Tbx20 acts upstream of Wnt signaling to regulate endocardial cushion formation and valve remodeling during mouse cardiogenesis

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SUMMARY

Cardiac valves are essential to direct forward blood flow through the cardiac chambers efficiently. Congenital valvular defects are prevalent among newborns and can cause an immediate threat to survival as well as long-term morbidity. Valve leaflet formation is a rigorously programmed process consisting of endocardial epithelial-mesenchymal transformation (EMT), mesenchymal cell proliferation, valve elongation and remodeling. Currently, little is known about the coordination of the diverse signals that regulate endocardial cushion development and valve elongation. Here, we report that the T-box transcription factor Tbx20 is expressed in the developing endocardial cushions and valves throughout heart development. Ablation of Tbx20 in endocardial cells causes severe valve elongation defects and impaired cardiac function in mice. Our study reveals that endocardial Tbx20 is crucial for valve endocardial cell proliferation and extracellular matrix development, but is not required for initiation of EMT. Elimination of Tbx20 also causes aberrant Wnt/β-catenin signaling in the endocardial cushions. In addition, Tbx20 regulates Left1, a key transcriptional mediator for Wnt/β-catenin signaling, in this developmental process. Our study suggests a model in which Tbx20 regulates the Wnt pathway to direct endocardial cushion maturation and valve elongation, and provides new insights into the etiology of valve defects in humans.

KEY WORDS: Heart development, Cardiac valve, Mouse, Tbx20

INTRODUCTION

Cardiac valves are highly organized, yet delicate structures that ensure unidirectional blood flow through the cardiac chambers and large vessels. Proper formation of the cardiac valves is crucial for normal heart function. Disturbed development of the cardiac valves leads to aberrant heart formation and function, accounting for a large proportion (~25-30%) of congenital heart disease (CHD) in humans (Armstrong and Bischoff, 2004).

The formation of cardiac valves is a dynamic process achieved by a series of complex events including lineage determination, cell proliferation, differentiation and migration. In mammals, the endocardium within the early bilateral heart tube gives rise to the first endocardial cells (Armstrong and Bischoff, 2004). Cardiac valve formation begins with the specification of these endocardial cells (Chakraborty et al., 2010). At embryonic day (E) 9.5-10.5 in mice, endocardium within the atrioventricular canal (AVC) and outflow tract (OFT) gives rise to cushion mesenchymal cells through epithelial-mesenchymal transformation (EMT). These mesenchymal cells subsequently migrate into the cardiac jelly secreted by the overlying myocardial cells to form the endocardial cushions (Person et al., 2005). Between E11.5 and E12.5, cushion mesenchyme undergoes rapid expansion to generate the tissues required for subsequent valve leaflet formation (Person et al., 2005); even at this early stage, the primitive valves are crucial for normal cardiac function. As gestation progresses (E12.5-17.5), the primitive valves elongate and are remodeled to transition from valve primordia to mature valve leaflets (Chakraborty et al., 2010).

The signaling cascades that regulate EMT initiation and mesenchymal cell proliferation during early valve development have been extensively studied (Person et al., 2005). Transcription factors and growth factors in the endocardium and myocardium (Person et al., 2005), as well as the extracellular matrix (ECM) in the cardiac jelly (Hinton et al., 2006), act cooperatively to initiate EMT and mesenchymal cell proliferation. It is far less clear, however, how these diverse signals are integrated to instruct valve elongation and remodeling. Previous studies revealed that Nfatc1, a transcription factor specifically expressed in the endocardium during early cardiogenesis, is required for valve elongation (Chang et al., 2004; de la Pompa et al., 1998; Ranger et al., 1998). Further studies showed that Nfatc1 regulates endocardial cell fate in the allocation of endocardial cells to EMT and valve elongation (Wu et al., 2011). VEGFs also regulate leaflet morphogenesis (Stankunas et al., 2010). The importance of BMP family members in this process is evident from the findings that endocardial deletion of 

Bmpr2 or 

Cxcr7 results in thickened valve leaflets (Beppu et al., 2009; Yu et al., 2011) and that 

Ltbp1L (long form of latent TGFβ binding protein 1) null mice exhibit late stage valve hyperplasia (Todorovic et al., 2011). Cardiac neural crest Pax3 and FGF/BMP signals also mediate the differentiation, remodeling and function of OFT semilunar valves (Jain et al., 2011; Zhang et al., 2010). In addition, both ECM content [e.g. periostin (Postn)] and ECM remodeling play important roles in leaflet development (Dupuis et al., 2011; Kruithof et al., 2007; Snider et al., 2008).
T-box (Tbx) genes encode transcription factors that are essential for proper organogenesis (Naiche et al., 2005). Mutations of T-box genes cause diverse genetic disorders in humans (Packham and Brook, 2003). Tbx20 is an ancient T-box family member whose expression in the heart is highly conserved across species (Griffin et al., 2000; Iio et al., 2001; Kraus et al., 2001; Meins et al., 2000). Previous studies showed that Tbx20 null (Tbx20−/−) mice die at E9.5-10.5 with severely hypoplastic myocardial tubes (Cai et al., 2005, 2012). Tbx20 is also expressed in the avian endocardial cushions and promotes cushion mesenchymal cell proliferation and ECM gene expression in vitro (Shelton and Yutzey, 2007). In addition, myocardial Tbx20 is crucial for early AVC formation and EMT initiation through activation of Bmp2 in mice (Cai et al., 2011). The role of Tbx20 in valve elongation and remodeling in mammals is largely unknown. These imperative questions as human Tbx20 mutations cause CHD with defective valvulogenesis (Kirk et al., 2007; Qian et al., 2008).

In this study, we evaluated Tbx20 expression with Tbx20floxed mice and found that Tbx20 is dynamically expressed in developing valves, including the early cushion endocardium, cushion mesenchyme and mature valve leaflets. To determine whether Tbx20 is required in the endothelium for valve development, we eliminated Tbx20 by crossing Tbx20 floxed mice to an endocardial-specific Cre mouse, Nfatc1Cre (Wu et al., 2012). Our data indicate that endocardial Tbx20 expression is not essential for EMT initiation but is crucial for endocardial cushion maturation and valve elongation. Tbx20 regulates β-catenin pathways (Kirk et al., 2007; Qian et al., 2008). In addition, myocardial Tbx20 is crucial for early AVC formation and EMT initiation through activation of Bmp2 in mice (Cai et al., 2011). The role of Tbx20 in valve elongation and remodeling in mammals is largely unknown. These imperative questions as human Tbx20 mutations cause CHD with defective valvulogenesis (Kirk et al., 2007; Qian et al., 2008).

**MATERIALS AND METHODS**

**Animals**

Tbx20 floxed (Tbx20fl/fl or Tbx20+/−) and heterozygous mice (Tbx20+/−/−) were described previously (Cai et al., 2005). Nfatc1 Cre (Nfatc1fl/fl) knock-in mice were reported recently (Wu et al., 2012). For Tbx20;lacZ/H2BGFP (Tbx20fl/−/H2BGFP) mice, a LoxP-lacZ-polyA-Loxp-H2BGFP-polyA cassette was introduced into the Tbx20 genomic locus (6 bp upstream of the ATG, with removal of exon 1 coding sequences). Mice derived from the positive embryonic stem cells (ESCs) were crossed to Flippase mice (Farley et al., 2000) to remove the Neo cassette. Tbx20;H2BGFP (Tbx20fl/−/H2BGFP) mice were obtained by crossing Tbx20fl/−/−;H2BGFP mice to Protamine-Cre mice (O’Gorman et al., 1997) to excise the lacZ-polyA fragment (supplementary material Fig. S1). TOPGAL transgenic indicator mice were obtained from the Jackson Laboratory (DasGupta and Fuchs, 1999). The Tbx20fl−/−b) biont tag knock-in mouse was generated as illustrated in Fig. 6B. In brief, V5 and Avi tags were fused to Tbx20 full-length cDNA at the 5′ and 3′ ends, respectively. The fusion cassette (V5-Tbx20-Avi) was inserted into the Tbx20 genomic locus through gene targeting (replacing exon 1 coding sequences). Mice derived from the positive ESCs were crossed to Rosa26Rcre mice (Driegen et al., 2005). Tbx20fl−/−;Avi-5′V5−/−;Rosa26Rcre/Ebox doubly homozygous mice were viable and normal (indistinguishable in development and appearance from wild type). All mice were bred in a mixed genetic background (Black Swiss). Experiments involving animals were carried out according to an approved protocol from the Institutional Animal Care and Use Committee at the Icahn School of Medicine at Mount Sinai, and were in compliance with the NIH animal welfare guidelines.

**RNA in situ hybridization and histology**

Whole-mount RNA in situ hybridization of mouse embryos was carried out as described (Wilkinson, 1992). Section RNA in situ hybridization was carried out on 12 µm cryosections. For histology, mouse embryos were fixed in 4% paraformaldehyde, dehydrated through an ethanol gradient and embedded in wax using a standard procedure. Paraffin sections were cut at 8 µm and stained with Hematoxylin and Eosin (H&E) as required.

**X-Gal and Alcian Blue staining**

For whole-mount X-Gal staining, mouse embryos were fixed in 4% paraformaldehyde for 30-40 minutes. After permeabilization (0.02% sodium deoxycholate, 0.01% NP40 in PBS), embryos were stained in X-Gal solution (5 mM potassium ferricyanide, 5 mM potassium ferrocyanide, 2 mM MgCl2, 1 mg/ml X-Gal in PBS) for 12 hours. For X-Gal staining on sections, mouse embryos were fixed, dehydrated and embedded in OCT Compound (Sakura). Cryosections were then stained in X-Gal staining solution. For Alcian Blue staining, tissue paraffin sections were rehydrated and stained in 3% Alcian Blue solution (pH 2.5) for 30 minutes. Sections were then washed in tap water and counterstained with Nuclear Fast Red using a standard procedure (Bancroft and Gamble, 2008).

**Immunohistochemistry and imaging**

In embryos in 4% paraformaldehyde and embedded in OCT Compound. Cryosections were cut at 8 µm. The following primary antibodies were used: rabbit anti-Tbx20 (1:100, Sigma), rabbit anti-Mmp13 (1:150, Abcam), mouse anti-Acan (1:150, Millipore), chicken anti-GFP (1:1000, Abcam), mouse anti-Nfatc1 (1:100, Abcam), rat anti-CD31 (1:500, BD Biosciences), mouse MF20 (anti-myosin heavy chain monoclonal; 1:100, DSHB) and rabbit anti-Lef1 (1:100, Cell Signaling). Secondary antibodies, including rabbit anti-chicken DyLight 488 (Abcam), donkey anti-mouse Alexa Fluor 594, donkey anti-rat Alexa Fluor 594 and donkey anti-rabbit Alexa Fluor 488 (Invitrogen), were diluted at 1:200 in blocking solution. DAPI was applied to detect nuclei.

**Echocardiography**

Pregnant female mice were lightly anesthetized with 0.5-1% isoflurane and the uterus was exposed. In utero echocardiography was performed using a high-resolution micro-ultrasound system (VisualSonics Vevo770) with a 30 MHz transducer (RMV-710). Doppler echocardiography was performed to detect blood flow through the atrial valves of the embryos. After imaging, the embryos were harvested for genotyping.

**Measurements of relative cushion size and valve length**

Comparable sections from mutant and control embryos were stained with H&E and then photographed using a Leica DM5500B microscope. For E11.5-12.5 hearts, cushion and ventricular chamber sizes from each section were measured in arbitrary units using Adobe Photoshop CS2. The cushion size ratio was determined by dividing the raw size of cushions by the raw size of the left ventricle to minimize the effect of developmental stage variation among the embryos. Relative cushion sizes were calculated by dividing the cushion size ratio of mutant embryos by that of control littermates (Jiao et al., 2006). For E14.5 hearts, the raw length of the valve leaflet was measured, and the relative valve length was determined by dividing the raw length of mutant embryos by that of control littermates (Stankunas et al., 2010). A minimum of four mutants and four control littermates were examined at each stage. Student’s t-test was conducted to examine the difference between the two groups. P<0.05 was considered significant.

**Cell proliferation and apoptosis assays**

EdU (5-ethyl-1′-deoxyuridine) was dissolved in PBS and injected intraperitoneally into timed pregnant mice (0.5 mg per 100 g body weight) 2 hours prior to harvesting. Embryos were fixed in 4% paraformaldehyde for 1 hour at 4°C, and embedded in paraffin for sectioning. Immunodetection of proliferative cells was performed using the Click-iT EdU Cell Proliferation Assay Kit (Invitrogen). Apoptotic cells were detected with the In Situ Cell Death Detection Kit (Roche).
High-throughput mRNA sequencing (mRNA-Seq) and data analysis

Total RNA was isolated from E12.5 hearts with Trizol (Invitrogen). mRNA and cdNA library preparation was performed using an mRNA-Seq Sample Preparation Kit (Illumina) according to the manufacturer’s protocol. Next-generation sequencing was performed using a HiSeq 2000 (Illumina). The clean reads from the Illumina pipeline were aligned to the mouse reference genome (mm9), RefSeq exons, splicing junctions and contamination databases (including ribosome and mitochondrial sequences) using the Burrows-Wheeler Aligner (BWA). After filtering reads mapped to contamination databases, the reads uniquely aligned to exons and splicing junction sites with a maximum of two mismatches for each RefSeq transcript were counted to represent the overall expression level of the corresponding transcript. To compare the expression levels of transcripts between samples, read counts were normalized by multiplying a factor of the maximum of the total read counts in all samples by the total read counts in the corresponding sample, and the log2 ratios were calculated based on normalized counts. Differentially expressed transcripts were identified using the M-A-based random sampling method implemented in the DEGseq package in BioConductor (http://bioconductor.org/packages/2.5/bioc/html/DEGseq.html). The transcripts were further filtered at >1.5-fold change and a minimum read count of 100 in either condition. Significant Gene Ontology (GO) terms were identified in differentially expressed genes using the Database for Annotation, Visualization and Integrated Discovery (DAVID) (National Institute of Allergy and Infectious Diseases, NIH).

Quantitative real-time PCR (RT-qPCR)

Total RNA was prepared with Trizol. First-strand cdNAs were synthesized with the QuantiTect Reverse Transcription Kit (Qiagen). Real-time PCR was performed using the QuantiTect SYBR Green PCR Kit (Qiagen) and normalized to β-actin (Actb) (primers are listed in supplementary material Table S1). Real-time PCR results are from three independent experiments with reactions performed in triplicate. Student’s t-test was applied for statistical analysis (P < 0.05).

Chromatin immunoprecipitation (ChIP)-PCR

The in vivo biotinylation ChIP assay was carried out as described previously (Kim et al., 2009). Briefly, E12.5 hearts in Tbx20 homozygous biotin tag alleles (Tbx203.9,2.9,1.7J/H2BGFP) were isolated in ice-cold PBS and cross-linked with 1% formaldehyde for 10 minutes at room temperature. Extracted chromatin was sheared to ~100–500 bp, and then incubated with Dynabeads MyOne Streptavidin T1 beads (Invitrogen) at 4°C overnight. The magnetic beads were sequentially washed with 2% SDS, high salt buffer, LiCl buffer and TE buffer (He and Pu, 2010) before reversing the cross-linking at 65°C in elution buffer (10 mM Tris-HCl pH 8.0, 1 mM EDTA, 1% SDS) overnight. The immunoprecipitated DNA was then treated with proteinase K and purified using the MinElute PCR Purification Kit (Qiagen). Purified DNA was used as template for PCR. ChIP-PCR primers are listed in supplementary material Table S1.

Luciferase reporter assay

Mouse primary endocardial cell cultures from E11.5 hearts (Zhou et al., 2005) were grown in endothelial cell growth medium (EGM-2MV BulletKit, Lonza) with 10% fetal bovine serum. Cells were seeded in 1% gelatin-precocated 24-well plates until 85–95% confluent. These cells were transfected with a mixture of 200 ng luciferase reporter plasmid containing Lef1 promoter fragments [or blank pGL3-TK vector (Promega) as control], 400 ng Tbx20 expression vector and 5 ng Renilla plasmid (pRL-TK as internal control) using X-tremeGENE 9 DNA Transfection Reagent (Roche) in Opti-MEM (Gibco) according to the manufacturer’s instructions. After 48 hours of incubation, cells were lysed and assayed using the Dual-Luciferase Reporter Assay System (Promega). Luciferase/Renilla activity was quantified with the GloMax-Multi Detection System Kit (Promega). Genomic DNA fragments upstream of Lef1 exon 1 were amplified by high-fidelity PCR and cloned into pGL3-TK (Fig. 6B). Primers used to generate the 3.9, 2.9 and 1.7 kb Lef1 promoter fragments are listed in supplementary material Table S1. Results are from one representative experiment carried out in triplicate. At least three independent transfection experiments were performed.

RESULTS

Tbx20 is highly expressed in endocardial cushions and valve leaflets throughout mouse heart formation

Tbx20 is expressed in myocardial and endocardial cells during mouse cardiogenesis (Stennard et al., 2005; Takeuchi et al., 2005). To fully characterize Tbx20 expression and its potential roles in heart formation, we generated a Tbx20lacZ/H2BGFP knock-in mouse by inserting a LoxP-lacZ-polyA-LoxP-H2BGFP-polyA cassette into the Tbx20 start codon (with minimal deletion of exon 1 coding sequence). The expression of lacZ/H2BGFP is driven by Tbx20 endogenous regulatory elements (supplementary material Fig. S1), and H2BGFP expression is blocked when the lacZ (nuclear lacZ) cassette is present. Whole-mount X-Gal staining showed that Tbx20lacZ faithfully recapitulates Tbx20 mRNA expression in the heart throughout embryogenesis (Fig. 1A,B; supplementary material Fig. S2). The Tbx20H2BGFP allele was generated by crossing Tbx20lacZ/H2BGFP to Promotase-Cre mice (O’Gorman et al., 1997). With Tbx20H2BGFP, we detected co-expression of Tbx20 and Nfatc1, a marker of early endocardial cells (including cushion endocardial cells) (de la Pompa et al., 1998; Ranger et al., 1998) (Fig. 1C-F). From mid to late gestation, Tbx20 expression continues in the cushion mesenchyme (Fig. 1G-J) and the leaflets of all four cardiac valves (Fig. 1K-N). Tbx20 expression is maintained at high levels in the valve leaflets postnatally and into adulthood (Fig. 1O-R). The prominent expression of Tbx20 in endocardial cushions and valve leaflets suggests a potential role in their development.

Disruption of Tbx20 in endocardium results in embryonic lethality and defective valve formation and function

To investigate the role of Tbx20 in endocardial cushion and valve morphogenesis, we crossed Tbx20+/− mice to Nfatc1Cre+/−;Tbx20−/− mice. During early cardiogenesis, Nfatc1 is expressed throughout the endocardium from E9.5–10.5; at ~E11, Nfatc1 expression becomes restricted to cushion endocardium (Chang et al., 2004). Lineage tracing analysis of Nfatc1Cre+ with R26RlacZ indicator mice revealed that Nfatc1Cre+ promotes recombination in the cushion endocardium and its mesenchymal derivatives (supplementary material Fig. S3) (Wu et al., 2012). Therefore, Tbx20 is eliminated in both cushion endocardium and mesenchyme in Nfatc1Cre+;Tbx20−/− mice.

Mice with heterozygous deletion of Tbx20 (Nfatc1Cre+;Tbx20+/− and Nfatc1Cre−;Tbx20−/−) were viable and normal, yet the mutants [Nfatc1Cre−;Tbx20−/−, Tbx20 conditional knockout (CKO)] died between E14.5 and E16.5 (Fig. 2A). At E15.5, most mutant embryos had peripheral hemorrhage (Fig. 2B,C). Given that embryonic lethality and defective valve formation (Fig. 2A) are similar in Nfatc1Cre−;Tbx20−/− and Nfatc1Cre−;Tbx20−/− (Fig. 2D-I), we hypothesized that Tbx20 expression is not essential for normal valve morphogenesis.
Cushion and valve endocardial cells are less proliferative in Tbx20 CKO embryos

Valve leaflets are formed by the elongation and thinning of valve primordia in a precisely controlled manner that is crucial for proper cardiac function (Hinton and Yutzey, 2011). To further characterize the valve defects in Tbx20 CKO embryos, we examined the relative length of the valve leaflets at E14.5. The distance between the valve cusp and cushion base was set as the valve length (Stankunas et al., 2010). Disruption of Tbx20 engendered much shorter and wider semilunar (pulmonary and aortic) valve leaflets (Fig. 3A-D), which were 66% and 69% of the length of the controls, respectively (Fig. 3G). Defective elongation of the mutant mitral and tricuspid valves was much more severe than that of the semilunar valves, both by histological examination (Fig. 3E,F) and by calculated relative valve length (Fig. 3G; 28% and 26% of control, respectively).

Cardiac valve elongation and remodeling start at E12.5 in mice and are characterized by rapid cell proliferation at the edge of the valve and apoptosis at the base of the cushion (Lin et al., 2012). The cardiac valve elongation defects in Tbx20 CKO mice suggested deficient cell proliferation and/or survival, so we assessed proliferation and apoptosis in E13.5 hearts. Co-immunostaining for CD31 (Pecam1 – Mouse Genome Informatics) was used to identify endocardial cells. Representative results for the mitral valve are shown in Fig. 3H,I. We categorized and counted endocardial cells based on their location (endocardium versus mesenchyme). Interestingly, mutant mitral valve endocardial cells were much less proliferative (18% in mutant versus 32% in control), whereas mesenchymal cell proliferation was unchanged (32% in mutant versus 28% in control; Fig. 3L). Similar observations were made for the pulmonary, aortic and tricuspid valves (Fig. 3L). In addition, we detected very few apoptotic cells in the cushions of controls and mutants (Fig. 3J,K). These observations indicate that decreased proliferation of endocardial cells contributes to the valve elongation defects of Tbx20 CKO embryos.

To determine the onset of the Tbx20 CKO valve defects, we inspected endocardial cushion formation in E12.5 embryos. AVC and OFT cushions were measured and relative cushion sizes were calculated (Jiao et al., 2006). The pulmonary and aortic valves were properly formed in the mutants with little or no change in cushion size at this stage (98% and 97% of control, respectively; Fig. 4A-D,I), whereas the AV cushions were smaller than in controls (64% of control; Fig. 4E-I). At E11.5, AV cushion size and morphology were indistinguishable from controls (supplementary material Fig. S4), as was cushion mesenchymal cell proliferation (28% in mutant and 26% in control; Fig. 4J-M,P). However, there were fewer proliferating cushion endocardial cells in mutant hearts (24% in mutant versus 35% in control; Fig. 4J-M,P). Very few apoptotic cells were detected in mutant or control AVC cushions at E11.5 (Fig. 4N,O). These observations indicate that the abnormal proliferation of the valve endocardial cells begins at E11.5 and disrupts atrioventricular cushion formation.

Endocardial Tbx20 is not required for EMT in AVC and OFT development

During early embryogenesis (~E7.5-8.0 in mice), the earliest endocardial cells derive from endothelium within the heart tube
After this transition, endocardial cells give rise to the cushion mesenchyme in the AVC and OFT through EMT (~E9.5-10.5 in mice). Previous studies suggest that perturbed EMT results in abnormal valve formation (Person et al., 2005). Based on this, we examined whether EMT initiation is disrupted by Tbx20 endothelial loss of function. We introduced the R26RlacZ allele (Soriano, 1999) into the genetic crosses to trace endocardial-derived cells in the mesenchyme. No significant difference was observed in the number of cushion mesenchymal cells in mutants and controls at E10.5 (supplementary material Fig. S5A-D). It is important to note that endocardial-derived mesenchymal cells are located in the proximal OFT [pOFT; positive for X-Gal staining (X-Gal+)], whereas cardiac neural crest-derived mesenchymal cells are located in distal OFT (dOFT, X-Gal–) (Lin et al., 2012; Park et al., 2008; Wu et al., 2011). Furthermore, we did not detect any differences in the number of X-Gal+ mesenchymal cells in the AVC and OFT at this stage (supplementary material Fig. S5E). We examined the expression of several genes important for EMT at E9.5-10.5, including Bmp2 and Tgfb2 in the AVC and OFT myocardium (Ma et al., 2005; Person et al., 2005) and Sox9 and Snail1 in cushion mesenchyme (Akiyama et al., 2004; Timmerman et al., 2004). RNA in situ hybridization showed that the expression of these genes was normal (supplementary material Fig. S5F-U).

To ensure that the unaffected EMT was not the result of inefficient deletion of Tbx20 in the endocardium, we examined Tbx20 protein by immunostaining and Tbx20 exon 2 RNA by in situ hybridization in the hearts (exon 2 was flanked by LoxP sites in Tbx20 floxed mice) (Cai et al., 2005). This confirmed complete ablation of Tbx20 in the AVC endocardial and mesenchymal cells of Tbx20 CKO hearts at E9.25, just prior to EMT initiation (supplementary material Fig. S6). The expression of other genes crucial for endocardial cushion and valve development, including Bmp4 (Jiao et al., 2003), Notch1 (Timmerman et al., 2004), Gata4 (Rivera-Feliciano et al., 2006), Tbx5 (Nadeau et al., 2010) and Nfatc1 (de la Pompa et al., 1998; Ranger et al., 1998) was unchanged in Tbx20 CKO hearts (supplementary material Figs S7, S8). These results suggest that endocardial Tbx20 is not essential for EMT initiation in the AVC or OFT.

**Disturbed Wnt/β-catenin signaling in Tbx20 CKO hearts**

To identify molecular mechanisms underlying the endocardial cushion and valve defects in Tbx20 CKO hearts, we applied high-throughput mRNA sequencing (mRNA-Seq) to identify differentially expressed genes in mutants versus controls. We chose E12.5 hearts for analysis because valve elongation and remodeling
begin at this stage in mice (Wirrig and Yutzey, 2011) and Tbx20 CKO valve defects are first evident (Fig. 4A-H). mRNA-Seq assays were carried out on three pooled mutant hearts with corresponding littermate controls. More than 30 million raw reads were generated per sample. Among these, more than 20 million reads were uniquely mapped to mouse RefSeq transcripts using BWA alignment.

A total of 112 differentially expressed genes were identified with at least a 1.5-fold change between the mutant and control (supplementary material Table S2). Ingenuity pathway analysis (Fig. 5A; supplementary material Table S3) as well as Gene Ontology enrichment analysis (Fig. 5B; supplementary material Table S4) identified Wnt/β-catenin pathway genes, including Wnt7b, Wnt9b and Lef1, among the significantly dysregulated genes (Fig. 5C). This bioinformatic result was validated by RT-qPCR on E10.5-12.5 hearts, and we detected changes in the expression of these genes as early as E11.5 (Fig. 5D), prior to the appearance of CKO mutants (Fig. 6A-H, Fig. 5D). Given the altered expression of these Wnt ligand genes, we then examined the expression of Tcf/Lef transcription factors (Alfieri et al., 2010) expression was confirmed by RT-qPCR on E10.5-12.5 hearts, we introduced the TOPGAL indicator allele into the genetic crosses (DasGupta and Fuchs, 1999). At E10.5-12.5, whole-mount X-Gal staining of the TOPGAL embryos revealed increasing Wnt/β-catenin signaling activity in the endocardial cushion regions, and later in all four developing valves (supplementary material Fig. S10). Signaling was greatest in the growing edge of the atrioventricular valves, including the endocardium and subadjacent mesenchymal cells (Fig. 5E,G,I,K). Interestingly, we found that lacZ-expressing cells were dramatically decreased in the mutant atrioventricular valves (Fig. 5F,H,J,L), consistent with reduced Wnt/β-catenin signaling in Tbx20 CKO hearts at E11.5-12.5 (Fig. 5D, Fig. 6A-Q). The reduced lacZ expression was confirmed by RT-qPCR (Fig. 5M).

Given the central role of Tcf/Lef transcription factors in mediating Wnt/β-catenin signaling, we questioned whether downregulation of Lef1 in Tbx20 CKO cushion endocardial cells was the result of direct regulation by Tbx20 as opposed to loss of Wnt/β-catenin signaling. We aligned orthologous genomic sequences flanking Lef1 in mouse, rat and human and found a conserved putative T-box binding site upstream of exon 1 (Fig. 6R,S). ChIP on E12.5 hearts isolated from doubly homozygous Tbx20 mutant tag knock-in mice (Tbx20V5-Avi/V5-Avi;Rosa26BirA/BirA) revealed that Tbx20 bound to this location (Fig. 6U, P1+P2), but not to a nearby control region (Fig. 6U, P3+P4). Cardiac tissues collected from Rosa26BirA/BirA control mice (without Tbx20F5-Avi alleles)

### Fig. 3. Tbx20 endocardial deletion disrupts valve elongation and endocardial cell proliferation.

A-F) Tbx20 CKO mutant and control valves at E14.5. Arrows indicate pulmonary valve (A,B), aortic valve (C,D), tricuspid valve and mitral valves (E,F). Valve length is indicated by doubleheaded arrows. Dashed lines mark the junctions between valve base and cusp. G) Relative valve length. (H) Proliferating cells in mitral valves detected by EdU staining (green) at E13.5. CD31 co-staining (red) marks valve endocardial cells. Arrowheads indicate proliferating endocardial cells. (J,K) Apoptotic cells (green) detected by TUNEL in control and mutant mitral valves at E13.5. Dashed lines in H-K indicate the junction between valve base and cusp. (L) Statistical comparison of valve endocardial and mesenchymal cell proliferation at E13.5. Decreased cell proliferation is observed in the valve endocardium but not the mesenchyme. *P<0.05, **P<0.01, versus control. n.s., not significant. Error bars indicate s.d.
showed no recruitment of Tbx20 (Fig. 6U, lane 3). Further, luciferase reporter assays with mouse embryonic endocardial cell cultures (Zhou et al., 2005) revealed activation of the Lef1 promoter by Tbx20 in the fragment containing the Tbx20 binding site (3.9 kb) but not in fragments without this site or that were negative in ChIP-PCR (2.9 kb and 1.7 kb) (Fig. 6R,U,V).

Combined with the aforementioned expression data, these results suggest that direct binding of Tbx20 to the Lef1 promoter regulates Lef1 expression in the cushion endocardium during cardiac valve formation. In addition, we scanned the Wnt4 and Wnt9b promoters (~3 kb upstream of the transcriptional start site) by ChIP-PCR to determine whether Tbx20 also binds to the regulatory elements of these genes, but no enriched elements were detected (data not shown).

**Disrupted ECM integrity in Tbx20 CKO endocardial cushion**

Endocardial cushion ECM composition is crucial for mesenchymal cell migration, proliferation and differentiation (Hinton et al., 2006), and subsequent valve leaflet formation is also inextricably linked to ECM remodeling (Chakraborty et al., 2010; Hinton and Yutzey, 2011). Thus, we further examined the transcription of ECM components in Tbx20 CKO hearts by RT-qPCR. Postn is essential for ECM integrity and is required for valve remodeling and maturation (Snider et al., 2008). We found that Postn was downregulated in Tbx20 CKO hearts (Fig. 7A). RNA in situ hybridization confirmed that downregulation of Postn was localized to the cushion cells (Fig. 7B-E). Matrix metalloproteinases (MMPs) are secreted extracellular proteases essential for the degradation and remodeling of ECM components in the valve (Shelton and Yutzey, 2007). Mmp13 expression was decreased in the cushion of Tbx20 CKO hearts, whereas expression of Mmp2 and Mmp9 was not (Fig. 7A,F,G). Chondroitin sulfate proteoglycans and collagens are important ECM components. RT-qPCR and immunostaining revealed downregulated Acan expression in Tbx20 CKO hearts (Fig. 7A,F,G). Chondroitin sulfate proteoglycans and collagen are crucial for ECM organization (Camenisch et al., 2000). Has2 expression was normal in mutant hearts (Fig. 7A), consistent with Alcian Blue staining showing a normal distribution of HA in the ECM (Fig. 7J-M). The altered expression of Postn, Mmp13 and Acan could affect ECM integrity in the cushion, which might further aggravate the proliferation and valve elongation deficiency of Tbx20 CKO hearts.

**DISCUSSION**

T-box transcription factors play fundamental roles in development and disease (Greulich et al., 2011). Ablation of Tbx1, Tbx2, Tbx3,
Tbx5 or Tbx20 in mice leads to cardiac malformations (Naiche et al., 2005). Human TBX1 mutations play a major role in 22q11 deletion syndrome, which includes serious cardiac defects (Merscher et al., 2001). TBX5 mutations cause Holt-Oram syndrome with atrial and ventricular septal defects (ASD and VSD) (Basson et al., 1997). Human TBX20 mutations are associated with a complex spectrum of cardiac developmental and functional abnormalities including total anomalous pulmonary venous connection (TAPVC), ASD (Liu et al., 2008; Posch et al., 2010), VSD (Qiao et al., 2012), tetralogy of Fallot (TOF) (Liu et al., 2008) and cardiomyopathies with defective valvulogenesis (Kirk et al., 2007; Qian et al., 2008). In the present study we eliminated Tbx20 in the endocardium of mouse embryos and provide the first genetic evidence that Tbx20 is crucial for endocardial cushion maturation and valve elongation in mammals. Our data suggest that decreased proliferation of valve endocardial cells contributes to the valve elongation defects in Tbx20 CKO hearts. These findings advance our understanding of the developmental and pathological processes leading to human congenital valve defects associated with TBX20 mutations.

Previous studies showed that Tbx20 regulates endocardial cushion mesenchymal cell proliferation in avian cushion explants...
In our analysis of Nfatc1Cre/+;Tbx20f/– mice, we detected lower proliferation in the valve endocardium but not cushion mesenchyme. The ECM gene Mmp13 was downregulated (as seen in chicken cushion cell cultures), whereas Mmp9 was not (in contrast to in chicken cushion cell cultures) (Shelton and Yutzey, 2007). These discrepancies might reflect divergent regulation of this developmental process in different species or the different experimental approaches used.

During mouse embryogenesis, several Wnt/β-catenin pathway genes are specifically expressed in the developing valves (Alfieri et al., 2010). A previous study of β-catenin endocardial deletion mice showed that Wnt/β-catenin signals play crucial roles in endocardial EMT, and mutant mice died at E11.5-13.0 with severe EMT abnormalities (Liebner et al., 2004). Despite the specific expression of Wnt/β-catenin pathway genes in the developing valves (Alfieri et al., 2010), it is largely unknown whether Wnt/β-catenin signaling is required for valve elongation and remodeling at mid to late gestation. In the mRNA-Seq analysis of Tbx20 CKO hearts, we found that the levels of transcripts encoding Wnt/β-catenin pathway genes were significantly changed (Fig. 5). Further analysis demonstrated that Wnt4, Wnt9b and Lef1 were downregulated in valve endocardial cells (Fig. 6). Misexpression of Wnt4 and Wnt9b in the cushion endocardial cells might affect β-catenin stabilization and translocation into the nucleus in Tbx20 CKO hearts (van Amerongen and Nusse, 2009).
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Lef1 belongs to the Tcf/Lef transcription factor family, which bind DNA through a high mobility group domain (Cadigan and Waterman, 2012). In the absence of Wnts, Tcf/Lefs repress transcription in association with co-repressors such as Groucho. Nuclear accumulation of β-catenin in response to Wnt signaling drives Tcf/Lef regulation of Wnt-responsive gene expression (Clevers and Nusse, 2012). It is important to note that Lef1-deficient mice have morphogenetic defects in several organs that require epithelial-mesenchymal interactions (van Genderen et al., 1994), and Wnt/β-catenin signaling has been widely proven to be essential for organ growth during development (Clevers and Nusse, 2012; Gessert and Kühl, 2010; Wang et al., 2012; Zimmerman et al., 2012). Based on this, we postulate that aberrant Wnt/β-catenin signaling is a major contributor to the proliferative defects in Tbx20 CKO cushions and valves. Additional studies are needed to determine whether there is an ongoing Tbx20 -mediated genetic excision from endocardium (de Lange et al., 2004) and thus have the largest number of cells affected by Nfatc1Cre/+ -mediated genetic excision (Wu et al., 2012).

Taken together, our studies revealed a crucial role for Tbx20 in endocardial cushion formation and valve elongation in mice. The valve elongation defects of Tbx20 CKO hearts are associated with fewer proliferative cushion endocardial cells, aberrant Wnt/β-catenin signaling and reduced ECM gene expression. Tbx20 directly regulates the key Wnt transcriptional effector Lef1 through binding its promoter element. These studies provide genetic insight into the etiology of human congenital valve disease associated with Tbx20 mutations.

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Competing interests statement
The authors declare no competing financial interests.

Author contributions
X.C. conceived the project, designed and performed the experiments, and prepared the manuscript. W.Z. performed RNA-Seq data analysis. J.H., L.Z., N.S. and W.C. provided experimental assistance. B.W. and B.Z. contributed to the reagents and manuscript preparation. C.-L.C. conceived the project, designed the experiments, and prepared and approved the manuscript.

Supplementary material
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