. Moreover, the most C-terminal cysteine residue (cysteine 8) of the AgFa2 C-propeptide is followed by three amino acids as in the fibrillar α chains of the B clade. In mosquito, two fibrillar collagen genes are present in the honeybee A. mellifera (Api-1 and Api-2). One of them (Api-2) encodes an α chain including a TSPN module and a minor triple helix in its N-propeptide (not shown). These results indicated that the formation of the B clade arose early during evolution.

The four C. intestinalis genes encoding fibrillar α chains have been named Ci759, Ci301, Ci606, and Ci916 (Table I). As shown in Fig. 1 and as in protostomes, C. intestinalis possesses two fibrillar α chains similar in their modular structure to vertebrate A and B clades, encoded by Ci759 and Ci301, respectively. These similarities were also observed for the exon/intron organization of the genomic region encoding the major triple helix (Fig. 2A). Hence, the Ci759 exon/intron organization is more closely related to the A clade than the B–C clades, whereas that of Ci301 has closer similarity to the B clade. One special feature of Ci759 is the presence of two exons of 100 and 62 bp in length corresponding to a 162-bp exon in the A clade. Insertion of an intronic sequence between the two first bases of a glycine codon in a 162-bp exon might explain this special feature (Fig. 2A). EST (citb100l05) covering these exons confirms the splice junctions. A special feature of Ci301 is the
presence of two 54-bp exons separated by an intervening sequence of 37 bp. Several ESTs (cilv063m20, citb072k01 and ciad11e06) covering this region indicated a mutual alternative use of these exons leading to the potential production of two α:H9251 chain isoforms, including a 1014 amino acid triple helix.

The third C. intestinalis gene, Ci606, encodes an α:H9251 chain sharing several features of the vertebrate α:H9251 chains of the C clade. Hence, the N-propeptide of Ci606 contains a TSPN module but not a minor triple helix. Moreover, the major triple helix of Ci606 is composed of 990 residues and presents several imperfections (Fig. 1). Finally, the exon/intron organization of the region encoding the major triple helix of Ci606 is closely related to the C clade (Fig. 2A). However, the Ci606 exon/intron organization also reminds the B clade. For the last C.intestinalis α chain, Ci916, we have not been able to identify the primary structure of the N-propeptide. The major triple helix is shorter, 996 residues in length, and contains two Gly-Xaa-Yaa-Xaa-Yaa and one Gly-Xaa imperfections, but also five glycine substitutions (Fig. 1).

**Phylogenetic Studies**

**Human Fibrillar Collagens**—Previous studies clearly indicated that human collagens could be divided into three clades (9, 12). The A and B clades are linked to the HOX and Notch paralogons, respectively (2, 24, 25). From their exon/intron organizations, the presence of a TSPN module in their N-propeptide and phylogenetic analyses, the C clade is more closely related to the B clade than the A clade (11, 12). This
relationship is confirmed at the genomic level because COE24A1 and COE27A1 belong to the NOTCH or 1/9p paralogon (26).

Use of Triple Helix Instead of C-propeptide in Phylogenetic Analyses—Most of the phylogenetic studies done on fibrillar collagenses have used the C-propeptide sequences and more often the conserved regions of this domain (9, 12). Until now, the C-propeptide domain has been defined as the most conserved region of fibrillar collagens. However, with the increase in invertebrate data, the robustness of this definition is less convincing. Hence, except for short regions of conserved sequences around the cysteine residues, the C-propeptide contains long stretches of poorly conserved sequences, especially in the region that contains the chain recognition sequence (see Fig. 3A). Moreover, the size of this domain is very variable (Fig. 1). For this reason, we decided to use in our phylogenetic analyses the major triple helical sequences in addition to the C-propeptide domain. Fig. 2 illustrates the correspondence between the exons encoding the major triple helix of human and invertebrate fibrillar α chains. With the exception of the 5'- and 3'-genomic regions, a perfect alignment can be made between them. In the case of the honeybee genes (Fig. 2B), the discrepancies arise probably from the insertion of new introns, as suggested by the presence of introns between the first two bases of the Gly codons.

For the phylogeny studies, the most conserved regions of the C-propeptide between all the α chains were used. For the triple helix, our first choice of sequence included the exon pattern [(54–45)5–(54)4–(54–45)2–(54)5–45–45]. Multiple alignment of the major triple helix of human and invertebrate fibrillar α chain sequences confirms our choice (data not shown) and permits us to define another set of triple helix sequences including 906 residues (Fig. 2A). This larger sequence was used in the phylogenetic analyses.

**FIG. 3. Multiple alignment of the C-propeptide.** A, part of the C-propeptide alignment obtained using human, sea urchin, ascidian, lugworm, and mosquito sequences. This region contains the cysteine residue number 5 and part of the chain recognition sequence. B and C, part of the C-propeptide alignment obtained using human, mosquito, and ascidian (Ci301 and Ci759) sequences. The regions presented in B and C include cysteine residues 1 to 5 and 7 to 8, respectively. Arrows indicate gaps that appear specific to the A or B clade chains. Identical residues between all the α chains analyzed are in bold. Numbering of the cysteine residues is indicated below the multiple alignments.
chains are distributed into the three previously defined clades (12). The distribution of human fibrillar \( \alpha \) chains into these three clades is corroborated by high bootstrap values at the node of clade separations. However, it is difficult to make any correlation between any one invertebrate \( \alpha \) chain and a vertebrate clade. Indeed the \( \alpha \) chains that include a \( \text{vWc} \) or a \( \text{TSPN} \) module in their N-propeptide seem to be more closely related.

The same analysis was done using the triple helical sequences, as shown in Fig. 4B, which confirms the assignment of some invertebrate \( \alpha \) chains to vertebrate clades as previously indicated from the modular structure of the fibrillar collagen chains (Fig. 1). The robustness of this tree was clearly shown when we indicated which chains included a \( \text{vWc} \) or a \( \text{TSPN} \) module in their N-propeptides. Hence, use of the triple helix data permit a clear separation of chains containing a \( \text{TSPN} \) module from chains including a \( \text{vWc} \) module. The \( \text{C. intestinalis} \) Ci759, Ci301, and Ci606 \( \alpha \) chains are included in groups including the A, B, and C clades, respectively. For Ci916, the maximum parsimony method seems to relate this fibrillar chain to the C clade (Fig. 4B) with the C-propeptide analyses (Fig. 4A) clustering this \( \alpha \) chain with the \( \text{C. intestinalis} \) C clade-like Ci606 fibrillar collagen chain. The \( \text{A. gambiae} \) AgFo1 and AgFo2 \( \alpha \) chains are related to the A and B clades, respectively. However, the A clade-like property of the AgFo1 \( \alpha \) chain is only supported by the neighbor joining analysis (see supplemental data) and its modular structure (Fig. 1). To validate the robustness of the triple helix analysis, we also eliminated every third glycine residue from sequences and made the phylogenetic analyses. The trees made with these sequences were comparable with those presented in Fig. 4B (data not shown).

For sea urchin, the data shown in Fig. 4A might indicate that \( 6 \alpha \) and \( 7 \alpha \) are related to the vertebrate B or C clades. Interestingly, a search of TSPN module in sea urchin genomic servers permitted us to obtain three sequences encoding this module. Multiple alignments of the TSPN modules from invertebrate and human \( \alpha \) chains were used to derive trees according to maximum parsimony (Fig. 5) and neighbor joining methods. Phylogenetic analysis made from this alignment confirms that Ci606 is a clade C-like \( \alpha \) chain. One of the sea urchin TSPN modules seems to be related to human type IX collagen, whereas the two other TSPN sequences could be part of an N-propeptide.

**Fig. 4.** Phylogenetic analysis of fibrillar collagens using C-propeptides (A) and triple helices (B). C-propeptide and triple helical sequences from human and invertebrates were aligned using the ClustalW program. Ungapped alignments were used to derived trees according to maximum parsimony method using the Phylo win program (23). The bootstrap values at nodes are indicated and represent the percentage of 1000 bootstrap replications. The presence of a \( \text{vWc} \) (W) or \( \text{TSPN} \) (T) module for each \( \alpha \) chain is shown at the right of each tree. The question mark indicates that the N-propeptide region of the corresponding chain has not been characterized to date. The three vertebrate clades are indicated. See the supplemental data for phylogenetic analyses inferred by the neighbor joining method.
The Vertebrate Elongated Chain Selection Sequence

Boot-Handford and Tuckwell (4) have indicated that all invertebrate \( \alpha \) chains characterized to date lack a large part of the elongated chain selection sequence. As shown in Fig. 3A, with the exception of the ascidian C759 chain, all the new invertebrate \( \alpha \) chains presented in this work show this deletion and present a short chain selection sequence. Although speculation about the appearance of a long chain selection sequence will be presented later, it is already clear that this sequence is present in a highly divergent region of the C-propeptide (Fig. 3A). When we used only human sequences and the \( A. gambiae \) and \( C. intestinalis \) \( \alpha \) chains related to clades A and B, we could observe some patterns that appeared specific to the A clade (Fig. 3B) or B clade (Fig. 3C).

**DISCUSSION**

The data presented in this work clearly indicate that the steps leading to the formation of the fibrillar collagen clades arose early during evolution. Although the presence of \( \alpha \) chains related to the A and B clades in insects is enough to justify this statement, evolutionarily studies point out that the divergence of the B and C clades arose before the emergence of vertebrates. Moreover, the data presented in this work argues against the Boot-Handford and Tuckwell model (4) indicating that the long chain selection sequence arose from a rare genomic event. Altogether, these data suggest that the major steps leading to the structural and functional diversity of fibrils are ancient and arose before the emergence of vertebrates.

**Exon/Intron Organization of Genes Encoding Fibrillar \( \alpha \) Chains**—In the genomic structure presented in Fig. 2, it is...
interesting to note that only the collagen genes of *A. gambiae* and *A. mellifera* present an original structure in comparison to other species. As for the *Drosophila* type IV collagen gene (27), both *A. gambiae AgF1α* and *AgF2α* are compact (less than 10 kb) and their coding sequences divided into 7 and 9 exons, respectively. These data exclude the sequence encoding the signal peptide. The coding sequences of *A. mellifera* are less compact and include more exons. However, as shown in Fig. 2B, several insertions seem to have occurred in these genes. These intronic insertions might explain the less convincing correlation of their exon/intron organization in comparison to other known fibrillar collagen genes. These intronic events might also explain the presence of exons beginning with the second base of a glycine codon instead of an intact glycine codon. With *Ci759*, the two *A. mellifera* fibrillar collagen genes are unique because of the presence of split glycine codons at the 5' end of some exons. An analogy can be made with the genes encoding the mouse and chick α2(XI) chain, with the presence of split codons in exons 19–24 in chick and intact glycine codons in corresponding exons in mouse (28).

**Triple Helix versus C-propeptide in Phylogentic Analysis—** For a long time, the C-propeptide domain has been considered to be the most conserved part of the fibrillar α chains and the region of choice for evolutionary studies. As shown in Fig. 3A, the C-propeptide also presents some regions highly variable in size and sequence between all the α chains characterized to date. Hence, for Fig. 4, the average length of the C-propeptide sequence used for each α chain is 168 residues. The maintenance of every third glycine in the major triple helix and the high percentage of proline residues can drive an experimental bias in a phylogenetic analysis. However, the length of the region used for the construction of the phylogenetic tree (906 residues *versus* 168 amino acids for the C-propeptide) gives a more accurate picture of the evolution of this family of proteins. Hence, the bootstrap values are higher than those obtained when C-propeptide sequences are used. The best indication that use of the triple helix in our phylogenetic analysis is justified is that we can predict the modular composition of the N-propeptide of an α chain from the primary structure of its major triple helix.

**Emergence of Vertebrate Fibrillar Collagen Clades—** During the last decades, several studies have suggested that some invertebrate fibrillar α chains appear to be closely related to vertebrate minor collagens (14, 29, 30). The recently suggested model of Boot-Handford et al. (12) was very surprising in our view, especially with regard to the appearance of the B and C clades in vertebrates or just before their emergence. Vertebrates possess quantitatively major (types I-III) and minor (types VXL) fibrillar collagens. Interestingly, all the α chains that include a TSPN module in their N-propeptide belong to the minor class and are members of the B clade. We previously demonstrated that invertebrates possess quantitatively minor collagens (17), and the availability of genome data from invertebrates clearly shows that they may produce fibrillar α chains including a TSPN domain. The presence of α chains from A and B clades in protostomes clearly argues against the Boot-Handford model (Ref. 12 and Fig. 6A). For this reason, we present a new evolutionary model (Fig. 6B), which is closely related to our previous model (16). In this model, an ancestral α chain possesses the major triple helix and the C-propeptide. From our evolution study it is difficult to define if the ancestral fibrillar α chain contains a vWC or a TSPN module or either of them in this N-propeptide. The presence of a minor triple helix corresponding to the N-propeptide is possible although uncertain. The divergence of the founder α chains from the A and B clades arose early during evolution as indicated by their presence in protostomes. It is difficult to date the emergence of the C clade during evolution, although the formation of this clade predated vertebrate appearance. The last suggestion of our model is that the formation of the long chain selection sequence is not caused by a rare genomic event but to an improvement during the evolution of this sequence.

**Functional and Structural Relevance of Fibrillar Collagen Evolution—** From previous invertebrate studies (17, 20, 31) and the present data, it has become apparent that the mechanisms at the origin of vertebrate fibril diversity arose step by step during evolution and are not contemporary with the emergence of vertebrates. Hence, we have shown that invertebrates possess quantitatively major and minor fibrillar collagens (17). Another important step arising in invertebrates is the formation of heterotypic fibrils made of minor and major collagen types displaying distinct maturations of their N-propeptide as demonstrated in sea urchin (17, 20). With the presence of at least two other fibrillar collagen chains (6α and 7α) which seem to be related to the B and C vertebrate clades, the diversity of sea urchin α chains clearly suggests that this invertebrate is able to produce a large variety of fibrils. Indeed, the general mechanisms leading to fibril formation are ancient, as noted in some specializations such as in sea urchin where two α chains contain several repeats of the sea urchin fibrillar module in their N-propeptide (17), a domain that appears to be specific to echinoderms. Moreover, genome duplications have increased the number of fibrillar collagen chains in vertebrates and consequently the diversity of collagen fibrils.

The appearance of vertebrates that arose in the lower Cambrian period and their phenotypic complexity have been attributed to large scale gene or genome duplications (“2R” hypothesis) at the origin of the group (32, 33). The linkage of the A–C fibrillar collagen clades with gene clusters in mammalian genomes is in agreement with the duplication events (2, 24, 25). From this 2R hypothesis and their evolutionary model, Boot-Handford and Tuckwell (4) suggested that the “vertebrate fibrillar collagen family evolved by molecular incest resulting from gene duplications.” The formation of the various vertebrate fibrillar collagen types has taken place over several hundred millions of years. During this period, fibrillar collagen genes developed their own pattern of expression and their actual coding sequence. As indicated above, the chain selection sequence is not caused by a rare genomic event but is the result of a long evolutionary process. We would prefer to describe the vertebrate evolution of fibrillar α chains as a non-incest theory or a classical model of the evolution of duplicated genes, i.e. from the loss of one of the duplicated genes to the acquisition of new functions that evolved with time. Fibrillar collagens are present from sponges to humans and can be considered as a protein specific to metazoan. Their evolution from the most primitive to the “more evolved” metazoan has followed some general rules from an ancestral gene. This story includes duplications, mutations, and acquisition of new genomic information leading to the formation of the vertebrate clades in invertebrates and introduction of some specialization like the presence of sea urchin fibrillar modules in sea urchins. The availability of genome data from other invertebrates such as the sponge and structural studies of invertebrate fibrils will lead to a better understanding of the evolution and functions of the fibrillar collagens.

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Evolution of Fibrillar Collagens