

Protein family review

Higher plant cellulose synthases

Todd Richmond

Address: Department of Plant Biology, Carnegie Institution of Washington, 260 Panama Street, Stanford, CA 94305, USA.
E-mail: todd@andrew2.stanford.edu

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Summary

Cellulose, an aggregate of unbranched polymers of β -1,4-linked glucose residues, is the major component of wood and thus paper, and is synthesized by plants, most algae, some bacteria and fungi, and even some animals. The genes that synthesize cellulose in higher plants differ greatly from the well-characterized genes found in *Acetobacter* and *Agrobacterium* sp. More correctly designated as 'cellulose synthase catalytic subunits', plant cellulose synthase (CesA) proteins are integral membrane proteins, approximately 1,000 amino acids in length. The sequences for more than 20 full-length CesA genes are available, and they show high similarity to one another across the entire length of the encoded protein, except for two small regions of variability. There are a number of highly conserved residues, including several motifs shown to be necessary for processive glycosyltransferase activity. No crystal structure is known for cellulose synthase proteins, and the exact enzymatic mechanism is unknown. There are a number of mutations in cellulose synthase genes in the model organism *Arabidopsis thaliana*. Some of these mutants show altered morphology due to the lack of a properly developed primary or secondary cell wall. Others show resistance to well-characterized cellulose biosynthesis inhibitors.

Gene organization and evolutionary history

Gross gene structure

A number of cellulose synthase (CesA) genes have been cloned from a variety of plant species, the first in 1996 [1]. The most information is known about the *Arabidopsis thaliana* CesA gene family, as the *Arabidopsis* genome sequence is nearly finished. CesA genes range in size from 3.5 to 5.5 kb, with 9-13 small introns (Figure 1). They produce transcripts ranging in size from 3.0 to 3.5 kb, encoding proteins 985 to 1,088 amino acids in length. The intron-exon boundaries are highly conserved, with differences in gene structure primarily due to the loss of introns.

Chromosomal location and organization

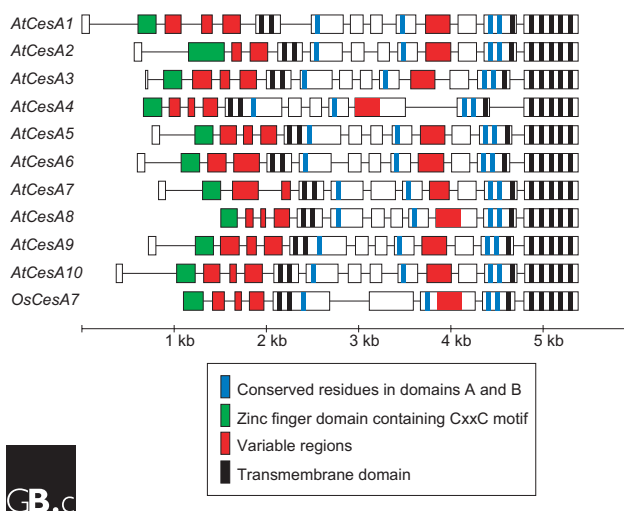
In *Arabidopsis thaliana*, there are at least ten cellulose synthase genes. These are scattered throughout the genome, with no apparent recent duplication events. Unlike bacterial cellulose synthase genes, there are no functionally linked genes in close proximity to one another. Sequence data

indicate that the CesA gene family is as large, or larger, in other plant species.

Evolutionary history

Plant cellulose synthases belong to family 2 of processive glycosyltransferases [2,3], a large family of enzymes with members from viruses, bacteria, fungi, and all other eukaryotes. The proteins in this family are inverting processive glycosyltransferases that make β linkages. Cellulose synthases synthesize β -1,4-glucans, homogeneous strands of glucose residues. In addition to higher plants, cellulose is synthesized by a number of bacterial species (i.e. *Acetobacter*, *Agrobacterium*, and *Rhizobium*), algae and lower eukaryotes (i.e. tunicates). While the end product is the same, there is little similarity at the amino-acid level between these genes and CesA genes from higher plants.

In *Arabidopsis thaliana*, there are a total of six families of genes, designated 'cellulose synthase-like' (Csl), that appear

**Figure 1**

Gene structure of the *Arabidopsis* CesA gene family and the rice CesA7 gene, the only CesA genes for which full genomic sequence is available. At, *Arabidopsis thaliana*; Os, *Oryza sativa*. Exons are represented by boxes and introns by connecting lines. Exons or portions of exons encoding the domains shown in Figure 3 are colored as indicated.

to be related to the CesA family, on the basis of sequence similarity, conserved protein domains, and overall gene structure [4,5] (Figure 2). The function of these families is not yet known; it is possible that one or more of these families is also part of the cellulose synthesis pathway.

Characteristic structural features

Overall structural organization

All cellulose synthases described to date have a number of conserved structural features. It is thought that CesA acts as a member of a protein complex that can be visualized by electron microscopy on the surface of the plasma membrane in structures called 'rosettes'. These appear to consist of six large subunits arranged in a hexagonal pattern, each approximately 9 nm in size. At the amino terminus of the CesA protein is an amino acid domain that bears some resemblance to a zinc finger or LIM transcription factor. It is thought that this domain might play a role in protein-protein interactions in the CesA complex. Within this domain is a strictly conserved sequence motif, the 'CxxC' motif, beginning 10-40 amino acids from the amino terminus: C_x2C_x12FxACx₂Cx₂PxCx₂Cx-Ex₅Gx₃Cx₂C in the single-letter amino-acid code, where x is any amino acid.

Also within the amino terminus of the protein is a region of about 150 amino acids originally designated as a 'hypervariable' region. It is clear, however, as additional full-length protein sequences have become available, that this region is

more conserved than was previously thought. This region is rich in acidic amino acids. The contribution of this region to the overall function of the enzyme is unknown.

Following the amino-terminal domains are two predicted transmembrane domains, near positions 270 and 300 in the *Arabidopsis* CesA proteins (Figure 3). The carboxy-terminal portion of the protein, extending from approximately amino acid position 850, contains six additional predicted transmembrane domains. The region between the sets of transmembrane domains is often designated as the globular domain or the soluble domain. Consisting of around 550 amino acids, it is thought to form a loop that extends into the cytoplasm. Within this domain are several characteristic conserved regions. There is a second variable region, approximately 50 residues in length, beginning near position 650. Also within the globular domain are the motifs indicative of processive glycosyltransferases. The first motif (Domain A) consists of several widely spaced aspartic acid residues; a single D followed by a DxD (see Figures 2,3). These residues are thought to bind the UDP-glucose substrate, and are found in both processive and non-processive enzymes. Processive enzymes catalyze the addition of many sugar residues to a growing chain. Non-processive enzymes catalyze the addition of only a single sugar residue to an acceptor molecule. The second motif (Domain B) is found only in processive enzymes. It consists of a third conserved aspartic acid residue and three conserved amino acids, QxxRW, which are thought to be part of the catalytic site. There are many conserved residues found around these motifs in the plant cellulose synthase proteins.

The various members of the plant CesA family range in size from 985 to 1,088 amino acids and can vary in sequence identity from 53% to 98%. Care must be taken to avoid confusing the cellulose synthase genes with members of the cellulose synthase-like families, especially the CslD family. The most distinguishing feature is the first 250 amino acids before the first predicted transmembrane domains; only the CesA proteins contain the CxxC motif.

Localization and function

Cellulose synthase has been localized to the plasma membrane by immunocytochemistry. As cellulose is a major component of all higher plant cell walls, CesA proteins are expressed in all tissues and cell types of the plant. Studies indicate, however, that the various members of the family in each species are differentially expressed - in tissue types and in primary versus secondary cell wall formation. For example, the AtCesA1 (RSW1) protein is responsible for primary cell wall biosynthesis throughout the plant, while the AtCesA7 (IRX3) protein functions only in secondary cell wall biosynthesis in the stem.

The sole function of cellulose synthase is the production of the biopolymer cellulose, a β -1,4-glucan chain, ranging in

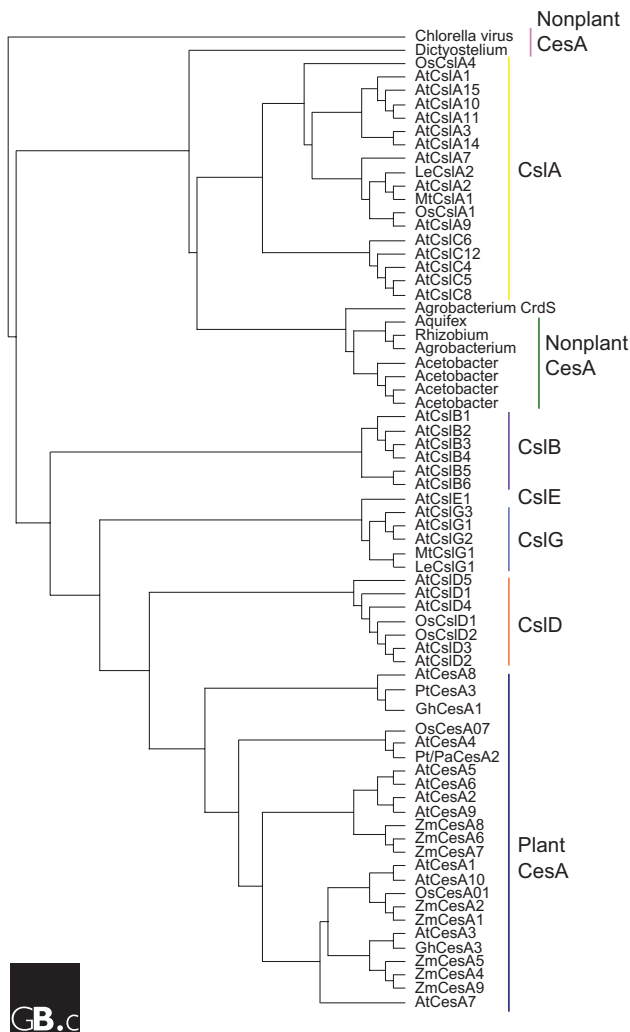


Figure 2

A cladogram of the plant CesA superfamily and related non-plant proteins. ClustalX (version 1.8) was used to create an alignment of the protein sequences that was then bootstrapped ($n = 1000$ trials) to create the final tree. Subfamilies are indicated with colored bars on the right. At, *Arabidopsis thaliana* (thale cress); Gh, *Gossypium hirsutum* (cotton); Le, *Lycopersicon esculentum* (tomato); Mt, *Medicago truncatula* (barrel medic); Os, *Oryza sativa* (rice); Pt, *Populus tremuloides* (quaking aspen); Pt/Pa, *Populus alba* x *Populus tremula* (gray poplar); Zm, *Zea mays* (maize).

size from 2,000 to 25,000 glucose residues. Cellulose is found as fibrils in plants, most often consisting of 36 glucan chains, although some cellulosic algae have very large microfibrils consisting of more than 1,200 glucan chains.

Enzyme mechanism

The mechanism by which cellulose synthase creates a β -1,4-glucan chain is not yet known. Although putative

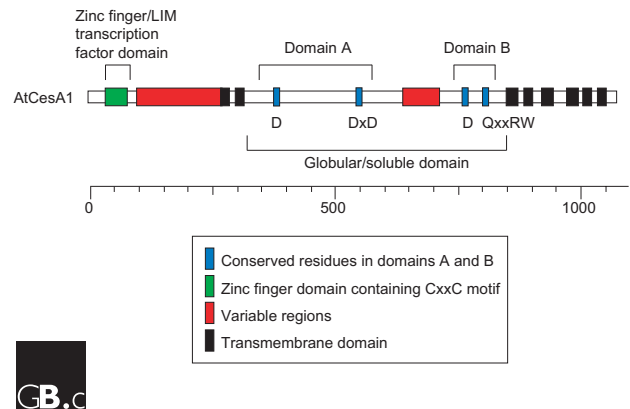


Figure 3

Protein features characteristic of plant cellulose synthase proteins, shown using the *Arabidopsis* CesA1 protein as a paradigm. Regions indicated above and below are described within the text and domains are colored as indicated.

substrate binding sites and catalytic residues have been identified, it is not clear whether cellulose chains are synthesized by the addition of single sugars or disaccharides. The β -1,4-linkage in cellulose requires that each glucose residue be flipped nearly 180° with respect to its neighbors. To make this chain one sugar residue at a time would require either the glucan chain or the synthase to rotate 180° , or the sugar residues to be added, then rotated into the proper orientation by another factor associated with the catalytic subunit. Reorientation problems are eliminated when models invoking two sugar-binding sites are used, however. But at present there is no experimental evidence for either model. Having the structure for cellulose synthase would be likely to help answer some of the mechanistic questions, but as yet there is no crystal structure available for any cellulose synthase or closely related enzyme. One of the hypothetical three-dimensional structures for the CesA proteins has the eight transmembrane helices forming a pore in the plasma membrane, through which the growing glucan chain passes to reach the newly forming cell wall [6] (Figure 4). The amino terminus, with the putative protein-protein interaction domain, would reside in the cytoplasm, free to make contact with other proteins or factors necessary for activity.

Important mutants

There are a number of mutants currently known in plant cellulose synthase genes. The *rsw1* temperature-sensitive mutation in *AtCesA1*, when grown at the non-permissive temperature, causes a specific reduction in cellulose synthesis, the accumulation of noncrystalline β -1,4-glucan, disassembly of cellulose synthase, and widespread morphological abnormalities [7]. The *irx3* (irregular xylem 3) point mutation

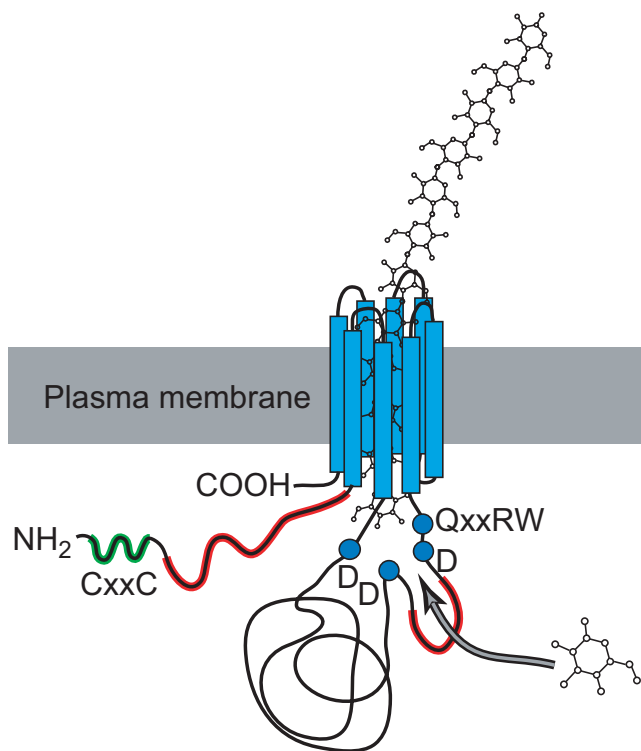


Figure 4
Hypothetical three-dimensional structure of CesaA proteins. The transmembrane helices of the CesaA protein are thought to form a pore in the plasma membrane through which the growing glucan chain passes. Regions are colored to follow those shown in Figure 2. This figure is adapted from [6].

in *AtCesA7* shows a defect in secondary cell wall formation in xylem. As a result, the tracheary elements in the *irx3* mutant have weakened walls and collapse upon themselves [8,9]. The *irx1* point mutation in *AtCesA8* is a member of the same family of mutants as *irx3* (N. Taylor and S. Turner, personal communication). Not to be confused with *irx* is *irx1* (isoxaben resistance). There are two mutant alleles, *irx1-1* and *irx1-2*, that confer resistance to the cellulose biosynthesis inhibitor isoxaben. Both alleles are point mutations in the *AtCesA3* gene (W. Scheible and C. Somerville, personal communication). Another mutation that confers resistance to isoxaben is *irx2*; *irx2-1* is a point mutation in the *AtCesA6* gene (H. Höfte, personal communication). Finally, *procuste1* is one of a class of mutants that show decreased elongation and increased radial expansion in hypocotyls in *Arabidopsis*; *procuste1* is mutation in the *AtCesA6* gene, the same gene as *irx2* (H. Höfte, personal communication).

Frontiers Issues most studied

There are a number of questions that are currently being addressed in the area of cellulose biosynthesis. Now that the

genes for the catalytic subunit of cellulose synthase are known, researchers are interested in the mechanism of synthesis and the regulation of cell wall deposition. Projects have been initiated in several different plant species to look at expression in different tissues and developmental stages using DNA microarrays, immunocytochemistry and RT-PCR. The function of the many *CesA* genes is being studied using genetic tools, including point mutations, T-DNA insertion lines and transposon lines, and through the use of chemical inhibitors of cellulose biosynthesis. Various groups are attempting to determine the crystal structure of cellulose synthases, a difficult task because these are integral membrane proteins. For a general review of cellulose synthase research, see [10,11].

Major unresolved questions

Key issues that remain concern the enzyme mechanisms, including whether monosaccharides or disaccharides are the substrates for cellulose synthase. And how are substrates delivered to the enzyme? It is not clear whether cellulose biosynthesis requires a primer; if so, what is the primer? How many proteins make up the cellulose synthase complex and what are their individual roles? There is growing evidence that more than one *CesA* protein may be required in each cell for normal function - do the various *CesA* proteins interact directly, and, if so, how are they arranged in the subunits of the rosette? Do the transmembrane helices of the *CesA* protein then form a pore through which the growing glucan chain passes through the membrane? And why are there so many *CesA* genes in plants? Given that there are so many, how does each plant cell use them to control the synthesis and deposition of cellulose? And is regulation controlled at the transcriptional or the post-translational level? Clearly cellulose synthases are amenable to much more work.

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