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Review

SOXopathies: Growing Family of Developmental Disorders Due to SOX Mutations

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The SRY-related (SOX) transcription factor family pivotally contributes to determining cell fate and identity in many lineages. Since the original discovery that *SRY* deletions cause sex reversal, mutations in half of the 20 human SOX genes have been associated with rare congenital disorders, henceforward called SOXopathies. Mutations are generally *de novo*, heterozygous, and inactivating, revealing gene haploinsufficiency, but other types, including duplications, have been reported too. Missense variants primarily target the HMG domain, the SOX hallmark that mediates DNA binding and bending, nuclear trafficking, and protein–protein interactions. We here review key clinical and molecular features of SOXopathies and discuss the prospect that the disease family likely involves more SOX genes and larger clinical and genetic spectrums than currently appreciated.

Highlights

SOXopathies are rare, severe disorders resulting from mutations in the SOX genes. They have been associated to date with half of the 20 SOX family members and the numbers of genes involved and pathogenic variants are still on the rise.

Most SOXopathies result in developmental defects and are syndromic, including such severe defects as sex reversal, intellectual disability, skeletal dysmorphism, and cardiovascular anomalies.

SOXopathies can be caused by many types of gene alterations, and most mutations are *de novo*, heterozygous, and loss-of-function, thus exposing gene haploinsufficiency.

Missense variants are almost exclusively located in the HMG domain, a distinctive and multifunctional feature of all SOX proteins.

Defining SOXopathies

A seminal discovery was made in 1990 with the cloning of ***SRY*** (see Glossary), the gene that occupies and defines the sex-determining region on the Y chromosome and whose inactivation underlies disorders of sex development (DSDs) [1]. *SRY* encodes a transcription factor with a high-mobility group (HMG)-type DNA-binding domain. This discovery prompted a search for close relatives, with the vision that SRY-related HMG box (**SOX**)-containing genes would also have critical roles. Major cloning efforts and completion of genome sequencing projects made it clear by the turn of the 21st century that humans and most mammals possess 19 SOX genes, in addition to *SRY* [2]. Both forward and reverse genetic approaches have uncovered pivotal functions for most SOX genes, such that it is now well recognized that the SOX family exerts master roles in many developmental, physiological, and pathological processes by governing cell type-specific genetic programs in both stem/progenitor cells and highly specialized cell types [3]. Thanks to major advances in genetic testing procedures, mutations in half of the SOX genes have been associated to date with congenital diseases. Several of these associations were made very recently, and the numbers of reported pathogenic mutations have been increasing exponentially over the years (Figure 1). SOX mutation-driven diseases affect various processes, but most are developmental disorders and due to ***de novo*** alterations inactivating one SOX allele. We henceforward refer to them as SOXopathies, just as RASopathies, for instance, are due to mutations in components of the RAS/MAPK pathway [4] and collagenopathies are primarily due to mutations in collagen genes [5]. We here review these diseases clinically and genetically and in the context of current knowledge of SOX functions. While focusing on developmental disorders due to germline mutations in SOX genes, we also briefly discuss other diseases, such as cancers, which may be triggered or influenced by somatic mutations in SOX genes or by factors altering SOX gene or protein activities. We end with a discussion on the perspective that SOXopathies likely involve more SOX genes and exhibit larger clinical and genetic spectrums than are currently known.

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Shared and Unique Features of SOX Proteins and Genes

SOX proteins, like TCF/LEF proteins, share significant identity in their DNA-binding domain with HMGB proteins (Figure 2A). The latter are ubiquitous chromatin architectural factors that run in SDS-PAGE with a high mobility [6], whereas SOX and TCF/LEF proteins are classical transcription factors expressed in discrete cell types. The **HMG domain** forms three α-helices that fold into an L-shaped structure, penetrates the minor groove of DNA, and sharply bends DNA (Figure 2B). Key residues responsible for these properties and for nuclear trafficking are conserved among HMGB, SOX, and TCF/LEF proteins, but the degree of residue identity is much higher within than across families (Figure 2A). Differences account for DNA sequence specificities and bending angles. SOX factors preferentially bind sequences matching or resembling C[A/T]TTG[A/T][A/T], referred to as **SOX motif**. **DNA bending** is critical for transcriptional activity, likely by facilitating enhanceosome assembly [7]. As further described later, missense variants in many HMG-domain residues cause SOXopathies, showing how important the domain and many of its residues are.

The SOX family comprises eight groups, SOXA to SOXH (Figure 2A,C). SOX proteins share almost 100% identity in the HMG domain with same-group relatives, but only about 50% with other-group members. They also share significant identity with same-group members outside the HMG domain, especially in functional domains, which include homodimerization, transactivation, and transrepression domains, but share virtually no identity with other-group members outside the HMG domain. One would expect that missense variants would cause diseases even if located outside the HMG domain, but as described later, only a few cases have been described so far.

SRY is located on the Y chromosome in a region ancestrally related to a segment of the X chromosome containing *SOX3*. The other SOX genes are spread across autosomal chromosomes (Figure 2D). Same-group SOX genes have identical exon–intron structures. The SOXA, SOXB, and SOXC genes are made of a single exon, whereas SOXD genes comprise at least 15 coding exons and multiple 5′ untranslated ones, and *SOX5* and *SOX6* are spread over hundreds of kb. The other SOX genes are small and feature two to five exons. Regardless of body size, most SOX genes are separated from coding neighbors by dozens to thousands of kb. These flanking regions typically house multiple enhancers that underlie complex modes of gene regulation. Accordingly, mutations in these regions have been shown in multiple cases to cause diseases. The expression pattern of each SOX gene is unique, typically including several cell types, but overlaps with that of same-group members, allowing the genes to exert additive or redundant functions. This property implies that inactivating mutations often cause disease only in processes where key roles of a gene cannot be compensated by those of a coexpressed close relative.

SOXopathies Reveal Key Roles for Human SOX Genes during and beyond Development

SRY

To date, several hundreds of distinct *SRY* mutations have been reported to cause disease, more than for any other SOX gene, likely because *SRY* is a master determinant of sex determination (Figure 3), is present at only one copy, and has no SOXA relative to share its functions with. Most *SRY* mutations cause XY sex reversal (Table 1, Key Table) [8,9]. They include full or partial gene deletions as well as point mutations affecting protein integrity [10,11]. Disease-causing missense variants have been identified in almost every HMG-domain residue, but rarely outside this domain [12]. This is explained by the fact that SRY has no functional domain other than its HMG motif. *SRY* translocations from the Y to the X chromosome also cause DSDs. In these cases, individuals carrying *SRY* on an X chromosome develop as males (XX sex reversal), and individuals with an *SRY*-depleted Y chromosome develop as females (XY sex reversal) [13]. Mouse models

Glossary

***De novo*:** refers to gene deletions or variants detected in a child, but not in the biological parents.
DNA bending: ability of the HMG domain to induce a strong bend of the DNA helix. This property is believed to have an architectural role in the formation of enhanceosomes (complexes of transcription factors bound to enhancer sequences).
Dominant negative: refers to a heterozygous mutation that results in a variant protein that negatively interferes with the activity of the wild type protein.
Haploinsufficiency: term referring to a gene located on an autosomal chromosome that is unable to fully achieve its normal functions when one of its alleles carries a loss-of-function mutation.
HMG domain: DNA-binding domain originally identified in HMGB proteins, which are members of the superfamily of nonhistone chromatin proteins that exhibit high mobility in SDS-PAGE. This domain also characterizes the SOX and TCF/LEF families.
SOX: acronym for SRY-related HMG box-containing gene or protein. SOX proteins share at least 50% similarity in the HMG domain with SRY and with one another. The SOX family counts 19 members in addition to SRY in humans and most mammals.
SOX motif: DNA sequence specifically recognized and bound by the HMG domain of SOX proteins. This motif corresponds to or resembles the C[A/T]TTG[A/T][A/T] sequence. Interactions occur at the level of A/T pairs in the minor groove of the DNA helix.
***SRY*:** gene located in the sex-determining region of the Y chromosome. SRY is the founder (first identified member) of the SOX family.

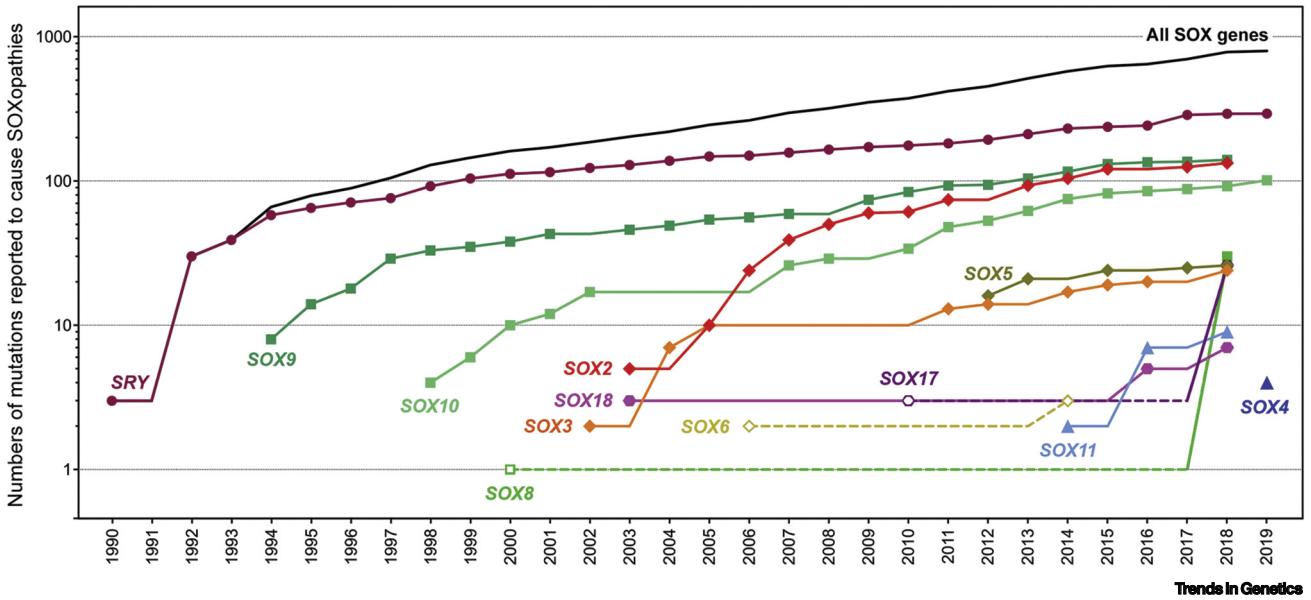


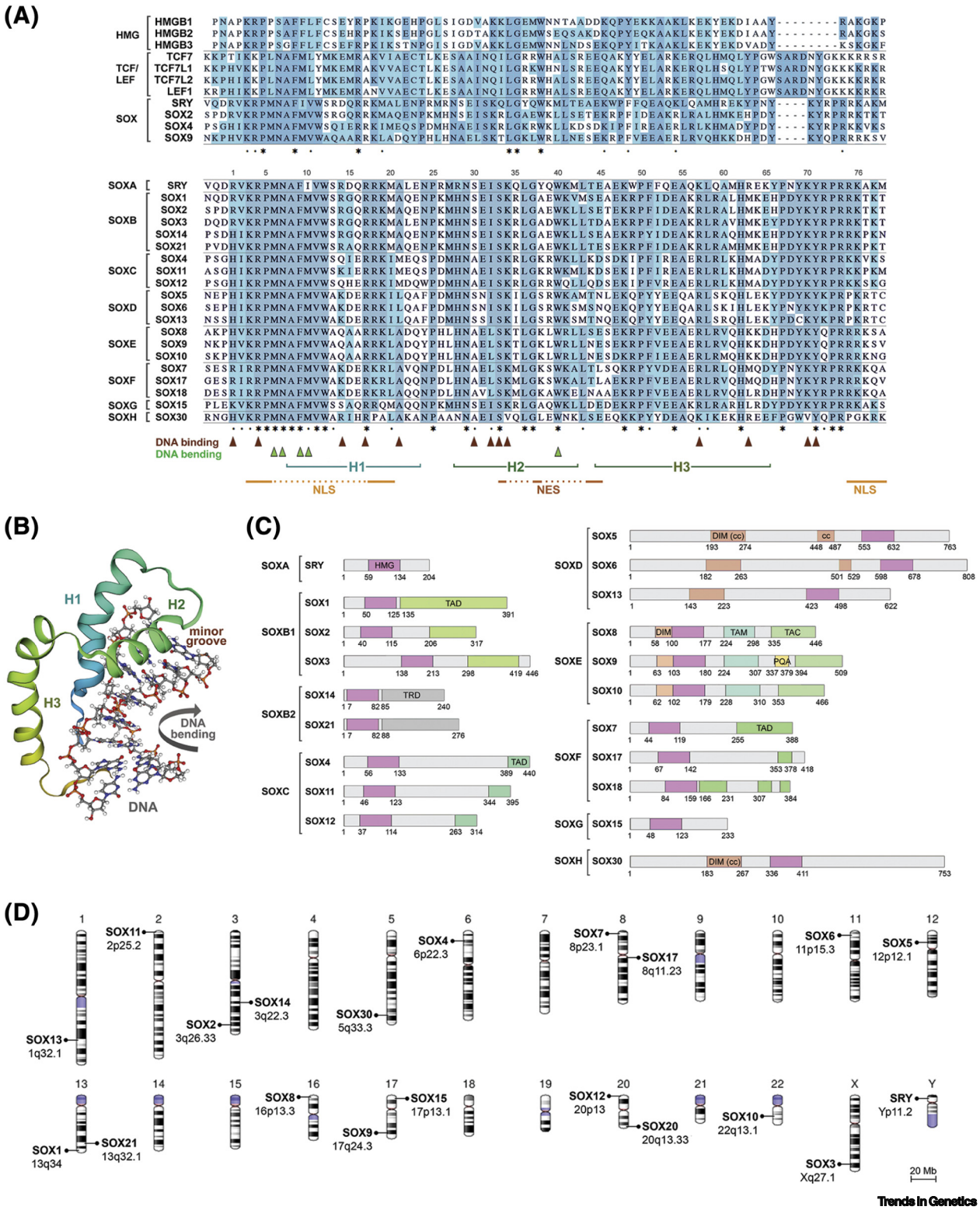
Figure 1. Timeline of SOXopathy Discovery. Cumulative graph showing the numbers of distinct pathogenic alterations identified within and around SOX genes over time. Filled symbols and unbroken lines represent validated gene-disease associations, whereas unfilled symbols and broken lines represent suggested associations. Links made through genome-wide association studies are not included because of undefined variants and numbers.

have confirmed and explained the master role of SRY in sex determination: XY mice lacking *Sry* develop as females, and XX mice carrying an *Sry* transgene develop as males [14,15]. *Sry* is transiently expressed in the embryonic gonad and its main role is to activate *Sox9*, which then activates other male sex differentiation genes, including *Sox8* [16].

SOXE Genes

The SOXE genes, *SOX8*, *SOX9*, and *SOX10*, were next after *SRY* to be associated with diseases. They encode transcriptional activators with critical functions in many processes.

Mutations inactivating one *SOX9* allele were first shown in 1994 to cause campomelic dysplasia (CD) [17,18]. The disease owes its name to the bending (campo) of limbs (melic), one of many features of this neonatally lethal skeletal dysplasia. The few individuals that have survived to adulthood presented such clinical features as mental retardation and hearing loss, in addition to short stature and generalized skeletal malformations [19]. SOX9 is a master regulator of chondrogenesis [20]. It is highly expressed in skeletal progenitor cells and throughout chondrocyte differentiation, and activates most chondrocyte-specific genes [21,22]. Its heterozygous inactivation in mice reproduces human CD and its homozygous inactivation precludes chondrogenesis [23,24]. Nonskeletal defects of CD patients reflect important functions of SOX9 in other processes, but based on data from homozygous mutant mice, they reveal only the 'tip of the iceberg' regarding SOX9 functions. As indicated earlier, *SOX9* is also a master of sex determination. Two-thirds of XY CD patients are sex reversed, and 17q duplications that include *SOX9* cause XX sex reversal [25]. In mice, *Sox9* homozygous inactivation causes XY sex reversal, as does *Sox9* heterozygous inactivation in a *Sox8*-null background [26,27]. More than a hundred different mutations affecting *SOX9* have been shown to cause disease. They are described in depth in Box 1 as a paradigm of the wide spectrums of mutations and diseases that can be associated with a SOX gene. In brief, CD with XY sex reversal is due to *de novo* heterozygous *SOX9* mutations that delete the gene body, translocate most of the upstream regulatory region, or preclude expression of a functional



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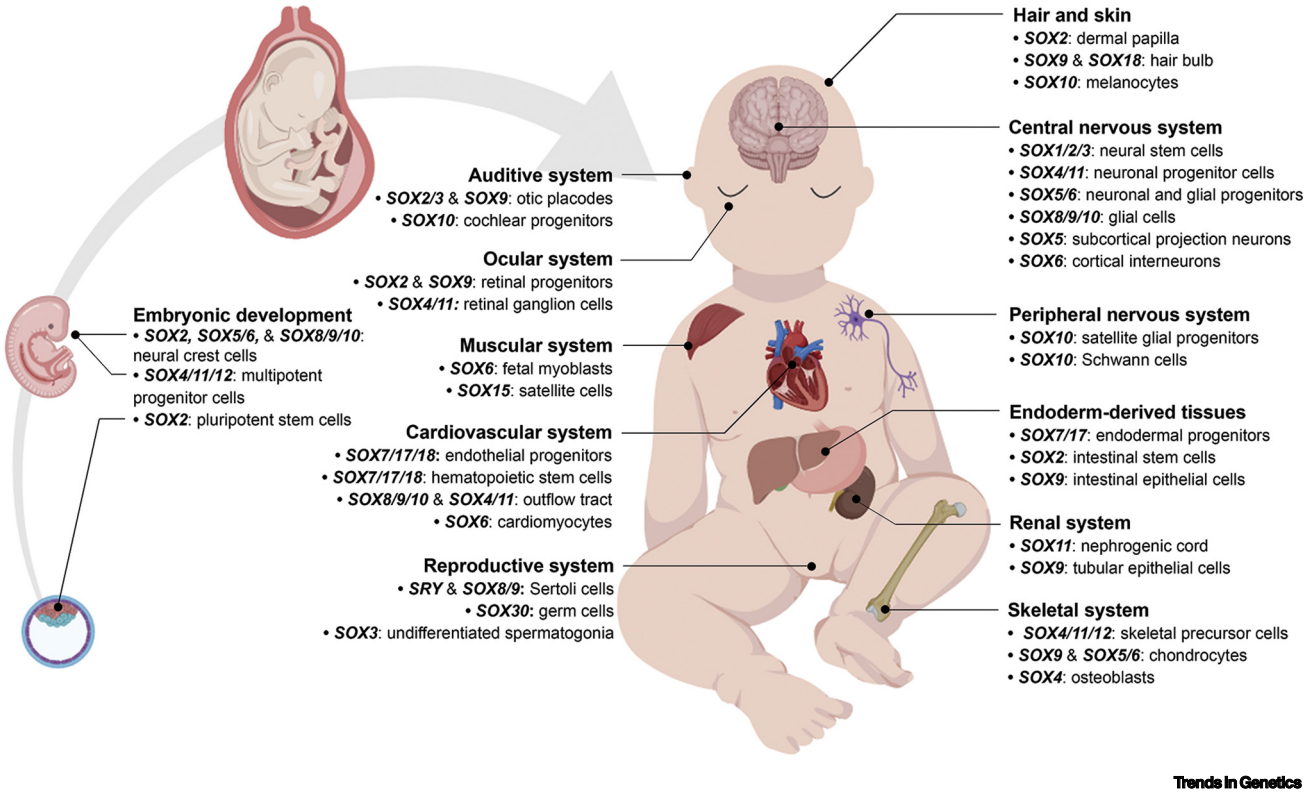

Figure 3. Examples of Key Roles of SOX Genes in Development Derived Primarily from Experiments *In Vitro* and in Animal Models. Drawings were created using BioRender.

protein. Missense variants are almost always located in the HMG and homodimerization domains, the latter allowing high-affinity binding of SOX9 to pairs of DNA recognition sites. Microdeletions and translocations occurring far upstream or downstream of *SOX9* cause milder diseases, namely acampomelic dysplasia, Pierre Robin sequence (PRS), and DSD without skeletal dysplasia, while duplications of specific upstream regions have been shown to cause XX sex reversal. While nonsense mutations affecting the C terminal transactivation domain cause CD and XY sex reversal, proving the critical role of this domain, missense mutations in this domain only cause testicular dysgenesis. The reason is likely that transactivation domains are intrinsically disordered and may thus tolerate missense variants better than the highly structured HMG and dimerization domains.

SOX8 inactivation was initially proposed to contribute to mental retardation in alpha-thalassemia/mental retardation (ATR-16), a syndrome caused by deletions or unbalanced translocations

Figure 2. Shared and Distinctive Features of SOX Proteins and Genes. (A) Alignment of the HMG domain sequences (including three flanking residues on each side) of the human HMGB and TCF/LEF proteins with those of a few SOX proteins (top) and all human SOX proteins (bottom) highlights full conservation (greyish blue) and semi-conservation (cyan blue) of specific residues. Residues involved in DNA binding, DNA bending, α-helices, nuclear localization signals (NLS), and nuclear export signal (NES) are indicated. (B) 3D solution NMR structure of the human SRY HMG domain complexed to DNA shows that the HMG domain is characterized by three α-helices (H1 to H3 from the N to the C terminus) that position themselves into an L-shape, contact DNA exclusively in the minor groove, and force bending of the DNA helix. This schematic was generated by SWISS-MODEL according to [94]. (C) Domain structure organization of the human SOX proteins. (D) Chromosomal distribution of the human SOX genes. Abbreviations: cc, coiled coil; DIM, homodimerization domain; HMG, HMG domain; PQA, PQA-rich domain; TAC, C terminal transactivation domain; TAD, transactivation domain; TAM, middle transactivation domain; TRD, transrepression domain.

Key Table

Table 1. Currently Known SOXopathies and Types of Mutations Involved

Group	Gene	Disease	Type of mutations						
			T	Del	Dup	Inv	Ms		Ns/Fs
							HMG	Other	
SOXA	*SRY*	Disorder of sex development (DSD)	✓	✓	–	–	✓	✓	✓
SOXB1	*SOX1*	–	–	–	–	–	–	–	–
	SOX2	Anophthalmia/microphthalmia syndrome	–	✓	–	–	✓	✓	✓
	SOX3	Mental retardation with panhypopituitarism, X-linked	–	–	✓	✓	✓	✓	–
		Septo-optic dysplasia syndrome	–	–	✓	–	–	✓	–
		XX male sex reversal	✓	✓	✓	–	–	–	–
SOXB2	*SOX14*	–	–	–	–	–	–	–	–
	SOX21	–	–	–	–	–	–	–	–
SOXC	*SOX4*	Neurodevelopmental syndrome with mild dysmorphism	–	–	–	–	✓	–	–
	SOX11	Coffin-Siris syndrome-like syndrome (CSSLS)	–	✓	–	–	✓	–	✓
	SOX12	–	–	–	–	–	–	–	–
SOXD	*SOX5*	Lamb-Shaffer syndrome	✓	✓	–	–	–	–	✓
	SOX6	Craniosynostosis and craniofacial dysostosis[a]	✓	–	–	–	–	✓	–
	SOX13	–	–	–	–	–	–	–	–
SOXE	*SOX8*	Alpha-thalassemia/mental retardation syndrome (ATR-16)[a]	–	✓	–	–	–	–	–
		Disorder of sex development (DSD)	–	–	✓	✓	✓	✓	✓
	SOX9	Campomelic dysplasia (CD)	✓	✓	–	✓	✓	✓	✓
		Acampomelic dysplasia	✓	✓	–	–	✓	✓	–
		Disorder of sex development (DSD)	✓	✓	✓	✓	✓	✓	✓
		Isolated Pierre Robin sequence (PRS)	✓	✓	–	–	–	–	–
	SOX10	Waardenburg-Hirschsprung syndrome	–	✓	–	–	✓	✓	✓
		Peripheral demyelinating neuropathy, central dysmyelination, Waardenburg syndrome, and Hirschsprung disease (PCWH)	–	✓	–	–	✓	–	✓
		Kallmann syndrome	–	–	–	–	✓	✓	✓
SOXF	*SOX7*	–	–	–	–	–	–	–	–
	SOX17	Congenital anomalies of the kidney and urinary tract (CAKUT)[a]	–	–	–	–	–	✓	–
		Pulmonary arterial hypertension and congenital heart failure	–	–	–	–	✓	✓	✓
	SOX18	Hypotrichosis-lymphedema-telangiectasia-renal defect syndrome	–	–	–	–	✓	–	✓
SOXG	*SOX15*	–	–	–	–	–	–	–	–
SOXH	*SOX30*	–	–	–	–	–	–	–	–

Abbreviations: Del, Deletion; Dup, duplication; Fs, frameshift mutation; Inv, inversion; Ms, missense mutation within (HMG) or outside (Other) the HMG domain; Ns; nonsense mutation; T, translocation.
[a]Unconfirmed diseases.

within a 1-Mb 16p13.3 region that includes *SOX8* [28]. However, this proposition remains unvalidated. Recently, genome rearrangements just upstream of *SOX8* and missense variants within and outside the HMG domain were identified in males and females with a DSD spectrum that included oligozoospermia, azoospermia, primary ovary deficiency, and XY sex reversal [29]. Noteworthily, mental retardation was not reported. These findings establish the importance

Box 1. A Variety of Mutations Can Cause SOXopathies: An Example from *SOX9*

Many mutations within and around *SOX9* have been associated with disease. The gene itself is small (5.4 kb), but embedded within a 2-Mb-long region lacking any other coding gene. This region constitutes the *SOX9* topologically associated domain (TAD), that is, a higher-order chromatin interaction structure controlling *SOX9* expression (Figure IA) [95]. It comprises many enhancers driving *SOX9* expression in Sertoli cells, chondrocytes, or other cell types, and translocations, deletions, duplications, and point variants at various locations within this TAD underlie skeletal dysplasias and DSD phenotypes with various degrees of severity [1,20,27,96–100]. Mutations within the *SOX9* gene body have also been associated with SOXopathies (Figure IB). Nonsense variants result in truncated proteins retaining partial activity or being completely inactive. Frameshift variants result in shorter or longer proteins with altered activities. Nonsense and frameshift mutations are widely distributed along the coding sequence, whereas missense variants are largely restricted to splice sites and to the dimerization, DNA-binding, or transactivation domains. Most missense mutations and in-frame deletions in the dimerization and HMG domains and in splice sites cause severe disease (CD with XY sex reversal), whereas missense variants outside these regions cause mild genitalia defects without skeletal abnormalities.

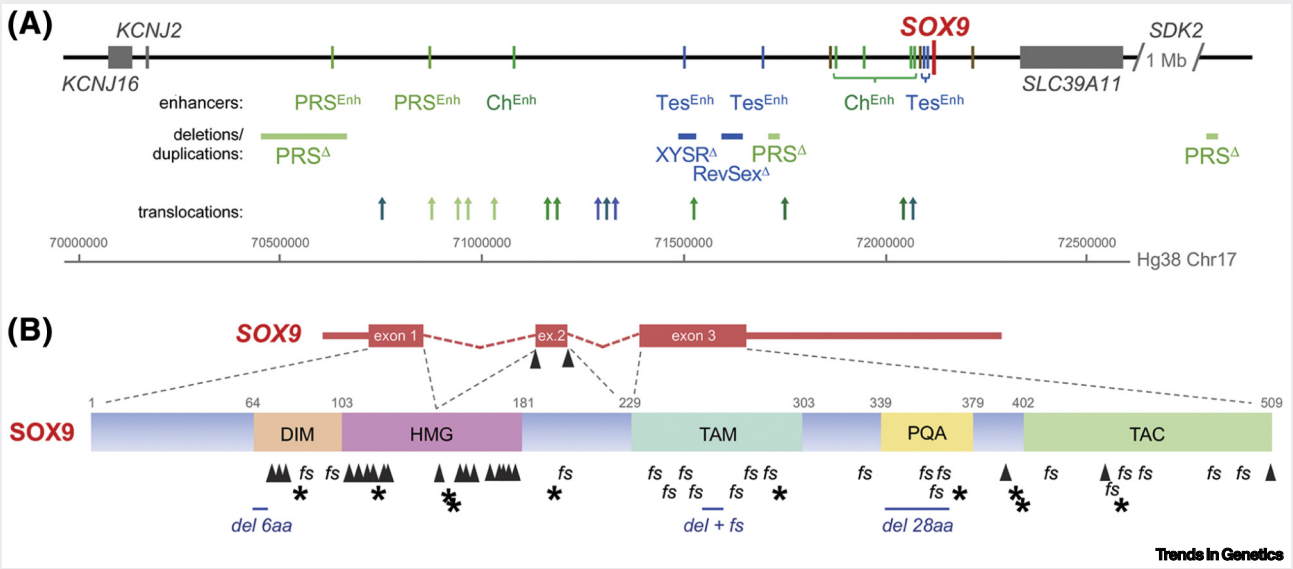

Figure I. Types and Distributions of Pathogenic Mutations in the *SOX9* Locus. (A) *SOX9* locus and flanking genes on 17q24.3, including enhancers primarily active in chondrocytes (Ch^{Enh}, green bars), Sertoli cells (Tes^{Enh}, blue bars), embryonic mandibular region (PRS^{Enh}, light green bars), and other cell types/tissues (brown bars); microdeletions causing Pierre Robin sequence (PRS^{Δ}) and XY sex reversal ($XYSR^{\Delta}$); a duplication causing XX sex reversal ($RevSex^{\Delta}$); and translocations causing campomelic dysplasia (dark green arrows), acampomelic dysplasia (lighter green arrows), Pierre Robin sequence (light green arrows), XY or XX sex reversal (blue arrows), or skeletal dysplasia and XY sex reversal (teal arrows). (B) SOX9 exon/intron and protein structures, including pathogenic microdeletions (del) and nonsense variants (*), frameshift variants (fs), and missense and splice variants (Δ). Abbreviations: DIM, Homodimerization domain; HMG, HMG domain; PQA, PQA-rich domain; TAC, C terminal transactivation domain; TAM, middle transactivation domain.

of human *SOX8* in sex determination, like mouse *Sox8*. *Sox8*-null mice are viable and leaner than normal [30]. Sex determination is unaffected unless, as reported earlier, the mice are also *Sox9* heterozygous null. *Sox8*-null males, however, become infertile early in adulthood [31].

Heterozygous mutations inactivating *SOX10* cause various neurocristopathies: Waardenburg disease, characterized by hearing loss and pigmentation defects; the Hirschsprung intestinal disorder; PCWH, which comprises peripheral demyelinating neuropathy, central demyelinating leukodystrophy, and Waardenburg and Hirschsprung diseases [32,33]; and Kallmann syndrome, a form of hypogonadism characterized by delayed or absent puberty and olfactory defects [34]. The diseases are reminiscent of the phenotypes of mice carrying spontaneous *Sox10* inactivating mutation (e.g., $Sox10^{DOM}$) or a *Sox10* null allele at the heterozygous state (megacolon and pigmentation defect) or homozygous state (namely, lack of peripheral nervous system glia and disrupted differentiation of oligodendroglia) [35–37]. Many aspects of these diseases reflect the fact that *SOX10* is essential to specify neural crest cells, controls the development of various

neural crest derivatives, including Schwann cells, cardiac crest cells, sensory neurons, and melanocytes, and is also essential for the development of oligodendrocytes from neuroectoderm [38,39].

SOXB Genes

The SOXB group comprises SOXB1 (*SOX1*, *SOX2*, and *SOX3*) and SOXB2 genes (*SOX14* and *SOX21*), originally described as encoding transcriptional activators and repressors, respectively. Recent studies, however, have shown that this functional distinction between the two subgroups may not be as strict as initially proposed, as SOX2, for instance, represses as many genes as it activates in neural stem cells [40]. All SOXB genes are expressed in progenitor cells from early development and most highly in the nervous system.

Expansions of a polyalanine tract within the *SOX3* coding sequence were shown in 2002 to cause X-linked mental retardation, short stature due to growth hormone deficiency, and, occasionally, facial dysmorphism and complete panhypopituitarism [41]. These alterations cause protein aggregation and thus loss of function. Other mutations, either reducing or increasing *SOX3* dosage, may cause variants of septo-optic dysplasia, a highly heterogeneous disease that includes optic nerve hypoplasia, corpus callosum and septum pellucidum agenesis, and panhypopituitarism due to pituitary hypoplasia [42]. Furthermore, unique rearrangements in the *SOX3* regulatory region, which likely led to ectopic expression of *SOX3* in the developing gonad, were reported in patients with XX male sex reversal [43]. Consistent with these diseases, *Sox3*-null mice have profound growth insufficiency, weakness, craniofacial abnormalities, hypopituitarism, and midline CNS defects [44]. They do not have sex reversal, but both males and females show severely reduced fertility.

SOX2 is well known for its master roles in specification, differentiation, and maintenance of pluripotent embryonic stem cells and other progenitor cell types [45]. Various kinds of heterozygous loss-of-function mutations were first associated in 2003 with anophthalmia or microphthalmia syndromes, often including craniofacial and other skeletal abnormalities, developmental delay, learning difficulties, esophageal atresia, sensori-neural hearing loss, and genital abnormalities [42,46]. In agreement with these data, *Sox2*-null mice die in early embryogenesis from failure to form pluripotent epiblast [47]; mice with *Sox2* hypomorphic mutations display a spectrum of eye and other malformations [48]; and $Sox2^{+/-}$ mice show impaired development of the hypothalamo-pituitary and reproductive axes [49].

It remains unknown whether *SOX1*, *SOX14*, and *SOX21* mutations cause diseases. It is also unknown whether mouse *Sox14* is critical. In contrast, *Sox1*-null mice have microphthalmia and cataract [50] and suffer from epilepsy associated with abnormal ventral forebrain development and olfactory cortex hyperexcitability [51], and *Sox21*-null mice are small, for unexplained reasons [52], and show cyclic alopecia, explained by master roles for SOX21 in hair shaft cuticle differentiation [53]. One can thus predict that SOXopathies may soon be revealed for these genes.

SOXF Genes

SOX7, *SOX17*, and *SOX18*, compose the SOXF group. They encode transcriptional activators that have been shown in animal models to be pivotal in several developmental processes, including cardiogenesis, vasculogenesis, and angiogenesis (SOX7, SOX17, and SOX18), lymphangiogenesis and hair follicle development (SOX18), and hemangioblastogenesis, definitive endoderm, and gastrointestinal system formation (SOX17) [54–60].

First described in 2003, *SOX18* loss-of-function mutations cause hypotrichosis-lymphedema-telangiectasia syndrome (i.e., sparse hair, absence of eyebrows and eyelashes, lymphatic edema, and peripheral vein anomalies) [61]. Following this report, one patient developed renal failure and additional patients with hypotrichosis-lymphedema-telangiectasia-renal defect syndrome were found to carry pathogenic *SOX18* variants [62]. Some variants were heterozygous and nonsense, truncating SOX18 before or within its transactivation domains. It was proposed, but not tested, that the mutant protein could **dominant-negatively** affect the wild type protein. Other variants were homozygous missense and found in consanguineous families, in which heterozygotes were unaffected. They constitute the first and, so far, only cases of recessive SOXopathy.

SOX17 variants were described in 2010 in patients with congenital anomalies of the kidney and urinary tract (CAKUT) [63]. Several patients were carrying a missense variant located in a region of unknown function and causing excessive accumulation of SOX17 protein *in vitro*. It was later found in an individual that did not have CAKUT disease [64]. Other patients also had missense variants outside the HMG domain of unknown functional impact. These SOX17 variants could generate risk rather than causative alleles for CAKUT. Very recently, *SOX17* heterozygous variants linked to pulmonary arterial hypertension (PAH) and congenital heart disease. Two studies reported frameshift, nonsense, and missense variants, the latter affecting highly conserved residues in the HMG domain or transactivation/β-catenin-binding domain [65,66]. Several alterations segregated with PAH in families. Further, genome-wide association studies found common genetic variations associated with PAH in a critical enhancer upstream of *SOX17* [67].

Mutations in *SOX7* have not been firmly linked to a disease yet, but recurrent microdeletions of 8p23.1 that include *SOX7* and *GATA4* confer a high risk of congenital diaphragmatic hernia (CDH) and cardiac defects [68]. CDH is partially penetrant in $Sox7^{+/-}$ and $Gata4^{+/-}$ mice, suggesting that combined **haploinsufficiency** of *SOX7* and *GATA4* may cause CDH.

SOXD Genes

The SOXD group comprises *SOX5*, *SOX6*, and *SOX13*. These genes encode proteins that homodimerize through coiled-coil domains and bind target genes preferentially to pairs of SOX sites. SOX5 and SOX6 are closer to one another than to SOX13, and control several developmental processes. They help either in transactivation or in transrepression, depending on the cell context. *Sox5* and *Sox6* single-null mice are born with discrete skeletal malformations, and double-null fetuses die *in utero* with a severe chondrodysplasia [69]. This is explained by cooperation of SOX5 and SOX6 with SOX9 in activating the chondrocyte program [20,21]. In contrast, these SOXD proteins inhibit transactivation by SOXC, SOXE, or other factors in neocorticogenesis (SOX5), oligodendrogenesis (SOX5 and SOX6), myogenesis (SOX6), erythropoiesis (SOX6), and melanogenesis (SOX5) [70–75].

In 2006, a child with craniosynostosis and other dysostosis features was found to carry a balanced translocation (t(9;11)(q33;p15) disrupting *SOX6* (11p15) [76]. Another child, with a 9q32-q34 deletion, had a similar phenotype but no craniosynostosis, and a third child, who inherited a missense variant from his unaffected mother, only had craniosynostosis. The variant was located in an N terminal region of SOX6 of unknown function. These cases concur that *SOX6* mutations might cause craniosynostosis, but this possibility needs validation.

In 2012, *de novo* heterozygous translocations and microdeletions disrupting *SOX5* were reported in patients with global developmental delay, intellectual disability, hypotonia, autistic-like features, and mild facial dysmorphism and skeletal malformations [77]. The disorder was

named Lamb-Shaffer syndrome and additional loss-of-function variants, including nonsense ones, were subsequently reported in other patients [78].

SOX13 is expressed in several tissues, including kidney, pancreas, lung, liver, and spinal cord. Its inactivation and overexpression in the mouse have revealed that it promotes gammadelta T cell development while opposing alphabeta T cell differentiation [79], and adds to SOX5 and SOX6 to control the development of mouse spinal cord oligodendrocytes [80]. To date, however, no human disease has yet been associated with mutations in *SOX13*.

SOXC Genes

SOX4, *SOX11*, and *SOX12* form the SOXC group. They encode transcriptional activators, of which SOX11 is the strongest and SOX12 the weakest. They are expressed in many progenitor cell types and critically control cell survival and fate determination in response to various signaling pathways [81,82]. *Sox4*-null mice die *in utero* from heart malformation and *Sox11*-null mice die at birth with abnormalities in the heart, skeleton, and multiple internal organs, whereas *Sox12*-null mice are healthy throughout development and adulthood under regular conditions [83–85]. Mouse conditional knockouts have uncovered redundant roles for *Sox4* and *Sox11* in many developmental processes from early organogenesis, including neurogenesis, skeletogenesis, and outflow tract formation [86–88].

In 2014, two *de novo* heterozygous missense variants in the *SOX11* HMG box were linked to a Coffin-Siris syndrome-like syndrome (CSSLS) characterized by intellectual disability, growth deficiency, facial dysmorphism, and hypoplasia of the fifth digit [89]. The variant proteins were unable to bind DNA. Consolidating the notion of *SOX11* haploinsufficiency, more *de novo* heterozygous mutations were later reported in patients with similar features [90]. They included *SOX11*-containing 2p25 deletions, a nonsense variant, and additional HMG-domain missense variants.

Very recently, four *de novo* heterozygous missense variants in the *SOX4* HMG box were identified in patients with intellectual disability and mild facial and digit dysmorphism [91]. Resemblance to CSSLS is consistent with combined roles for mouse *Sox4* and *Sox11* in many processes. Interestingly, the patients' variants were nonfunctional *in vitro*, whereas all 12 variants listed in gnomAD, a database of control individuals, were functional. Thus, while many HMG-domain variants have been reported in SOX genes to cause diseases, this finding calls for caution in interpreting diagnostic data as it implies that not every such variant should be considered pathogenic.

To date, *SOX12* has not been linked to a disease. *Sox12*-null mice were recently found to show impaired regulatory T cell/lymphocyte differentiation during colitis [92]. This first finding of an important role for mouse *Sox12 in vivo* should encourage studies to link human *SOX12* variants to SOXopathies.

SOXG and SOXH Genes

Although *SOX15* and *SOX30* are classified as SOXG and SOXH genes, respectively, *SOX15* shares recent ancestry with SOXB1 genes and *SOX30* with SOXD genes. Neither gene has been linked to a human disease yet, but important roles have been shown for their mouse orthologs. *Sox15*-null mice develop normally and have an unremarkable adult life, except for a reduced ability to regenerate skeletal muscle in response to a crush injury [93]. This weakness is explained by the expression of *Sox15* in satellite cell-derived myoblasts and its involvement in myogenic determination. *Sox30*-null mice look normal too, but males are sterile, due to a block

of spermiogenesis at the round spermatid stage [40]. Based on these data, it is tempting to speculate that mutations in human *SOX15* and *SOX30* underlie yet-to-be-uncovered SOXopathies.

Concluding Remarks and Future Perspectives

The study of SOX genes and discovery of SOXopathies have provided seminal information on genetic, cellular, and molecular mechanisms underlying fundamental processes from early development onwards. With all the current information, we can tentatively provide a unified view of SOXopathy disease features. Indeed, most SOXopathies are rare developmental syndromes. Based on findings in animals, most SOXopathies only show 'the tip of iceberg' regarding crucial involvement of SOX genes in human processes. Intellectual disability, DSDs, and skeletal and cardiovascular malformations are common, but defects in virtually every system have been reported. Additionally, most SOXopathies result from *de novo* heterozygous loss-of-function mutations and thus reveal gene haploinsufficiency. Of course, there are exceptions. For example, *SRY* loss-of-function variants fully reveal *SRY* functions because *SRY* has no close relative and is expressed from a single allele. Also, reduced fertility due to *SOX8* mutations are adult rather than developmental diseases; and *SOX3* and *SOX9* duplications, as well as *SOX18* missense variants outside the HMG domain, have been associated with diseases. All cases, however, reflect the importance of proper gene dosage to achieve normalcy.

To date, the discovery of SOXopathies is merely midway completed. Many important questions remain unanswered (see Outstanding Questions). Half of the SOX genes are still disease-orphan and more disease associations may remain unknown for the other half. One might think that the remaining diseases are benign, otherwise they would be known by now, but this argument is easy to counter since *SOX17* was linked to PAH and congenital heart failure only in the last year. In addition to developmental disorders, some still-elusive SOXopathies may arise only with increasing age and in specific contexts, such as cancer, tissue repair, and immune response (Box 2). Further research is also needed to better understand the cellular and molecular basis of SOXopathies and, in particular, the issue of disease penetrance and severity. For this, we need to learn how to distinguish pathogenic from risk and benign variants. To explain diseases and

Outstanding Questions

Are all 20 human SOX genes involved in SOXopathies? Are SOXopathies primarily developmental disorders or do they also include a broad range of adult-onset diseases? How broad is the spectrum of diseases associated with any single SOX gene? Are diseases the only outcome of SOX gene variants or are there any phenotypic advantages conferred by some rare or common SOX gene variants to human carriers?

Are pathogenic SOX missense and nonsense variants primarily resulting in null alleles? Do some confer reduced, increased, dominant-negative, or ectopic activity?

Have SOX genes acquired new functions or new expression level requirements during evolution that could explain why several SOXopathies are detected in humans but not in mice upon heterozygous inactivation of some SOX genes? In particular, as many SOX genes are required for brain development, has the evolution of human brain-specific features relied on regulatory changes in SOX gene dosage and expression pattern?

What are the treatment options for SOXopathies? Is gene therapy an option? Are SOX proteins druggable? When should therapies be initiated?

Box 2. SOX Genes and Nondevelopmental Diseases

Many types of diseases implicate SOX genes, but are not due to germline SOX mutations and therefore do not classify as SOXopathies. The great majority of these are cancers [101]. In fact, all SOX genes have been shown to be dysregulated in at least one tumor type. Deregulation can occur at the genetic level, or at the epigenetic, transcriptional, translational, and post-translational levels, resulting in either increased or decreased SOX activities. SOX factors being master determinants of cell fate, their deregulation can cause drastic changes in cell stemness, survival, proliferation, migration, and differentiated activities. SOX genes can be either tumor repressors or promoters depending on tumor types and environment.

Among other adult-onset and degenerative diseases, single nucleotide polymorphisms within and around *SOX4* correlate with moderate risks for osteoporosis and reduced expression of *SOX4* in bone correlates with postmenopausal osteoporosis [102,103]. A significant association exists between *SOX5* variants and a familial form of late-onset Alzheimer's disease [104]. Also, a single nucleotide polymorphism in *SOX8* was identified as a genuine multiple sclerosis susceptibility locus [105], a finding consistent with the importance of mouse *Sox8* in oligodendrocyte myelination [106]. If confirmed, these polymorphisms within or around *SOX4*, *SOX5*, and *SOX8* could classify these disease forms as SOXopathies. Additionally, *SOX5*, *SOX6*, and *SOX9* downregulation [107] and *SOX4* and *SOX11* upregulation correlate with cartilage degeneration in osteoarthritic patients [108]. Also, *SOX2* downregulation is seen in brain sections from Alzheimer's patients, which is consistent with neurodegeneration features resembling Huntington's and Alzheimer's disease described in mice with *Sox2* deficiency [109].

Autoimmune diseases are another class of disorders worth mentioning. Like other transcription factors, several SOX proteins are inclined to generate pathogenic autoimmune responses. For instance, SOX13 was initially discovered in humans as an autoantigen in type 1 diabetes [110] and later in primary biliary cirrhosis [111], and SOX9 and SOX10 are vitiligo autoantigens in autoimmune polyendocrine syndrome type I [112].

develop therapeutic strategies, we also have to further characterize the factors that functionally interact with SOX genes and proteins. All new knowledge will undoubtedly be very valuable to inform genetic counseling and to better understand and treat many other diseases, including those in which SOX genes may intervene abnormally even if intact.

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