Analysis of BMP3 variants in the causality of ocular coloboma

Sabrina Fox¹, Sonya Widen¹, Mika Asai-Coakwell², Serhiy Havrylov¹, Matthew Benson¹, Lisa Prichard³, Pranidhi Baddam¹, Daniel Graf¹, Ordan Lehmann¹, and Andrew J. Waskiewicz¹

¹University of Alberta

²University of Saskatchewan

³MacEwan University

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Abstract

Coloboma, a congenital disorder characterized by gaps in ocular tissues, is caused when the choroid fissure fails to close during embryonic development. Several loci have been associated with coloboma, but these represent less than 40% of those that are involved with this disease. Here, we describe a novel coloboma-causing locus, BMP3. Whole exome sequencing and Sanger sequencing of patients with coloboma identified three variants in BMP3, two of which are predicted to be disease causing. Consistent with this, *bmp3* mutant zebrafish have aberrant fissure closure. *bmp3* is expressed in the ventral head mesenchyme and regulates phosphorylated Smad3 in a population of cells adjacent to the choroid fissure. Furthermore, mutations in *bmp3* sensitize embryos to Smad3 inhibitor treatment resulting in open choroid fissures. Micro CT scans and Alcian blue staining of zebrafish demonstrate that mutations in *bmp3* cause midface hypoplasia, suggesting that *bmp3* regulates cranial neural crest cells. Consistent with this, we see active Smad3 in a population of periocular neural crest cells, and *bmp3* mutant zebrafish have reduced neural crest cells in the choroid fissure. Taken together, this data suggests that Bmp3 controls Smad3 phosphorylation in neural crest cells to regulate early craniofacial and ocular development.

Analysis of *BMP3* variants in the causality of ocular coloboma

Sabrina C. Fox^{1,3,§}, Sonya A. Widen^{1,2,3,§}, Mika Asai-Coakwell^{4,7}, Serhiy Havrylov^{6,7}, Matthew Benson^{6,7}, Lisa B. Prichard⁵, Pranidhi Baddam⁸, Daniel Graf^{6,8}, Ordan J. Lehmann^{3,6,7}, Andrew J. Waskiewicz^{1,3*}

¹Department of Biological Sciences, University of Alberta, Edmonton, Alberta, Canada

²Institute of Molecular Biotechnology of the Austrian Academy of Sciences (IMBA), Vienna BioCenter, Vienna, Austria

³Women and Children's Health Research Institute, University of Alberta, Edmonton, Alberta, Canada

⁴Department of Animal and Poultry and Animal Science, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

⁵Department of Biological Sciences, MacEwan University, Edmonton, Alberta, Canada

⁶Department of Medical Genetics, University of Alberta, Edmonton, Alberta, Canada

⁷Department of Ophthalmology, University of Alberta, Edmonton, Alberta, Canada

⁸Department of Dentistry, University of Alberta, Alberta, Canada

*Information for correspondence:

Andrew J. Waskiewicz

Department of Biological Sciences, 11455 Saskatchewan Drive, University of Alberta, T6G 2E9, Edmonton, Alberta, Canada.

Email: aw@ualberta.ca

Telephone: (780) 492-4403

Fax: (780) 492-9234

[§]These authors contributed equally.

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Abstract

Coloboma, a congenital disorder characterized by gaps in ocular tissues, is caused when the choroid fissure fails to close during embryonic development. Several loci have been associated with coloboma, but these represent less than 40% of those that are involved with this disease. Here, we describe a novel coloboma-causing locus, *BMP3*. Whole exome sequencing and Sanger sequencing of patients with coloboma identified three variants in *BMP3*, two of which are predicted to be disease causing. Consistent with this, *bmp3* mutant zebrafish have aberrant fissure closure. *bmp3* is expressed in the ventral head mesenchyme and regulates phosphorylated Smad3 in a population of cells adjacent to the choroid fissure. Furthermore, mutations in *bmp3* sensitize embryos to Smad3 inhibitor treatment resulting in open choroid fissures. Micro CT scans and Alcian blue staining of zebrafish demonstrate that mutations in *bmp3* cause midface hypoplasia, suggesting that *bmp3* regulates cranial neural crest cells. Consistent with this, we see active Smad3 in a population of periocular neural crest cells, and *bmp3* mutant zebrafish have reduced neural crest cells in the choroid fissure. Taken together, this data suggests that Bmp3 controls Smad3 phosphorylation in neural crest cells to regulate early craniofacial and ocular development.

Keywords

Coloboma, ophthalmology, Ocular development, periocular mesenchyme, zebrafish, BMP, TGF- β

Introduction

Vertebrate ocular development is a deeply conserved and highly coordinated developmental process. As such, even minor perturbations can lead to ocular malformations which, in many cases, are blinding. During gastrulation, retinal tissues in the eye field evaginate to form bilateral optic vesicles (Zuber, Gestri, Viczian, Barsacchi, & Harris, 2003). These vesicles migrate laterally until they contact the overlying ectoderm and induce lens formation. Subsequent coordinated invagination of the vesicles forms the bi-layered structure of the optic cup, with the lens-facing layer forming the neural retina and the lens-averted layer becoming the retinal pigmented epithelium (Kagiyama et al., 2005; Kwan et al., 2012; Schmitt & Dowling, 1994). During optic cup invagination, a transient opening forms on the ventral side of the optic cup known as the optic or choroid fissure (Kwan et al., 2012; Schmitt & Dowling, 1994). The choroid fissure acts as a conduit for the early embryonic ocular vasculature and optic nerve, and closure of the choroid fissure is necessary for normal ocular development (Schmitt & Dowling, 1994). Failure of choroid fissure closure results in gaps in ocular tissues such as the iris and retina (Shah et al., 2012). In humans, this congenital ocular malformation is referred to as coloboma and is present in 2-19 of 100,000 live births (ALSomiry, Gregory-Evans, & Gregory-Evans, 2019; Patel & Sowden, 2019; Williamson & FitzPatrick, 2014; Yoon, Fox, Dicipulo, Lehmann, & Waskiewicz, 2020). Coloboma and its related disorders microphthalmia (reduced ocular size) and anophthalmia (absence of one or both eyes), frequently described as MAC, account for up to 11% of cases of pediatric blindness (Yoon et al., 2020).

Although coloboma can be caused by changes to environmental factors during gestation, it is primarily caused by mutations in genes necessary for ocular development (ALSomiry et al., 2019; Patel & Sowden, 2019; Williamson & FitzPatrick, 2014; Yoon et al., 2020). To date, more than 40 coloboma-causing loci have been identified (ALSomiry et al., 2019; Yoon et al., 2020). These genes have well characterized roles in critical developmental processes essential to choroid fissure closure, including axial patterning of the optic cup (proximal-distal, nasal-temporal and dorsal-ventral), cell movement and shape changes, cell adhesion, extracellular matrix remodeling, and apoptosis (ALSomiry et al., 2019; Yoon et al., 2020). Despite the substantial genetic heterogeneity, the majority of patients with coloboma do not have mutations in any known loci (Yoon et al., 2020). In addition, coloboma exhibits highly variable inheritance, with instances of coloboma pedigrees that display incomplete penetrance and reduced expressivity, suggesting that modifier loci, environmental factors, and stochastic developmental events may confound the identification of disease-causing loci. This is further complicated by marked phenotypic heterogeneity with a diverse spectrum of severity, involvement of distinct ocular structures, and frequent unilateral disease (Hornby, Dandona, Jones, Stewart, & Gilbert, 2003; Morrison et al., 2002; Prokudin et al., 2014; Shah et al., 2012).

Of the loci that regulate choroid fissure closure, a significant proportion belong to the Transforming Growth Factor Beta (TGF- β) superfamily of signaling ligands (ALSomiry et al., 2019; Patel & Sowden, 2019; Williamson & FitzPatrick, 2014; Yoon et al., 2020). All TGF- β superfamily members contain three centralized disulfide bonds termed a “cysteine knot”, as well as an additional disulfide bond that allows for homo- or heterodimerization of ligands (Goebel, Hart, McCoy, & Thompson, 2019). This cysteine knot structure and additional disulfide bond are essential for the secretion, stability, and function of these ligands, and loss of this structure severely impairs the activity of these ligands (Goebel et al., 2019). Binding of the extensive family of TGF- β ligand dimers to a smaller cohort of tetrameric complex of Type I and Type II receptors triggers the phosphorylation of receptor-associated Sma- and Mad-related (r-Smad) proteins (Bassing, Howe, Segarini, Donahoe, & Wang, 1994; Wrana et al., 1992; Y. Zhang, Feng, Wu, & Derynck, 1996). Phosphorylated r-Smad recruits co-Smad4, and this complex translocates to the nucleus, where it regulates target gene expression (Liu et al., 1996). TGF- β ligands can be divided into two groups: the Bone Morphogenetic Protein (BMP) subgroup, which typically trigger the phosphorylation of Smad1/5/8, and the Activin/Nodal/TGF- β subgroup, which predominantly induce the phosphorylation of Smad2/3 (Graff, Bansal, & Melton, 1996).

Of the two groups of TGF- β ligands, BMPs have been studied most extensively in ocular development and disease. Mutation of BMP pathway members (including ligands, antagonists, co-receptors, receptors and Smads) in patients and/or model organisms contributes to MAC, and mutations in these pathway components are also associated with related phenotypes such as orofacial clefts, craniofacial disorders, and neural tube closure defects (Abouzeid et al., 2011; Asai-Coakwell et al., 2007, 2009; Bakrania et al., 2008; Beleggia et al., 2015; French, Erickson, French, Pilgrim, & Waskiewicz, 2009; Hanel & Hensey, 2006; Morcillo et al., 2006; Okada et al., 2011; Pfirrmann et al., 2015; Reis et al., 2011; Sakuta et al., 2001; Suzuki et al., 2009; Wyatt, Osborne, Stewart, & Ragge, 2010; Yan et al., 2020; Ye et al., 2010; R. Zhang et al., 2013). BMP ligands are required for ocular cell survival, maintenance of stem cell pools, migration of ocular precursors, and axial patterning of the developing retina (Adler & Belecky-Adams, 2002; Asai-Coakwell et al., 2007; Morcillo et al., 2006; Peters & Cepko, 2002). Yet, despite intensive investigation, a clear molecular mechanism for how these ligands regulate fissure closure or a plausible explanation for complex patterns of inheritance for genes encoding these pathway components has yet to be deduced.

Early eye development is dependent not only on the intrinsic population of optic cup neuroectoderm cells, but also on a population of extraocular cells that surround the developing eye cup known as the periocular mesenchyme (POM). These cells, which are principally derived from neural crest and cranial mesoderm, migrate over the eye cup and through the choroid fissure and contribute to many structures of the anterior segment, including the iris stroma, the cornea, and components of the intraocular drainage system (Creuzet, Vincent, & Couly, 2003; Gage, Rhoades, Prucka, & Hjalt, 2005; Langenberg, Kahana, Wszalek, & Halloran, 2008). POM cells have also been implicated in choroid fissure closure. Notably, neural crest cells and mesodermally-derived endothelial cells are present in the fissure at times that are critical for choroid fissure

closure (Bernstein et al., 2018; Gestri, Bazin-Lopez, Scholes, & Wilson, 2018; James et al., 2016). Embryos with no appreciable neural crest contribution have open choroid fissures, suggesting that neural crest cells are necessary for closure of the choroid fissure (Bryan, Casey, Pfeiffer, Jones, & Kwan, 2020; Gestri et al., 2018). Additionally, mutations in transcription factors and signaling molecules associated with neural crest function, including *BMP7*, *ZIC2*, *FOXC1*, *LMX1B*, *ALX1*, and *TFAP2A*, have been shown to cause coloboma, further implicating this population of cells in choroid fissure closure (Dee, Szymoniuk, Mills, & Takahashi, 2012; Gestri et al., 2009; Lupo et al., 2011; McMahon, Gestri, Wilson, & Link, 2009; Morcillo et al., 2006; Sedykh et al., 2017; Skarie & Link, 2009).

Here, we characterize a novel coloboma causing locus that was identified by exome sequencing a three-generation pedigree of patients with autosomal dominant coloboma and microphthalmia. Additional variants in *BMP3* were identified in unrelated MAC patients using Sanger sequencing. Use of *in-silico* predictions and protein secretion assays provided the first evidence that variants have deleterious effects to *BMP3* protein function. Zebrafish CRISPR-generated *bmp3* mutants display both delayed choroid fissure closure and altered jaw development. This prompted us to test the hypothesis that *Bmp3* functions in periorcular cells to regulate neural crest cell behavior. We demonstrated that *bmp3* mutants display marked reduced Smad phosphorylation in periorcular neural crest cells. Furthermore, overall migration of periorcular neural crest cells is dramatically reduced in *bmp3* mutants. Our data thus provide the first evidence of a contribution of *BMP3* to coloboma and highlight the importance of signaling pathways in regulating the function of periorcular neural crest during ocular development.

Results

Patients with coloboma and/or microphthalmia have mutations in BMP3

To reveal the genetic cause of coloboma in archival samples, we first performed whole exome sequencing (WES) on samples from four individuals affected by autosomal dominant coloboma and one unaffected control individual from a three-generation European pedigree (Figure 1A). Identified variants were filtered using standard criteria (Beaulieu et al., 2014). Comparison to SNP databases (allele frequency < 1%), *in-silico* prediction algorithms (MutationTaster, SIFT and PolyPhen), and ocular expression patterns were used to identify rare, potentially damaging variants within genes expressed during ocular morphogenesis (Figure 1A). This strategy identified 10 variants present in the affected individual's samples (II:2, III:6, III:1, and IV:4) and absent in the unaffected individual's sample (IV:5), of which the point mutation (c.1408G>C) in *BMP3* represented the most promising candidate pathogenic variant (Table 1). Notably, this variant exhibited Mendelian segregation in the larger pedigree, is absent from local control DNA samples, and is absent from the National Heart, Lung and Blood Institute, 1000 Genomes, and gnomAD databases (total of 87,888 exomes and genomes) (Table 2). This mutation alters a residue (p.Ala470Pro (A470P)) that is located between cysteines that mediate the disulfide bonding necessary to form the cysteine knot structure that is essential for TGF- β ligand stability (Figure S1). This residue is also highly conserved among vertebrate species, further suggesting that it is necessary for the stability and/or function of the mature *BMP3* protein (Figure S1). Collectively, this strongly indicates that changes to this residue will deleteriously impact protein function. Given that numerous TGF- β superfamily members have essential roles in ocular development and mutations in multiple TGF- β paralogs cause coloboma, we concluded that this *BMP3* variant represented the most plausible pathogenic variant of those identified in this family (Abouzeid et al., 2011; Asai-Coakwell et al., 2007; Bakrania et al., 2008; Lo, Chen, Shi, Pavletich, & Massagué, 1998; Ye et al., 2010).

Additional BMP3 variants are present in an unrelated cohort of MAC patients.

To determine whether this exceedingly rare mutation indicates that *BMP3* might contribute to coloboma, we searched for additional *BMP3* mutations by conducting Sanger sequencing of *BMP3* in patients unrelated to the pedigree family. DNA samples from a cohort of individuals with microphthalmia, anophthalmia and coloboma phenotypes were collected over the past 20 years through national and international collaboration. Sanger sequencing of 154 samples identified two additional point mutations in *BMP3* that cause single amino acid substitutions in the mature TGF- β domain of the *BMP3* protein (c.1178C>T (p.Ser393Phe)

and c.1349T>A (p.Phe450Tyr)) (Figure 1A-B). Both variants occur at exceedingly low rates in genome databases (Table 2). *In-silico* modeling using SIFT, PolyPhen2, and MutationTaster predict that the three variants are damaging to protein function, further suggesting that these are pathogenic variants (Table 3). Subsequent use of ANOLEA to bioinformatically predict protein structure indicated that each variant would also increase the free energy required to fold the BMP3 protein (Fig S2) (Melo, F., Devos, D., Depiereux, E., Feytmans, 1997). Such predictions, together with the rarity of the alleles in the general population, suggested that S393F, F450Y and A470P represented pathogenic variants (Table 3).

Functional abnormalities induced by the BMP3 mutations

To determine whether these variants altered the stability and secretion of the BMP3 ligand, the expression of V5-tagged wildtype and variant BMP3 proteins was assayed by immunoblotting. While both wildtype and variant V5-tagged BMP3 were initially expressed in transfected COS cells, differences were observed in the secretion of the BMP3 variants. There was a reduced amount of BMP3-S393F, and complete absence of BMP3-A470P, from the tissue culture media fraction when compared to wildtype BMP3 (Figure 1C). In contrast, BMP3-F450Y was still found to be secreted at levels comparable to wildtype BMP3 (Figure 1C). When quantified and compared to the level of wildtype BMP3 protein in the culture media, the intensity of the bands corresponding to the S393F and A470P variant protein in the culture media exhibited a fold change of 0.18 and 0.038, respectively (Figure 1D). Interestingly, the band corresponding to the F450Y variant exhibited a fold change of 1.71, indicating that more of this variant was secreted into the culture media when compared to wildtype (Figure 1D). The reduction of S393F and absence of A470P from the cell culture media suggests that these variants impact the stability of mature protein or the process by which the protein is secreted from cells.

*Zebrafish *bmp3* mutants have choroid fissure closure defects*

To determine whether mutation of *BMP3* in a vertebrate model accurately recapitulated the patient phenotype, we generated zebrafish *bmp3* mutants using CRISPR/Cas9 mutagenesis. The resulting allele, *bmp3^{qua1020}* (hereafter referred to as *bmp3^{-/-}*), contains two in-frame 3 base pair (bp) deletions and a 5 bp deletion (Figure S3A, Figure 2A). Each 3 bp deletion induces the loss of a single amino acid in the Bmp3 protein, while the 5 bp deletion causes a frameshift mutation that introduces a premature stop codon immediately upstream of the sequence encoding the mature TGF- β domain (Figure S3B). This results in a truncated protein lacking the domain essential for normal BMP function (Figure 2A), and our analyses revealed no evidence that the mutant transcript undergoes nonsense mediated decay (Figure S4). Furthermore, the absence of *bmp3* transcript in 2-cell stage embryos suggests that there is no compensatory maternally deposited mRNA (Figure S5).

The basement membrane surrounding the temporal and nasal retinal lobes, which must be disassembled to allow the lobes to fuse, provides an accurate readout for choroid fissure closure (I Hero, 1990; Isabelle Hero, 1989; James et al., 2016; Tsuji, Kita, Ozaki, Narama, & Matsuura, 2012). Therefore, the absence of the basement membrane lining the fissure is an accurate measure of fissure closure. Loss of this basement membrane is readily visualized with Laminin immunofluorescence. At 48 hpf, the stage just prior to choroid fissure closure, both wildtype and mutant choroid fissures were open (Figure 2B-C).

In contrast, at 65 hpf 18% (23/130) of *bmp3^{-/-}* mutant embryos retained the basement membrane surrounding the fissure compared to 0% (0/38) of wildtype controls demonstrating that *bmp3* contributes to normal choroid fissure closure (Figure 2D-F). Statistical analysis (two-sided Fisher's exact test) confirmed that open choroid fissures occur more frequently in *bmp3^{-/-}* mutants when compared to wildtype animals at 65 hpf ($p=0.0025$, Fisher's exact test). These data also provide evidence that the *bmp3^{-/-}* choroid fissure phenotype is partially penetrant, as is observed in some coloboma pedigrees (Figure S6).

**bmp3* is expressed in the ventral head mesenchyme surrounding the eye*

To explore the mechanisms by which *bmp3* facilitates choroid fissure closure, the spatial expression of *bmp3* mRNA was assessed. The earliest localized cranial expression of *bmp3* begins at approximately 22 hpf, with

dorsal flat mounts demonstrating *bmp3* is expressed in the vicinity of the forebrain and the eye (Figure 3A). Cranial coronal sections reveal that *bmp3* is expressed in a single-cell thick layer in the head mesenchyme immediately ventral to the eye (Figure 3B). Transverse sections of the head further confirm *bmp3* expression in the head mesenchyme between the brain and retina and not within the neuroepithelial cells of the retina or brain (Figure 3C and D). In conclusion, *bmp3* is expressed in the ventral head mesenchyme adjacent to the choroid fissure, a cell population that is composed of POM cells.

Bmp3 does not regulate dorsal-ventral patterning of the early eye

During ocular morphogenesis, the eye must be patterned along the dorsal-ventral axis (Peters & Cepko, 2002). This is achieved through opposing gradients of dorsally-restricted targets of BMP signaling and ventrally-restricted targets of Sonic Hedgehog signaling (Peters & Cepko, 2002). To determine whether *bmp3* facilitates dorsal-ventral axis patterning of the optic cup, the spatial expression of genes that are restricted to either the dorsal (*tbx5a*, *aldh1a2*) or the ventral (*vax2*, *aldh1a3*) regions of the eye were examined in wildtype and *bmp3*^{-/-} mutants using *in-situ* hybridization (Peters & Cepko, 2002). In wildtype embryos, the expression of dorsal markers is restricted to the dorsal half of the optic cup, and ventral markers are restricted to the ventral optic cup, as expected (n=25) (Figure 4A, C, E, G). Identical expression patterns are observed in *bmp3*^{-/-} mutants (n=25) (Figure 4B, D, F, H), suggesting that *bmp3* does not regulate axial patterning of the retina.

Bmp3 does not regulate proliferation or apoptosis in the early eye

In addition to dorsal-ventral patterning of the optic cup, aberrancies in optic cup cell proliferation and cell death have also previously been shown to contribute to the appearance of a coloboma phenotype in several animal models (Kim, Goodman, Anderson, & Niswander, 2007; Lee, Lee, & Gross, 2013; Noh, Lee, Park, & Park, 2016; Sghari & Gunhaga, 2018; Van Nostrand et al., 2014; Viringipurampeer et al., 2012). Therefore, it is plausible that *bmp3* regulates proliferation or apoptosis of neuroectodermal optic cup cells, and the loss of *bmp3* results in aberrant proliferation or apoptosis, thereby leading to choroid fissure closure defects. To determine whether *bmp3* regulates cell proliferation or apoptosis, immunofluorescence was conducted on 28 hpf wildtype and *bmp3*^{-/-} embryos using primary antibodies against phosphorylated Histone H3 (to assay for proliferation) or activated Caspase 3 (to assay for apoptosis). We do not observe an obvious change in proliferation of the optic cup in *bmp3*^{-/-} mutants (n=20) when compared to wildtype controls (n=20) (Figure 4I, J), indicating that *bmp3* does not regulate proliferation of the optic cup. Likewise, there is no obvious change in apoptosis of the optic cup between *bmp3*^{-/-} mutants (n=19) when compared to wildtype controls (n=19) (Figure 4K, L), indicating that *bmp3* does not regulate apoptosis of cells in the optic cup. Taken together, these results indicate that *bmp3* does not regulate proliferation or apoptosis of the optic cup cells.

Bmp3 facilitates choroid fissure closure via Smad3 phosphorylation

The majority of BMP ligands signal via the phosphorylation of Smad1/5/8 rather than Smad2/3 phosphorylation, which is typical of other TGF- β family members such as Activin and Nodal (Miyazono, Ten Dijke, & Heldin, 2000). Interestingly, BMP3 has been shown to activate Smad2/3 rather than Smad1/5/8, suggesting it functions in a noncanonical manner compared to other BMP ligands (Bahamonde & Lyons, 2001; Daluiski et al., 2001; Stewart, Guan, & Yang, 2010). To determine the level of Smad3 phosphorylation adjacent to the choroid fissure, immunofluorescence using an anti-phosphorylated Smad3 (pSmad3) primary antibody was first assessed in wildtype embryos. Confocal imaging revealed active phosphorylated Smad3 restricted to cells in the proximal portion of the nasal lobe, adjacent to the choroid fissure (Figure 5A). In contrast, z-stacks from the medial to distal regions of the eye demonstrated little detectable pSmad3 (Figure 5B, C). In conclusion, this indicates that pSmad3 is present in cells that are positioned optimally to facilitate fissure closure.

We next assessed the presence of pSmad3 in wildtype and *bmp3*^{-/-} embryos to determine whether Bmp3 facilitates choroid fissure closure via Smad3 phosphorylation. While the distinct population of pSmad3 positive cells adjacent to the choroid fissure are present in both wildtype and *bmp3*^{-/-} embryos (Figure 5D, E), there was a subtle, yet statistically significant, reduction in the number of cells containing phosphorylated

Smad3 in the ventro-proximal retina of *bmp3*^{-/-} mutants (18.3 ± 1.09 cells) when compared to wildtype siblings (22.2 ± 1.12 cells) (two-sample t-test, $t_{38}=2.49$, $p=0.0172$) (Figure 5F). Since compensation by other TGF- β ligands represents one explanation for the subtlety of the pSmad3 phenotype, we treated *bmp3*^{-/-} mutants with the pharmacological agent Specific Inhibitor of Smad3 (SIS3) and measured choroid fissure closure. SIS3 was titrated to yield an incompletely penetrant phenotype, and the suboptimal dose selected (12 μ M SIS3) yielded open choroid fissures in 15-20% of wildtype embryos. SIS3 treatment from 24-30 hpf resulted in a significantly higher proportion of open choroid fissures in *bmp3*^{-/-} mutants compared to wildtype embryos (*bmp3*^{-/-} 23/31 (74%), WT 5/28 (18%), two proportion z-test, $z=-4.33$, $p<0.00001$, Figure 5G-I). In summary, these data show that *bmp3* mutation synergizes with pharmacological inhibition of Smad3 to impede choroid fissure closure.

Smad3 phosphorylation is active in neural crest cells in the choroid fissure

POM cells are derived from neural crest cells and cranial mesoderm and have previously been shown to be necessary for choroid fissure closure (Bryan et al., 2020; Gestri et al., 2018; James et al., 2016). In a study of canine brachycephaly, the loss of *BMP3/bmp3* during development results in craniofacial phenotypes including the loss or hypoplasia of early craniofacial cartilage in certain dog breeds and morphant zebrafish (Schoenebeck et al., 2012). This is consistent with our own observations of adult *bmp3*^{-/-} mutants. Midfacial hypoplasia is present in 18-month-old adult *bmp3*^{-/-} zebrafish and is visible under a dissecting microscope (Fig. 6A, B). This is further confirmed by Micro-Computerized Tomography (Micro-CT) scans of adult wildtype and *bmp3*^{-/-} mutants; *bmp3*^{-/-} mutants ($n=5$) have visually altered craniofacial anatomy when compared to wildtype siblings ($n=5$) (Figure 6A-D). When quantified, *bmp3*^{-/-} mutants display significantly shortened average pre-maxilla (1.20 ± 0.167 mm), maxilla (1.58 ± 0.0676 mm), and mandible (2.23 ± 0.112 mm) length when compared to wildtype siblings (1.58 ± 0.250 mm, 1.88 ± 0.0823 , and 2.68 ± 0.146 mm, respectively) (two sample t-test, $t_8=2.85$, 6.22 , and 5.50 , $p=0.000255$, 0.0214 , and 0.000573) (Figure 6G-I). Additionally, analysis of 7 dpf larval zebrafish jaws stained with Alcian blue revealed that 40% ($n=8/20$) of *bmp3*^{-/-} embryos display jaws that are hypoplastic when compared to wildtype controls ($n=0/20$) (Figure 6J, K). The morphology of the chondrocytes that make up Meckel's cartilage are also severely compromised in *bmp3*^{-/-} mutants; the chondrocytes of Meckel's cartilage in affected *bmp3*^{-/-} mutants appear rounder, undifferentiated, and less organized when compared to Meckel's cartilage from wildtype animals, where the chondrocytes are elongated, stacked, and columnar (Figure 6J', K'). This evidence implicates *bmp3* as a regulator of craniofacial development. Since all craniofacial cartilage and bone is derived from neural crest cells, and since there is no change in patterning, proliferation, apoptosis and size of the optic cup in *bmp3*^{-/-} mutants, we hypothesize that *bmp3* regulates neural crest cell-mediated choroid fissure closure.

To determine whether pSmad3 is present in cells in the vicinity of periocular neural crest cells, we performed pSmad3 immunofluorescence on *Tg(sox10:EGFP)* embryos, a strain that specifically labels migratory neural crest cells. It has previously been shown that periocular neural crest cells are readily apparent in the choroid fissure at 28-30 hpf (Bernstein et al., 2018; Gestri et al., 2018; James et al., 2016). Therefore, to assess the state of phosphorylated Smad3 in the context of neural crest cells, pSmad3 immunofluorescence was conducted on wildtype *Tg(sox10:EGFP)* embryos at 24, 28, and 32 hpf. We observe neural crest cells in close proximity to the choroid fissure and in the choroid fissure itself at 24, 28, and 32 hpf (Figure 7A, D, and G). At 24 hpf, neural crest cells have initiated infiltration of the choroid fissure (Figure 7A). At this time, there is also a small amount of retinal pSmad3 in the proximal retina, suggesting that 24 hpf is one of the earliest stages when TGF- β signaling is active in the choroid fissure (Figure 7B). Moreover, the appearance of this early population of neural crest cells coincides with the first appearance of pSmad3 in the retina (Figure 7C). At 28 hpf, the choroid fissure and ventral eye have become highly infiltrated with neural crest cells, and within the choroid fissure neural crest cells appear to completely wrap around both lobes of the choroid fissure, namely the nasal lobe (Figure 7D), and pSmad3 is readily detectable in the ventro-nasal retina and ventral POM (Fig 7E, F). At 32 hpf, neural crest cells are still present in the choroid fissure in numbers comparable to that of 28 hpf (Figure 7G). A fraction of these cells have migrated dorsally behind the lens, where they form pericytes that line the hyaloid vasculature that forms here (Figure 7G) (Trost et al., 2013). At this stage, ventro-nasal retinal pSmad3 has faded; the only detectable pSmad3 in the eye

corresponds to the proximal lens tissue (Figure 7H). There is no longer a clear domain of neural crest cells that colocalize with the pSmad3 signal (Figure 7J). Taken together, this data suggests that neural crest cells may be regulated by TGF- β ligands in the ventro-nasal retina at 28hpf.

Bmp3 regulates neural crest cell numbers in the choroid fissure

Given that Smad3 phosphorylation is active in neural crest cells and that Bmp3 appears to regulate fissure closure via Smad3 phosphorylation, we hypothesized that Bmp3 is a regulator of periocular neural crest function. To test this, we crossed our *bmp3*^{-/-} mutant line to our *Tg(sox10:EGFP)* transgenic line of zebrafish, which fluorescently label neural crest cells. In wildtype embryos, we observe many neural crest cells lining the fissure, particularly around the nasal lobe at 28 hpf (Figure 7J) (n=18 eyes). In contrast, there are visibly fewer neural crest cells in the ventral eye of *bmp3*^{-/-} mutant embryos (Figure 7K) (n=18 eyes). When quantified, the average number of neural crest cells in the choroid fissure is significantly reduced in *bmp3*^{-/-} mutants (6.56 ± 1.04 cells) when compared to wildtype animals (10.0 ± 1.00 cells) (student's t-test, $t_{34} = 4.76$, $p < 0.0001$, Figure 7L). This suggests that Bmp3 regulates the number of neural crest cells in the choroid fissure at 28 hpf, a timepoint that is critical for choroid fissure morphogenesis and closure.

Discussion

Despite being a significant cause of pediatric blindness, the genetic origins of coloboma are still incompletely understood. Here, we identify and characterize the role of *BMP3* in ocular morphogenesis and coloboma for the first time. Using both human patient data and zebrafish experimental evidence, we show that *BMP3* regulates choroid fissure closure through non-canonical Smad3 phosphorylation. We also provide evidence for *BMP3* regulating choroid fissure closure via the periocular mesenchyme, a process that remains poorly understood.

Studies performed using human patient data and model organisms have identified a number of loci that are involved in coloboma, collectively referred to as “the coloboma gene network” (Williamson & FitzPatrick, 2014). Notably, genes that are overrepresented in this network encode components and downstream targets of developmental signaling pathways. This includes the TGF- β /BMP, sonic hedgehog, retinoic acid, fibroblast growth factor, and Wnt pathways (ALSomiry et al., 2019; Patel & Sowden, 2019). This overrepresentation highlights the importance of developmental signaling pathways in ocular development, choroid fissure closure, and organ morphogenesis in general. This, in part, led us to choose *BMP3* as a candidate for investigation; BMPs have well characterized roles in the patterning of multiple organs, including the eye (Peters & Cepko, 2002). Although some other candidates identified by WES are expressed in the developing eye, we were able to systematically eliminate them as candidates, as mutations in these genes are not significant contributors to MAC. Moreover, *BMP3* remained the most likely candidate due to its previously established role as a developmental signaling molecule (Bahamonde & Lyons, 2001; Daluiski et al., 2001). In addition to the *BMP3* variant identified by our WES experiments (A470P), the two additional *BMP3* variants (S393F and F450Y) identified from Sanger sequencing 154 unrelated MAC patients strongly suggests that *BMP3* is a locus involved in the etiology of coloboma. These variants are extremely rare, suggesting that they are not benign variants found in the general population; rather, it is likely that these variants contribute to the etiology of MAC in these patients. This is supported by both predictive algorithms of protein folding and cell secretion assays, which show that at least two of the variants, A470 and S393, result in the absence of these variant proteins from the media of COS-7 cells. Both A470 and S393 are located near cysteine residues that participate in the disulfide bonds that are critical for the stability of mature BMP3 dimers. Consistent with this, there is another variant at the A470 residue listed in gnomAD (p.Ala470Thr) that is rare (7/75 435 individuals) and is predicted by SIFT and PolyPhen2 to be damaging to protein structure and, therefore disease causing, further suggesting that the A470 residue is essential for BMP3 protein structure and function. Therefore, the presence of amino acid substitutions at either of these residues may result in aberrant cysteine knot formation, resulting in lowered extracellular stability of BMP3 and thus its absence from the cell culture media (Goebel et al., 2019). Surprisingly, we do not observe any secretion aberrancies when the F450Y variant is present in the BMP3 protein. Although aberrant secretion or stability of BMP3-F450Y is likely not contributing to its pathogenicity, this residue is located in close proximity to the receptor-

biding domain of the BMP3 protein (Allendorph, Isaacs, Kawakami, Izpisua Belmonte, & Choe, 2007). The receptor binding domain of BMP3 is extremely sensitive to amino acid composition, and single amino acid substitutions have been shown to reduce its affinity for its receptor (Allendorph et al., 2007). This evidence strongly suggests that the patient variants identified through WES and Sanger sequencing have deleterious consequences to protein activity, further implicating *BMP3* as a novel coloboma-causing locus.

We show that zebrafish *bmp3*^{-/-} mutants have an incompletely penetrant coloboma phenotype. Additionally, we show that this phenotype is a delay in fissure closure, as all *bmp3*^{-/-} mutants assayed have closed fissures at 72 hpf. The nature of the choroid fissure closure defects observed in these mutants may give some indication as to *bmp3*’s role in fissure closure. It has been proposed that coloboma can be broadly separated into two classes: morphogenetic coloboma, which arises from defects the morphogenesis of the eye cup, and fusion defective coloboma, which arises from defects in degradation of the basal lamina or adhesion of the retinal cells that make up the choroid fissure (Eckert, Knickmeyer, & Heermann, 2020; James et al., 2016). Eyes from *bmp3*^{-/-} mutants are not smaller in size than those from wildtype embryos, and the fissure lobes are fully apposed without any gross morphological defects, suggesting that *bmp3* is not a regulator of early ocular morphogenetic events such as optic vesicle evagination or choroid fissure formation, as perturbations to these process usually cause overt morphological defects such as microphthalmia and severe, very obvious coloboma (Patel & Sowden, 2019). Due to the subtlety of the choroid fissure closure defects in *bmp3* mutants, it is more likely that *bmp3* facilitates processes that occur later in choroid fissure closure, such as basement membrane breakdown or intercalation of the retinal cells that make up the lobes of the choroid fissure. Indeed, the phenotypes of *bmp3* mutants resemble other zebrafish models of defective basement membrane degradation and cellular intercalation, further suggesting that *bmp3* plays a role in these processes (Hardy et al., 2019; James et al., 2016).

Previous studies of *bmp3* function have shown that it non-canonically activates the phosphorylation of Smad2/3 rather than Smad1/5/8 (Bahamonde & Lyons, 2001; Daluiski et al., 2001; Stewart et al., 2010). We show that *bmp3* is likely facilitating choroid fissure closure through this mechanism, as indicated by the presence of phospho-Smad3 adjacent to the fissure and the increased sensitivity of *bmp3*^{-/-} embryos to SIS3. Recent work on zebrafish has shown that there are other TGF- β ligands expressed in the fissure, and that TGF- β signaling is active in the fissure at the same time we detect phospho-Smad3 in the retina (Knickmeyer et al., 2020). Therefore, *bmp3* may act in concert with other TGF- β ligands to facilitate choroid fissure closure (Knickmeyer et al., 2020). The mechanism behind this process is still not clear; others have proposed that TGF- β signaling via Smad2/3 phosphorylation in the fissure promotes the expression of BMP antagonists which leads to the inhibition of dorsal BMP signaling (Knickmeyer et al., 2020). This thereby creates a restricted domain of BMP expression in the dorsal eye and conferring dorsal identity (Knickmeyer et al., 2020). Indeed, BMP3 has been shown to inhibit both canonical BMP signaling and Activin signaling (Gamer, Nove, Levin, & Rosen, 2005; Knickmeyer et al., 2020). This mechanism has also been well documented in other developmental processes including axis patterning and gastrulation (Little & Mullins, 2006). However, this is somewhat at odds with our results; we do not observe any changes to the expression of dorsal markers, especially *tbx5a*, which is a direct transcriptional output of BMP signaling in the dorsal eye, suggesting that *bmp3* doesn’t antagonize dorsal BMP signaling. Therefore, more research is needed to determine the precise pathway through which Bmp3 inhibits canonical BMP signaling in eye development.

Interestingly, *bmp3* is not expressed in the dorsal eye like other ocular BMP ligands, such as *gdf6a* (French et al., 2009; Gosse & Baier, 2009). Rather, it is expressed in the ventral head mesenchyme adjacent to the fissure. The head mesenchyme is populated by both cranial neural crest cells and paraxial and splanchnic mesoderm (Creuzet et al., 2003; Gage et al., 2005). Accordingly, there has been evidence that *bmp3* functions in both the mesoderm and the cranial neural crest; *bmp3* expression has been detected in the tail paraxial mesoderm of zebrafish and has also been shown to be a regulator of neural crest-derived craniofacial structures (Mueller, Huang, & Ho, 2010; Schoenebeck et al., 2012). Here, we provide evidence that *bmp3* is a regulator of cranial neural crest cells rather than cranial mesoderm, as indicated by microCT scans of adult fish and Alcian blue staining of larval jaw cartilage. Although this is consistent with other reports of *bmp3* function,

we find that the larval mutant phenotypes are far less severe and have lower penetrance than previously reported (Schoenebeck et al., 2012). However, these previous studies were performed using morpholino oligonucleotides, which have been shown to produce more severe phenotypes when compared to mutants (Eve, Place, & Smith, 2017). Regardless, we provide further evidence that *bmp3* regulates neural crest-derived structures and is novel regulator of craniofacial development, particularly structures that contribute to the jaw. This is somewhat unsurprising, as craniofacial abnormalities and coloboma commonly occur together in syndromes including CHARGE syndrome and BOFS syndrome (Gestri et al., 2009; Siebert, Graham Jr, & MacDonald, 1985). These studies, together with our own studies of *BMP3*'s involvement in coloboma, suggest that there is likely a shared neural crest-derived etiology of coloboma and craniofacial abnormalities in many contexts (Bajpai et al., 2010; Gestri et al., 2009). Moreover, it wouldn't be entirely surprising to find craniofacial abnormalities in patients with damaging mutations in *BMP3*, given that we see craniofacial abnormalities in our zebrafish model. In our studies of cartilage development in *bmp3*^{-/-} mutants, we observe jaw chondrocytes that are less organized and undifferentiated when compared to wildtype controls, suggesting that *bmp3* doesn't affect the migration of neural crest cells to form the cartilage, but rather regulates the differentiation of cranial neural crest cells into chondrocytes. Moreover, only anterior structures derived from pharyngeal arch 1 and 2 (such as Meckel's cartilage, the palatoquadrate, and the ceratohyal) are affected, whereas structures derived from the more posterior pharyngeal arches 3-7 (such as the ceratobranchials) remain largely unaffected, suggesting that *bmp3*'s role on craniofacial development is restricted to the neural crest cells of the first pharyngeal arch; indeed, other studies of *bmp3*'s role on craniofacial development found its expression to be highest in the anterior pharyngeal arches and lower or absent in the more posterior arches (Schoenebeck et al., 2012). This suggests that *bmp3* may be regulating the differentiation of arch 1 and 2 neural crest cells, and the absence of *bmp3* in the first arch results in undifferentiated chondrocytes and, thus, the craniofacial defects we observe in *bmp3*^{-/-} mutants. Alternatively, *bmp3* could be regulating cranial neural crest cell division, survival, or death; a lack of *bmp3* results in an incorrect number of chondrocyte precursors, which, ultimately, results in disorganization of the cartilage seen in *bmp3* mutants. Consistent with this, there appears to be more chondrocytes present in the jaws of *bmp3*^{-/-} mutants. Once the cranial neural crest cells condense into cartilage, convergence extension elongates the chondrocytes and facilitates chondrocyte stacking (Kimmel et al., 1998). Other studies have shown that disrupting genes necessary for convergence extension results in jaw phenotypes similar to *bmp3*^{-/-} mutants, suggesting that *bmp3* could have a role in regulating the number of cells necessary for convergence extension to occur properly (Rochard et al., 2016). Further research is needed to establish the precise role of *bmp3* in craniofacial development and cranial neural crest function.

In addition to regulating the neural crest-derived craniofacial skeleton, we also show that *bmp3* regulates periocular neural crest cells during choroid fissure closure. There have been several studies that have shown that these populations of cells are necessary for choroid fissure closure, further solidifying the role of these cells as necessary mediators of choroid fissure closure (Gestri et al., 2018; James et al., 2016). This is also supported by our studies, where ventral periocular neural crest cells colocalize with pSmad3 signal, suggesting that neural crest cells are responsive to TGF- β signaling. This is in agreement with other studies of periocular neural crest cells and TGF- β signals, which show that neural crest-specific deletion of *Tgfbbr2* results in compound ocular defects in mice (Ittner et al., 2005). Therefore, this represents a plausible mechanism for TGF- β signaling in the eye, where cranial neural crest cells are responsive to Bmp3 and potentially other TGF- β ligands. This also fits with our model of Bmp3 facilitating later stages of choroid fissure closure; although some reports of neural crest-mediated choroid fissure closure have shown that periocular neural crest cells are necessary for early eye vesicle morphogenesis, others have proposed that neural crest cells are necessary for later stages of choroid fissure (Bryan et al., 2020; Gestri et al., 2018; Hardy et al., 2019; James et al., 2016). We also observe a reduction in the number of neural crest cells in the choroid fissures of *bmp3*^{-/-} mutants at 28 hpf, suggesting that Bmp3 regulates the number of neural crest cells in the choroid fissure. However, it is unclear whether Bmp3 regulates neural crest number, guidance, or differentiation. Previous reports and our own studies of Bmp3 function in craniofacial development have shown that the neural crest-derived craniofacial cartilage is severely reduced in *bmp3* morphants, suggesting that *bmp3* plays a role in neural crest differentiation (Schoenebeck et al., 2012). In contrast, other reports

of periocular neural crest migration suggest that TGF- β signals emanating from the lens regulate periocular neural crest migration into the anterior segment (Takamiya et al., 2020). Therefore, it is plausible that ocular TGF- β signals are also necessary for facilitating migration of periocular neural crest cells into the choroid fissure.

In summary, we present the discovery of a novel locus involved with choroid fissure closure, *BMP3*. We have shown that BMP3 likely facilitates fissure closure through Smad3 phosphorylation, and we also provide evidence that BMP3 may regulate periocular neural crest cells during the process of fissure closure. Although the present study has advanced our understanding of choroid fissure closure biology and, thus, coloboma, further work will need to be done to identify additional loci that are involved in this process. Additionally, more investigation is warranted to identify and characterize loci that are expressed by the periocular mesenchyme and their role in choroid fissure closure as well as paracrine factors that regulate the periocular mesenchyme which will, in turn, inform our understanding of vertebrate ocular morphogenesis.

Materials and Methods

Ethics Statement

Embryonic, larval, and adult zebrafish were cared for according to guidelines set by the Canadian Council of Animal Care and protocols were approved by the University of Alberta's Animal Care and Use Committee (Protocol #427).

Whole exome and Sanger sequencing of human patient DNA

Whole exome sequencing (WES) was performed on genomic DNA from each proband as

part of FORGE Canada Consortium at the McGill University and Genome Quebec Innovation Centre. Exome target enrichment was performed using the Agilent SureSelect 50Mb (V3) All Exon Kit and sequencing was performed on the Illumina HiSeq 2000, multiplexing three samples per lane. The mean coverage of coding sequence regions, after accounting for duplicate reads was greater than 70x. WES data was analyzed by performing alignment with BWA, duplicate read removal with Picard, local indel realignment with GATK, variant calling with SAMtools, and annotation with Annovar and custom scripts.

For Sanger sequencing of the MAC patient cohort unrelated to individuals in the pedigree from Figure 1, intronic primers were used to amplify *BMP3* in 154 patients with MAC. The amplicons were then purified and sent for Sanger sequencing at the at the Genome Quebec Innovation Centre.

Zebrafish husbandry

Adult zebrafish were kept on a 10-hour dark/14-hour light schedule. Embryos were raised at 25.5°C, 28.5°C or 33°C in embryo media and staged according to standardized developmental hallmarks (Kimmel, Ballard, Kimmel, Ullmann, & Schilling, 1995). Embryos that were grown past 24 hpf were treated with 0.004% 1-phenyl 2-thiourea (PTU, Sigma Aldrich P7629) prior to 22hpf to block pigment formation. Anesthesia of larval and adult zebrafish was performed with a 4% dilution of 0.4% tricaine methanesulfonate (TMS) stock solution (Sigma Aldrich E10521). The AB wildtype strain, the *bmp3*^{-/-} mutant line, and the *Tg(sox10:EGFP)* transgenic line were used. The *bmp3*^{-/-} line contains two in-frame 3 base-pair (bp) deletions (NM_001077765.1:c.543_545del and NM_001077765.1:c.840_842del) and a 5bp deletion (NM_001077765.1:c.886_890del). Both of the 3bp deletions cause the deletion of a single glutamine residue (NP_001071233.1:p.Gln182del and NP_001071233.1:p.Gln281del). The 5bp results in a frameshift and premature stop codon upstream of the mature TGF- β signaling domain (NP_001071233.1:p.Thr296GlyfsTer2).

Atomic Non-Local Environment Assessment (ANOLEA)

Using the previously solved crystal structure for BMP3, the effect of patient amino acid substitutions on protein function were modeled *in silico* using Swiss-pdb Veiwier and analyzed using the ANOLEA server (<http://melolab.org/anolea/>) (Allendorph et al., 2007; Melo, F., Devos, D., Depiereux, E., Feytmans, 1997).

Using the ANOLEA data, the difference in energy requirement needed to fold the BMP3 protein with each amino acid substitution was plotted in Microsoft Excel.

Site-directed mutagenesis

The open reading frame for wildtype human *BMP3* was obtained from ASU BioDesign Institute in pDNR-Dual and was moved into pcDNA3.2/V5. Oligonucleotide primers for site-directed mutagenesis were designed to generate constructs carrying c.1178C>T (p.S393F), c.1349T>A (p.F450Y), and c.1408G>C (p.A470P) variants individually. The PCR reaction for site-directed mutagenesis contained: 500 ng of template plasmid DNA, 17 μ l of master mix (100 μ l 10x PFU buffer, 792 μ l water, 2 μ l each of 100 mM dNTPs), 1 μ l (10 mM) NAD, 0.5 μ l (200 ng) each primer, 0.5 μ l DMSO, 0.3 μ l Taq DNA Ligase (NEB, M0208S), 1 μ l PfuUltra DNA Polymerase (Agilent, 600670), and 1.5 μ l water. The PCR cycle conditions were denaturation at 95°C for 2 mins, then 30 cycles of 95°C for 1 min, 55°C for 1 min, and 65°C for 10 mins. PCR products were then digested with 1 μ l of DpnI (NEB, R0176S) for 30 mins at 37°C to digest the original plasmid. Constructs were verified by Sanger sequencing to ensure the mutation was introduced correctly. DNA for the four constructs was isolated by maxi prep (Qiagen, 12165) and Sanger sequenced to confirm the mutation sites.

Tissue Culture and Immunoblotting

COS-7 cells were plated to 6-well dishes and transfected at 80% confluency. 3 μ g of DNA was transfected per well using Lipofectamine 2000 (ThermoFisher Scientific, 12566014) according to the manufacturer's instructions. Transfected cells were grown in low serum (0.1%) conditions for 48 hours and then harvested. Media was removed and saved for secreted protein analysis. Cell monolayers were rinsed once in phosphate buffered saline (PBS), and 500 μ l of cold lysis buffer was added. Lysis buffer components were 50mM Tris, 150mM NaCl, 1mM EDTA, 1.5% SDS, and one cComplete mini protease inhibitor tablet (Millipore/Sigma 11836170001), pH7.5. Cells sat on ice for 10 minutes and were then scraped and collected in Eppendorf tubes. Samples were boiled, transferred to QiaShredder tubes (Qiagen, 79656), centrifuged, and the flow-through was collected in new tubes. Proteins from media were concentrated by acetone precipitation (1:1.5 media to acetone volume) and air dried. A minimal volume of lysis buffer was added to resuspend the pellets. Protein concentration was determined using the Bradford colorimetric protein assay (BioRad, 5000201). Cell lysates and concentrated media lysates were run on 4-12% Bis-Tris gradient gels (Invitrogen NP0336) for 1 hour at 200 volts. Resolved proteins were transferred to polyvinylidene difluoride (PVDF) membranes (Millipore IPVH00010) at 22 volts for 1 hour on a semi-dry blotter (Amersham Biosciences). Blots were blocked in 5% milk in Triton buffered saline with Tween 20 (TBST) for 2 hours and primary antibody was added for overnight incubation at 4°C. Mouse monoclonal anti-V5 primary antibody (ThermoFisher, MA5-15253) was used at 1:5000 dilution in 5% milk and mouse monoclonal anti-tubulin primary antibody (Sigma, T9026) was used at 1:10,000. After washing, sheep anti-mouse IgG HRP-conjugated secondary (Amersham, NA931) was added at 1:5000 for 1 hour at room temperature. Membranes were washed in SuperSignal West Pico PLUS ECL reagent (ThermoFisher, 34577) for 3 minutes and detection was performed using the ChemiDoc MP Imaging System (BioRad).

CRISPR/Cas9 Mutagenesis

Short guide RNA (sgRNA) design and synthesis were performed as previously described (Gagnon et al., 2014). The sequences for the oligonucleotides used to generate the templates for sgRNA synthesis are: 5'-GGGACTTCATCTCATGGCAGTGG-3', 5'-GGGAGCTCATTGTTCTGCAGTGG-3' and 5'-GGCTGGCCTCATCCCATGTAGGG-3'. Cas9 protein (PNA Bio, CP01) was reconstituted in sterile water to a concentration of 50 μ g/mL and 2 μ L was mixed with 1 μ L of each sgRNA. One- or Two-cell stage embryos were injected with 1nL of Cas9/sgRNA mixture and allowed to develop to sexual maturity. Carriers for frameshift mutations were identified by high resolution melt (HRM) analysis using the Type-It HRM PCR kit (Qiagen, 206544) on a Rotor Gene Q qPCR machine (Qiagen, 9001560) and Sanger sequencing.

Zebrafish genotyping

bmp3^{-/-} mutants were genotyped using polymerase chain reaction (PCR) followed by gel electrophoresis.

Genomic DNA was extracted from fin clips in 20 μ L of 50mM NaOH at 95°C for 15 minutes and subsequently neutralized using 2 μ L Tris-HCl, pH 8.0. Samples were diluted 1/2 in sterile water and used as template for PCR using the following primers: Forward: 5'-CTTCATATGCTGGAATCGCATAAC-3', Reverse: 5'-TTGCTCTCCATCGGATCATAAG-3'. PCR was performed using the following conditions: Denaturation at 94°C for 2 minutes, 40 cycles of 94°C for 15 seconds, 58°C for 15 seconds, and 72°C for 12 seconds, followed by a final extension cycle at 72°C for 3 minutes. PCR products were then run on a 3% agarose gel to resolve the wildtype and mutant amplicons (167bp and 156bp, respectively).

In-situ hybridization

Antisense riboprobes labeled with digoxigenin (DIG) were synthesized from purified, linearized expression plasmid containing a gene-specific insert or from a gene-specific PCR product with an integrated T7 RNA polymerase site. Probe synthesis was performed as previously described (Thisse & Thisse, 2008).

Embryos were fixed overnight at 4°C in 4% paraformaldehyde (PFA) and subsequently permeabilized for 5 minutes at room temperature (RT) using 10 μ g/ml Proteinase K in PBST. *In-situ* hybridization was performed as previously described except probes were not hydrolyzed (Prince, Moens, Kimmel, & Ho, 1998). For experiments analyzing *bmp3* expression, embryos were either manually de-yolked and flat-mounted under a coverslip in 70% glycerol or embedded in paraffin wax, sectioned, and mounted under a coverslip using Dibutylphthalate Polystyrene Xylene (DPX) mountant. Flat-mounts and sections were imaged on a Zeiss Axiomager Z1 compound microscope with Axiocam HR digital camera. For experiments analyzing *tbx5a*, *alhd1a2*, *vax2* and *alhd1a3* expression, embryos were mounted in 3% methyl-cellulose on a spot plate and imaged with an Olympus SZX12 stereomicroscope and Qimaging micropublisher camera.

Immunofluorescence

For laminin immunofluorescence, embryos were fixed in 4% PFA for two hours at RT. Embryos were permeabilized with 10 μ g/ml Proteinase K for 30 minutes. After permeabilization, embryos were blocked for at least 1 hour at RT using 5% normal goat serum and 2% bovine serum albumin (BSA) in PBST. Embryos were incubated O/N in rabbit anti-laminin primary antibody diluted in block (1:200, L-9393, Sigma-Aldrich). After washing, embryos were incubated for 2 hours at RT in goat anti-rabbit Alexa Fluor 555 secondary antibody (1:1000, A32732, Invitrogen).

For Phosphorylated Histone H3 immunofluorescence, embryos were fixed in 4% PFA for two hours at RT. Embryos were permeabilized in ice-cold acetone for 7 minutes at -20°C. After permeabilization, embryos were incubated in 10mM citric acid at 95°C for 10 minutes for antigen retrieval. Embryos were then blocked in 3% BSA in 0.5% TritonX-100 in PBS for 1 hour at RT. Embryos were then incubated in rabbit anti-phospho-Histone H3 antibody (1:1000, ab183626, Abcam) O/N at 4°C, washed, and incubated in goat anti-rabbit Alexa Fluor 488 secondary antibody (1:1000, A32732, Invitrogen) plus TO-PRO-3 (1:1000, T3605, Invitrogen) for 2 hours at RT.

For cleaved Caspase 3 immunofluorescence, embryos were fixed in 4% PFA for two hours at RT. Embryos were permeabilized with ice-cold acetone for 7 minutes at -20°C. After permeabilization, embryos were blocked in 5% goat serum (GS) in PBS/DTT (PBST + 1% DMSO + 0.1% TritonX-100) for 2 hours at RT. Embryos were then incubated in rabbit anti-cleaved-Caspase3 (1:400, 559565, BDBiosciences) O/N at 4°C, washed, and incubated in goat anti-rabbit Alexa Fluor 488 secondary antibody (1:1000, A32732, Invitrogen) plus TO-PRO-3 (1:1000, T3605, Invitrogen) for 2 hours at RT.

For phosphorylated Smad3 (pSmad3) immunofluorescence, embryos were fixed overnight at 4°C. Embryos were permeabilized with 10 μ g/ml Proteinase K for 5 minutes. After permeabilization, embryos were incubated in 4% BSA in 0.15% TritonX-100 in PBS. Embryos were incubated in rabbit anti-pSmad3 primary antibody (1:200, ab59203, Abcam) O/N at 4°C, washed, and incubated in goat anti-rabbit Alexa Fluor 488 or 568 secondary antibody O/N at 4°C (1:1000, A32732, Invitrogen).

After immunofluorescence was performed, embryos were washed and passed through a 30, 50, and 70% glycerol series. Eyes and the surrounding head mesenchyme were dissected from whole embryos and mounted

in 70% glycerol on a glass slide. All immunofluorescence experiments were imaged using a Zeiss AxioImager Z1, Zeiss LSM700 laser scanning confocal microscope.

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To inhibit TGF- β signaling, Specific Inhibitor of Smad3 (SIS3) was used (566405-1MG, Calbiochem). The structure and activity of SIS3 has been described elsewhere (Jinnin, Ihn, & Tamaki, 2006). 1mg of SIS3 was resuspended in DMSO to a stock concentration of 3mM, aliquoted, and stored at -20°C. Prior to treatment, the stock was mixed with pre-warmed embryo media to a final concentration of 12 μ M. For controls, an equivalent volume of DMSO alone was added to pre-warmed embryo media. Embryos were stage-matched at 10 hpf. At 24 hpf, embryos were de-chorionated, transferred to 35mm petri dishes in groups of 15 embryos per dish, and 5 mL of SIS3- or DMSO-treated media was added to the appropriate dishes. Embryos were incubated for six hours at 28.5°C until 30 hpf. The media was then removed, embryos were washed 3 times with fresh embryo media, and all dishes were returned to 28.5°C. Embryo media was changed at 48 hpf, and embryos were fixed at 72 hpf for 2 hours at RT with 4% PFA. Embryos were then used for laminin immunofluorescence. Eyes from these embryos were then dissected, mounted on glass slides in 70% glycerol, and imaged using a Zeiss AxioImager Z1, Zeiss LSM700 laser scanning confocal microscope.

Micro-computed tomography (micro-CT) of adult zebrafish

18-month-old wildtype (n=5) and *bmp3*^{-/-} (n=5) zebrafish were scanned using MILabs μ CT at the School of Dentistry, University of Alberta. Zebrafish were fixed at 4% PFA for 24 h. The parameters for scanning and reconstruction were conducted as previously described (Miyashita et al., 2020). AVIZO (Life Technologies) software was used to visualize and quantify premaxilla, maxilla, and mandible length. Landmarks used to quantify the midfacial region are demonstrated in Figure S7.

Alcian blue staining of larval zebrafish

Alcian blue staining of 7 dpf larval zebrafish was performed as previously described, except Alizarin red staining was not performed (Walker & Kimmel, 2007). Briefly, larval zebrafish were euthanized using a 4% dilution of 0.4% TMS and fixed in 1% PFA for one hour at RT. Embryos were washed for 10 minutes in 10 mM MgCl₂ buffered with 100 mM Tris pH 7.5, and then stained overnight in 0.04% Alcian blue staining solution. Embryos were removed from staining solution, rehydrated, bleached for 10 minutes in 3% H₂O₂/0.5% KOH, and de-stained with two 10-minute washes of 25% Glycerol/0.1% KOH and two 10-minute washes of 50% Glycerol/0.1% KOH. Embryos were then transferred to 70% glycerol and mounted on glass slides for imaging. Images were taken using a Zeiss AxioImager Z1 compound microscope with Axiocam HR digital camera.

Statistical analysis

Statistical significance was determined using a two-proportion z-test (Figure 5) or an unpaired t-test (Figure 5, 6, and 7). Quantitative results are presented as percentage or mean $\pm$ S.E.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Legends to Figures

Figure 1. *BMP3* missense mutations identified in patients with ocular coloboma and microphthalmia.

A) Four-generation pedigree of a family with autosomal dominant coloboma and/or microphthalmia. Whole exome sequencing (WES) was performed on DNA samples from specified individuals (arrows), and identified variants were filtered according to standardized criteria (flow chart, right). WES identified a variant in *BMP3*(c.1408G>C), and two additional variants were identified from Sanger sequencing of an independent cohort of unrelated patients (c.1178C>T and c.1349T>A). Below, chromatograms showing DNA sequence variants indicated by their base change within the coding sequence of *BMP3*. **B**) Schematic of the *BMP3* cDNA and protein, with the position of each nucleotide variant and resulting amino acid substitution indicated. (SP=signal peptide, ORF=open reading frame). **C**) Immunoblots for V5-tagged *BMP3* wildtype

and variants. Cos-7 cells were transfected with equal amounts of plasmid DNA encoding V5-tagged BMP3 proteins, then immunoblots were performed on protein extracted from either the culture media or cell lysates. Immunoblots performed on cell lysates (top, V5-lysate) show that all BMP3 proteins are made in approximately equal amounts, but those performed on protein extracted from the culture media (middle, V5-secreted) demonstrate that the S393F and A470P variants, but not F450Y, result in reduced secretion of BMP3 protein. **D**) Quantification of three independent immunoblots. Band intensity for V5-secreted WT, S393F, F450Y, and A470P was measured using ImageJ software and the fold change in intensity for S393F, F450Y, and A470P was calculated relative to WT. Quantification indicates that the bands for V5-secreted S393F, F450Y, and A470P variants display a 0.18, 1.71, and 0.04-fold change in intensity relative to WT. Results are representative of three independent experiments and immunoblots. (NTC=no transfection control, kDa=kilodaltons).

Figure 2. Zebrafish with mutations in *bmp3* exhibit delayed fissure closure.

A) Partial coding sequence alignment of wild type and *bmp3*^{gua1020} mutant zebrafish (top) and schematics of each resulting protein (bottom). A 5bp deletion (c.887_891del) was generated with CRISPR-Cas9, resulting in a frameshift and subsequent premature stop codon (p.Thr96GlyfsTer2). The resulting truncated protein lacks the entire TGF- β mature domain. (SP=Signal peptide) **(B-E)**) Larvae from *abmp3*^{-/-} heterozygous incross were fixed at 48 or 65 hpf and laminin immunofluorescence was conducted to visualize the extracellular matrix. Eyes were manually dissected and mounted in pairs, then imaged on a confocal microscope. Both wild type and *bmp3* mutant larvae at 48 hpf (B,C) show fissure lobes in apposition but incomplete fissure closure (indicated by arrows). In contrast, at 65 hpf (D,E) wild type larvae have completed fissure closure, while 23/130 *bmp3* mutants show bilateral open fissures (arrowheads). **F**) Quantification of fissure phenotypes in B-E, showing 18% bilateral open fissures in *bmp3* mutant larvae at 65 hpf. (WT=Wild-type, Open=Open choroid fissures, Closed=Closed choroid fissures).

Figure 3. *bmp3* is expressed in the periocular mesenchyme during ocular morphogenesis.

Whole mount *in situ* hybridization was conducted on wildtype embryos to assess the localization of *bmp3* mRNA during early ocular morphogenesis. **A**) Dorsal view of dissected and flat mounted embryo at 22 hpf. *bmp3* expression is localized head mesenchyme between the retina and the forebrain. **B-D**) Embryos were embedded in paraffin wax after *in situ* hybridization, then sectioned and mounted on slides. Coronal sections through the middle of the optic cup (B) show *bmp3* expression in a single cell-thick layer in the head mesenchyme directly ventral to the eye. Transverse sections (C, D) show that *bmp3* transcript is specifically expressed in the head mesenchyme between the forebrain and the retina. The box in C indicates the area magnified in D. (A=anterior, P=posterior, D=dorsal, V=ventral, le=lens, br=brain, ret=retina).

Figure 4. *bmp3* does not regulate dorsal-ventral patterning, cell proliferation or apoptosis of the optic cup .

A-H) To assess dorsal-ventral patterning of the optic cup in wildtype and *bmp3* mutants, whole mount *in situ* hybridization was conducted on 22 hpf embryos from *abmp3*^{+/-} incross, using probes for transcripts that provide a readout of dorsal (*tbx5a*, *aldh1a2*; A-D) and ventral (*vax2*, *aldh1a3*; E-H) optic cup identity. The expression of dorsal and ventral genes in *bmp3*^{-/-} mutants (B, D, F and H) is comparable in both intensity and domain to wildtype embryos (A, C, E and G). Embryos were imaged laterally in 3% methylcellulose on a dissecting microscope then used for genomic DNA extraction and genotyping (n=25/probe-genotype combination). **I-L**) To assess proliferation and apoptosis of the optic cup in wildtype and *bmp3* mutants, phosphorylated Histone H3 and cleaved Caspase 3 immunofluorescence was conducted on wildtype and *bmp3*^{-/-} mutant embryos at 28hpf. There is no observable difference in proliferation between wildtype (I) and *bmp3*^{-/-} mutant (J) embryos (n=20/genotype), nor is there an observable difference in the amount of apoptosis in the optic cup of wildtype (K) or *bmp3*^{-/-} mutant (L) embryos (n=19/genotype). (pHH3=phospho-Histone H3, c-Casp3=cleaved Caspase 3).

Figure 5. Smad3 phosphorylation is necessary for choroid fissure closure.

A-C) pSmad3 immunofluorescence conducted on wildtype 28 hpf embryos indicates that TGF- β signaling is active in the nasal lobe of the proximal-ventral eye cup (A, arrowheads) but is largely absent in more distal regions of the choroid fissure (B-C). **D-F**) To assess Smad3 phosphorylation in *bmp3* mutants, pSmad3 immunofluorescence was conducted on *bmp3* mutants (E) and wildtype siblings (D) at 28 hpf. The number of pSmad3+ cells is reduced in *abmp3* mutants when compared to wildtype siblings (arrowheads, quantified in F). **F**) When quantified, there is a significant decrease in the number of pSmad3+ cells in *bmp3* mutants (18.3 ± 1.09 cells) when compared to wildtype (22.2 ± 1.12 cells) (two-sample t-test, $t_{38}=2.49$, $p=0.0172$) **G-I**) Wildtype and *bmp3* mutant embryos were treated with a suboptimal dose ($12\mu\text{M}$) of SIS3 from 24-30 hpf, and the presence of open choroid fissures was assessed using laminin immunofluorescence. Both wildtype and *bmp3*^{-/-} embryos display open choroid fissures when treated with SIS3 (H, arrowhead), compared to embryos treated with vehicle (DMSO) alone (G) (Wildtype embryos shown as an example) **I**) A significantly higher proportion of *bmp3*^{-/-} mutant embryos have open choroid fissures compared to wildtype when treated with SIS3 (two-proportion z-test, $z=-4.32$, $p<0.0001$), suggesting that Bmp3 and Smad3 function in the same pathway. Results are representative of three independent experiments. (WT=Wildtype, Open=Open choroid fissure, Closed=Closed choroid fissure).

Figure 6. *bmp3*^{-/-} mutants have midface hypoplasia.

Dissecting microscope images (**A, B**) and Micro-CT analysis (**C-F**) of 18-month-old wildtype (A, C, D) and *bmp3*^{-/-} (B, E, F) zebrafish demonstrate significantly shorter premaxilla (**G**), maxilla (**H**) and mandible (**I**) in the mutant fish ($n=5$) when compared to wildtype siblings ($n=5$) (two sample t-test, $t_8=2.85$, 6.22 , and 5.50 , $p=0.000255$, 0.0214 , and 0.000573) (WT=wildtype). **J-K'**) Alcian blue staining of craniofacial cartilage in 7 dpf larvae indicates that 40% (8/20) of *bmp3*^{-/-} mutants (K) have disrupted jaw cartilage formation when compared to wildtype (J) larvae (0/20). The overall anatomy of Meckel's cartilage, the palatoquadrate, and the ceratohyal (J and K) as well as chondrocyte organization and morphology (J'-K', arrowheads) are abnormal in a subset of mutants ($n=8/20$) when compared to wildtype controls ($n=0/20$) (M=Meckel's cartilage, Pq=Palatoquadrate, Ch=Ceratohyal).

Figure 7. Bmp3 regulates periocular neural crest cells.

A-I) pSmad3 immunofluorescence was conducted on wildtype *Tg(sox10:EGFP)* transgenic embryos at 24, 28, and 32 hpf. Almost no colocalization of neural crest cells with pSmad3 is seen at 24 hpf (A-C), but at 28 hpf there are several neural crest cells in the ventral eye that colocalize strongly with pSmad3 (D-F, arrowheads). By 36 hpf (G-I), the colocalization between pSmad3 and *sox10* + neural crest cells in the ventral eye has diminished. **J-L**) To assess the effect of *bmp3* on periocular neural crest cells, the number of *sox10*+ cells was examined in *bmp3*^{-/-} mutants (K) and wildtype siblings (J) on a *Tg(sox10:EGFP)* transgenic background at 28 hpf. L) There are significantly fewer neural crest cells in the choroid fissures of *bmp3*^{-/-} embryos (6.56 ± 1.04 cells, $n=18$ eyes) compared to wildtype siblings (10.1 ± 1.00 cells, $n=18$ eyes) (two sample t-test, $t_{34}=4.76$, $p<0.0001$). (WT=wildtype).

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