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SHOX2 Overexpression Favors Differentiation of Embryonic Stem Cells into Cardiac Pacemaker Cells, Improving Biological Pacing Ability

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SUMMARY

When pluripotency factors are removed, embryonic stem cells (ESCs) undergo spontaneous differentiation, which, among other lineages, also gives rise to cardiac sublineages, including chamber cardiomyocytes and pacemaker cells. Such heterogeneity complicates the use of ESC-derived heart cells in therapeutic and diagnostic applications. We sought to direct ESCs to differentiate specifically into cardiac pacemaker cells by overexpressing a transcription factor critical for embryonic patterning of the native cardiac pacemaker (the sinoatrial node). Overexpression of SHOX2 during ESC differentiation upregulated the pacemaker gene program, resulting in enhanced automaticity in vitro and induced biological pacing upon transplantation in vivo. The accentuated automaticity is accompanied by temporally evolving changes in the effectors and regulators of Wnt signaling. Our findings provide a strategy for enriching the cardiac pacemaker cell population from ESCs.

INTRODUCTION

Since their first derivation (Thomson et al., 1998), embryonic stem cells (ESCs) have been validated to faithfully recapitulate early cardiogenesis (Boheler et al., 2002; Van Vliet et al., 2012) and touted for their potential as an unlimited source of de novo cardiomyocytes for replacement of diseased myocardium (Kehat et al., 2001). While the most commonly pursued therapeutic goal has been to boost contractile function, ESC-derived cardiac cells may also be useful as alternatives to electronic pacemakers (Cho and Marbán, 2010); we and others have exploited the automaticity of ESC-derived cardiomyocytes to create biological pacemakers (Kehat et al., 2004; Xue et al., 2005). The risk of teratoma may be diminished by technical refinements to increase general yield of ESC-derived cardiomyocytes (Dubois et al., 2011; Kattman et al., 2011; Nunes et al., 2013) and by attaining a “pure” cardiomyocyte population post-differentiation (Dubois et al., 2011; Hattori et al., 2010). An outstanding issue, however, remains in the innate heterogeneity of ESC-derived (or any pluripotent stem cell) cardiac cells. The action potential (AP) profiles of de novo cardiomyocytes vary considerably from ventricular/atrial myocyte-like to nodal/Purkinje-like (He et al., 2003; Kolossov et al., 2005; Maltsev et al., 1993; Zhang et al., 2009). Such heterogeneity could result in unpredictable biological pacemakers, as reported in a subset of spontaneously contracting embryoid bodies (EBs) in which the beating rate either ceased or accelerated over time (Mandel et al., 2012).

We set out to develop a way to instruct the ESCs to differentiate into a cardiac pacemaker subtype with a factor relevant to embryonic pacemaker development. Native cardiac pacemaker cells are anatomically confined in the sinoatrial node (SAN), a diminutive structure comprising just a few thousand genuine pacemaker cells (Bleeker et al., 1980). During embryonic development, cardiac pacemaker cells originate from a subset of progenitors distinct from the first (marked by Nkx2.5) and second (marked by Isl1) heart fields not only in their genetic makeup (Christoffels et al., 2010; Wiese et al., 2009), but also in their anatomic location (Bressan et al., 2013). However, an area of Hcn4-positive primordial SAN is reported to express Isl1 (Mommersteeg et al., 2007), suggesting that second heart field progenitors may also contribute to the developing SAN. We have recently demonstrated that postnatal re-expression of an embryonic transcription factor, Tbx18, converts ventricular cardiomyocytes to pacemaker cells, recapitulating morphological as well as electrophysiological hallmarks of genuine SAN pacemaker cells (Kapoor et al., 2013). Elsewhere, transgenic overexpression of Tbx3 has been shown to elicit ectopic rhythm in mouse atrial myocardium (Bakker et al., 2012). Noting the powerful capacity of embryonic transcription factors in determining the fate of cardiac cell subtype, we hypothesized that overexpression of a SAN-specific transcription factor may steer ESC differentiation toward pacemaker cell subtype. Here, we report that heterologous expression of SHOX2 during early stages of mouse ESC (mESC) differentiation strongly favors a SAN-specific gene program,
leading to enhanced pacemaker cell specification. The differentiated cells exhibit greater automaticity in vitro and perform biological pacemaker function when injected into the rat heart in vivo.

RESULTS

**Shox2 Is Specific to Embryonic Development of the Cardiac SAN**
mESCs were differentiated to form EBs by culturing them in suspension media for 6 days and then transferring them to adherent media (Wobus et al., 1991). The EBs were analyzed at three time points, based on the time course of electrophysiological maturation of mESC-derived cardiomyocytes (Maltsev et al., 1994): 4 days after transfer to adherent culture as an early time point of differentiation (D6+4), 7 days afterward (D6+7) as the mid phase of differentiation, and 14 days afterward (D6+14) as the terminal phase of differentiation (Figure 1A). A few transcription factors figure prominently in embryonic development of the SAN, notably the T box transcription factors Tbx18 and Tbx3 (Wiese et al., 2009), as well as the homeodomain transcription factor Shox2.
We reasoned that overexpression of one of these transcription factors could steer ESCs to differentiate into cardiac pacemaker cells. To this end, we sought to identify a gene highly specific to the developing mouse SAN. Quantitative measurements of the mRNA levels of these transcription factors reveal that Shox2 expression is most specific to, and significant in, the SAN compared with the right atrium (RA), left atrium (LA), and left ventricle (LV) of the mouse heart at mouse embryonic day (ED) 18 (Figure 1B, top). The SAN-specific expression of Shox2 closely follows that of Hcn4, a marker of SAN pacemaker cells. Initially, we anticipated that Tbx18 expression might be the most specific to the SAN since mice deficient for Tbx18 fail to form sinus horns (Christoffels et al., 2006), bolstered by our recent demonstration that Tbx18 re-expression converts ordinary ventricular myocytes to native SAN-like induced pacemaker cells in vitro and in vivo (Kapoor et al., 2013). Yet, the present data indicate that Tbx18 is comparably expressed between the SAN and all major chambers, including the right atrium (RA), left atrium (LA), and left ventricle (LV) at ED 18 (Figure 1B, top). This may be due to the abundance of Tbx18+ proepicardial progenitor cells in the embryonic heart (Cai et al., 2008; Christoffels et al., 2009). Likewise, our data indicate that Tbx3 is comparably expressed in the SAN and LV (Figure 1B), which may be due to its expression in ventricular conduction system (Bakker et al., 2008). Analogous results were obtained at an earlier embryonic development time point (ED 15.5; Figure 1B, bottom). Guided by these insights, we selected Shox2 as the most SAN-specific transcription factor so as to boost SAN pacemaker cell-specific differentiation of the ESCs.

Exogenous SHOX2 Expression Activates Endogenous Shox2

We set out to facilitate the pacemaker-specific gene program at a time when endogenous Shox2 expression is low, from D3 to D7 (Figure 2A). To this end, we transduced the EBs with an adenoviral vector expressing human SHOX2 on D3, D6, and D6+1 (D7) in order to maximize adenoviral somatic gene transfer. Experiments were performed on six independent mouse ESC cultures (i.e., six biological replicates).

Figure 2. Exogenous Expression of Human SHOX2 Increases Endogenous Shox2 Expression

(A) Quantitative measurements of endogenous mouse Shox2 expression throughout the differentiation stages indicate that its expression is at the lowest during the first 6 days of differentiation. In SHOX2-treated group, the differentiating cells are transduced with an adenoviral vector expressing human SHOX2 on D3, D6, and D6+1 (D7) in order to maximize adenoviral somatic gene transfer. Experiments were performed on six independent mouse ESC cultures (i.e., six biological replicates).

(B) Human SHOX2-specific, quantitative PCR measurements of Shox2 over time. No PCR product was detected in the GFP-EB group, indicating the specificity of human SHOX2 PCR primers.

(C) The level of endogenous Shox2 expression is higher in the SHOX2-EB group compared with control in all three time points. Data are represented as mean ± SEM. All experiments were performed on three independent biological replicates. See also Figure S1.
Ca\textsuperscript{2+} exchanger (NCX) couples spontaneous intracellular depolarization through the propagation of electrical signals from cell to cell. Hyperpolarization-activated cyclic nucleotide-gated channel 4 (HCN4) is the molecular correlate of \( I_f \) in the SAN, which directly contributes to the linear rise of spontaneous depolarization during phase 4 of an AP (DiFrancesco, 2010; Yamamoto et al., 2006). Immunostaining of the whole SHOX2-EBs demonstrates that SHOX2 expression heightens HCN4 channel expression compared with control (Figure 3A). Total HCN4 protein expression was twice higher in SHOX2-EBs compared with control throughout the stages of differentiation (Figure 3B, left and middle). Na\textsuperscript{+}-Ca\textsuperscript{2+} exchanger (NCX) couples spontaneous intracellular Ca\textsuperscript{2+} release events to voltage oscillations in SA nodal pacemaker cells (Lakatta and DiFrancesco, 2009). The NCX1 protein level increased 4-fold in SHOX2-EBs at the later stages of differentiation (Figure 3B, right; Figure S2).

The space constant at the core of the SAN is significantly lower than that of the neighboring atrial myocardium or the ventricles (>500 \( \mu \)m versus 1–2 mm, respectively) (Bonke, 1973). The high intercellular electrical resistance in the SAN allows its automaticity to propagate into the right atrium, which due to its highly hyperpolarized membrane potential would otherwise dissipate the electrogenic signals from the SAN (Joyner and van Capelle, 1986). The weak electrical coupling in the SAN pacemaker cells is mediated by a low-conductance gap junction protein, CX45, while the chamber myocardium predominantly expresses a large-conductance gap junction, CX43 (Jansen et al., 2010). SHOX2 overexpression increased the transcript level of Gja7, the gene that encodes CX45, throughout the differentiation phases. This is complemented by an ~4-fold increase in CX45 protein expression (Figure 3C). Conversely, SHOX2 overexpression decreased CX43 expression at the transcript (33% \( \pm \) 5%, \( p < 0.05 \)) and protein (30% \( \pm \) 10%, \( p < 0.05 \)) levels compared with control (Figure 3D). In order to gauge the extent of total cardiac myocyte differentiation, we examined the expression levels of pan-cardiac myocyte markers, cardiac troponin T (Tnnt2), and cardiac actin (Actc1), as well as Nkx2-5, a negative marker of SAN but positive for ventricular and atrial cardiomyocytes. Quantitative RT-PCR data demonstrate that the expression level of Nkx2-5 is lower in SHOX2-EBs, while that of the pan-cardiac myocyte genes remains similar (Figure S3). The data indicate that the total cardiac differentiation efficiency remains similar in SHOX2-EBs and EBs transduced with a green fluorescent protein (GFP-EBs). Furthermore, the increased automaticity in SHOX2-EBs is likely to be a direct result of heightened pacemaker cell differentiation at the expense of diminished ventricular cardiomyocyte content. Thus, exogenous SHOX2 expression upregulates a number of electrophysiological hallmarks of SAN pacemaker cells during cardiac differentiation of ESCs.

To quantify the automaticity of SHOX2-EBs, we scored the number of spontaneously beating EBs and the number of individual beating foci in each EB. At the early stage of differentiation, the majority of SHOX2-EBs beat spontaneously, while the majority of GFP-EBs were quiescent (83% \( \pm \) 7% versus 15% \( \pm \) 6%, respectively, \( n = 7 \) independent experiments; Figure 4A, left). Over time, most of the GFP-EBs eventually began to beat (Figure 4A, left). Still, SHOX2-EBs exhibited more than twice the number of spontaneously beating foci within each beating EB compared with control, a pattern that persisted throughout differentiation (Figure 4A, right). The beating rates of the EBs were analyzed by recording extracellular field potentials (FPs) from the EBs on multielectrode arrays (MEAs) (Figure 4B). The beating rates of SHOX2-EBs were similar to those of control at the beginning of differentiation and then became significantly faster compared with control beyond the mid phase of differentiation (Figures 4C and 4D). Taken together, the data demonstrate that SHOX2-EBs develop greater numbers of pacemaker foci with faster beating rates and that the increased automaticity persists throughout differentiation.

**SHOX2-EBs Function as a Biological Pacemaker after Transplantation In Vivo**

Motivated by the greater automaticity of the SHOX2-EBs, we tested whether SHOX2-EBs could provide biological pacemaker function when implanted in vivo. We and others have previously demonstrated that spontaneously beating human ESC-derived EBs could electrically couple with and drive the beating of host myocardium upon implantation in vivo (Kehat et al., 2004; Xue et al., 2005). In those studies, spontaneously beating areas of several EBs were microsurgically dissected prior to injection so as to remove nonbeating areas, thereby maximizing the proportion of beating cardiac tissue to nonbeating cells. Here, we tested whether the increased automaticity in SHOX2-EBs suffices to provide biological pacemaker function even without microsurgical removal of nonbeating cells. To this end, 10–12 spontaneously beating GFP-EBs or SHOX2-EBs were randomly selected at D6+4 and directly injected into the left ventricular apex of the rat heart in vivo. Two to 4 days after in vivo transplantation, the heart was isolated and retrogradely perfused so that its electrical activity could be optically mapped. In sinus rhythm,
Figure 3. Changes to Ion Channel and Gap Junction Profiles in SHOX2-EBs Favor Automaticity

(A) Immunostaining images of GFP-EB (left) and SHOX2-EB (middle and right) with an antibody against HCN4 channel proteins. DAPI (blue), nuclear staining.

(B) Quantitative measurements of HCN4 (left and middle) and NCX1 (right) protein levels. D6+14 for NCX1.

(C) Transcript (left) and protein (right) level measurements of Cx45 in GFP-EBs and SHOX2-EBs. Protein level was determined with D6+14 samples.

(D) Transcript (left) and protein (right) level measurements of Cx43 in GFP-EBs and SHOX2-EBs. The protein level was determined with D6+14 samples. Data are represented as mean ± SEM. All experiments were performed on three independent biological replicates.

See also Figures S2 and S3.
Figure 4. SHOX2-EBs Exhibit Intensified Automaticity In Vitro and Function as Biological Pacemakers when Implanted In Vivo

(A) The percentages of spontaneously contracting EBs were measured at D6+4 and D6+14 (left) by direct visualization. More than one beating focus could be detected in some EBs, and thus, the number of spontaneously beating foci per EB was measured at the same time points (right).

(B) The spontaneous beating rates were measured by culturing the EBs in MEAs and measuring the extracellular FPs from the GFP-EBs and SHOX2-EBs. Shown is a six-well MEA (left) in which two to three EBs were cultured per well (right).

(C) The average beating rates were measured at five time points by recording the spontaneous FPs for 20 min at 37°C in normal Tyrode’s (n > 10 for each data point).

(D) Representative raw FP traces are shown for a GFP-EB and a SHOX2-EB at D6+14.

(E) Whole-heart optical mapping recordings were performed on the rat hearts injected with GFP-EBs or SHOX2-EBs in vivo 2–3 days prior to the heart harvest. Raw AP traces reported as di-8-ANNEPS signal from one photodiode (123) are shown before (baseline) and after (complete heart block).
hearts injected with either GFP-EBs or SHOX2-EBs exhibited similar heart rates at room temperature (Figure 4E, “baseline”). Then complete heart block was implemented by surgically disrupting both the SA and atrioventricular nodes to unleash potential biological pacemaker activity. Afterward, control hearts injected with GFP-EBs exhibited slow junctional rhythms of 34 ± 2 beats per minute (bpm) (n = 4). In contrast, the SHOX2-EB-injected hearts exhibited a significantly higher ventricular rate (44 ± 3 bpm, n = 4, p < 0.05). Since the SHOX2-EBs were injected in the ventricular myocardium, heartbeats initiated from the injection site are expected to propagate more slowly than a junctional rhythm, which travels via the fast secondary conduction system. Under sinus rhythm, conduction velocities from hearts implanted with SHOX2-EBs were comparable to those from the hearts injected with GFP-EBs, with rapid spreading of the depolarization wave front. After the induction of complete heart block, conduction velocity slowed significantly in the SHOX2-EB-injected hearts, as anticipated for a wave front propagating through non-specialized myocardium (Figures 4F and 4G; Movies S1 and S2). In contrast, the conduction velocity of GFP-EB-injected hearts did not change in complete heart block (Figure 4H, bar graphs). Electrical coupling between the donor and the host myocardium is evidenced by the presence of gap junction proteins at the interface between SHOX2-EBs and the rat ventricular myocardium (Figure S4). Taken together, the data indicate that SHOX2-EBs, but not GFP-EBs, function as biological pacemakers when the EBs were randomly selected and injected into the left ventricular apex of the rat heart.

**Electrophysiology of Single Cells Isolated from SHOX2-EBs**

In order to investigate the pacemaker phenotype of SHOX2-EBs at the single-cell level, we characterized APs from freshly isolated, spontaneously beating cells from SHOX2-EBs or GFP-EBs. The majority (62%) of single cells isolated from SHOX2-EBs exhibit a pacemaker-like AP profile, while 74% of the single cells isolated from GFP-EBs exhibit ventricular/atrial-like APs (Figures 5A and 5B). Single cells from SHOX2-EBs also fired APs at a higher rate than control cells (Figure 5C, left). The mean amplitude of spontaneous APs was lower in SHOX2-EB cells (Figure 5C, second from left), consistent with the lower \( I_N \) density in genuine SAN pacemaker cells (Kapoor et al., 2013). Action potential duration (APD) was shorter, and each AP was preceded by faster phase 4 depolarization in SHOX2-EB cells compared with control (Figure 5C, right two panels). The density of \( I_N \), a key contributor to spontaneous phase 4 depolarization (Lakatta and DiFrancesco, 2009), was significantly higher in SHOX2-EB cells compared with control (Figures 5D and 5E). Thus, SHOX2-EB cells more often display SAN-like AP parameters. Furthermore, the spontaneously beating single cells from both groups responded predictably to adrenergic stimulation and muscarinic challenge (Figures 5F and 5G), demonstrating their responsiveness to neurohumoral input.

**DISCUSSION**

*Shox2* is indispensable for proper formation and development of the SAN. *Shox2* null/null mouse embryos exhibit severe hypoplasia of the SAN accompanied by an aberrant expression of chamber cardiomyocyte-specific markers in the SAN (Blaschke et al., 2007; Espinoza-Lewis et al., 2009). Mouse *Shox2* is first detected at ED8.5 in the posterior region of the developing heart tube, and its expression terminates by ED 13.5, being restricted to the cardiac conduction system (Blaschke et al., 2007; Espinoza-Lewis et al., 2009). Genetic ablation of *Shox2* results in slowed contraction rate in mESC-derived EBs (Hashem et al., 2013). Here, we demonstrate that transient and heterologous expression of SHOX2 greatly increases the percentage of spontaneously beating EBs, the number of beating foci in each EB, and the EB contraction rate compared with control (Figures 4A–4D). The enhanced automaticity correlates directly with more HCN4+ cells present in SHOX2-EBs compared with control (Figure 3A). Direct injection of SHOX2-EBs into isolated hearts upon complete heart block. Upon complete heart block, the hearts injected with SHOX2-EBs demonstrated significantly higher heart rate compared to control (right).

(F) Optically recorded isochronal maps superimposed on the whole-heart injected with GFP-EBs (left) or SHOX2-EBs (right). A white circle indicates the EB implantation site, and the aorta is positioned at the bottom of the image. The anterior side of the heart was positioned to face the CMOS camera. Note the differences in the time scale of the isochronal map; 16 and 27 ms for end-to-end AP propagation for GFP-heart and SHOX2-heart, respectively.

(G) Frame-by-frame analysis of the optical mapping exhibiting AP propagation. The data illustrate slower AP propagation upon complete heart block in the hearts injected with SHOX2-EBs compared with control. Each hexagonal frame, recorded with a photodiode array, measures to a small area of about 8 mm² on the heart.

(H) The conduction velocity of SHOX2-EB injected hearts was significantly slower than that from the control heart upon complete heart block. Data are represented as mean ± SEM. All experiments were performed on three independent biological replicates.

See also Figure S4 and Movies S1 and S2.
Figure 5. Single-Cell Electrophysiology of SHOX2-EBs Demonstrate SAN Pacemaker Cell-like Electrophysiology

(A) Representative raw traces of APs recorded from spontaneously-beating single cells from GFP-EBs (left) or SHOX2-EBs (right).

(B) Percentage of cells with pacemaker-like, atrial-like, or ventricular-like APs in GFP (n = 23) and SHOX2 (n = 21) groups.

(C) Comparison of AP parameters (from left to right): spontaneous beating rate, amplitude of the AP upstroke, spontaneous phase 4 diastolic depolarization rate, and ratio of AP duration at 20% repolarization (APD20) to 80% repolarization (APD80). *p < 0.05.

(D) Representative HCN ionic currents (I_f) recorded from a GFP-EB cell (left) and a SHOX2-EB cell (right). Lower panels show the inhibition of time-dependent currents upon addition of 10 μM ivabradine in the bath solution. HCN currents were recorded in normal Tyrode’s solution containing 1 mM BaCl2 in order to block contaminating inward rectifier K+ currents. The I_f currents were elicited with a family of voltage steps from −135 mV to +35 mV for 1.5 s with 10 mV increment from a holding potential of −35 mV.

(legend continued on next page)
into the rat left ventricular apex created ectopic automaticity indicative of induced biological pacing at a rate faster than the junctional escape rhythm observed in hearts injected with GFP-EBs (Figure 4E). The enhanced automaticity is accompanied by increased expression of automaticity-promoting genes and gene products such as HCN4, NCX1, and CX43 (Figure 3).

As rationale for the timing of SHOX2 overexpression, it may have been more logical to base it when Shox2-positive progenitors exist. In this regard, Shox2 expression is detected as early as day 6 of differentiation (Hashem et al., 2013) in an mESC-derived EB system. This largely coincides with the time points of exogenous SHOX2 overexpression (D3, D6, D7) in our study. It is notable that the beating rates of the GFP-EBs rise and then recede between D6+9 and D6+11 (Figure 4C). The majority of embryonic cardiac myocytes have the tendency to beat spontaneously but become more quiescent as they mature electrophysiologically (Pelleg et al., 1980). Likewise, the rapid decrease in the beating rates of GFP-EBs may be due to changes in their electrophysiological components, similar to the swift increase in \(I_{\text{Na}}\) density in differentiating, mESC-derived EBs (Maltev et al., 1994). In contrast, the spontaneous beating rates remain high in SHOX2-EBs (Figure 4C), further supporting the notion that the superior automaticity of SHOX2-EBs is due to enhanced differentiation to pacemaker cells rather than to nonspecific deterioration of chamber cardiomyocytes.

Cardiac derivatives from ESCs consist of cardiomyocytes of atrial and ventricular phenotypes as well as pacemaker-like cells (Wobus et al., 1995). Because of the absence of specific extracellular epitopes, no live cell sorting method exists to purify pacemaker, ventricular, or atrial myocytes without genetic tagging. As such, the inherent heterogeneity of pluripotent stem cell-derived cardiomyocytes poses a critical impediment to therapeutic/diagnostic applications. For biological pacemaker applications, contaminating ventricular/atrial myocytes in the newly derived cardiac derivatives may compromise pacemaking activity from the implanted cells. Conversely, the presence of pacemaker cells may be arrhythmogenic if ESC-derived cardiomyocytes were to replace a large mass of damaged myocardium. Although implantation of human ESC-derived cardiomyocytes in the guinea pig hearts was shown to be antiarrhythmic (Shiba et al., 2012), delivery of the same cells in nonhuman primates resulted in premature ventricular contractions and ventricular tachycardia in all experimental animals (Chong et al., 2014).

As an in vitro diagnostic tool, induced pluripotent stem cell-derived cardiac myocytes have been proposed as an in vitro platform for drug screen for arrhythmic diseases such as Long QT syndrome (Itzhaki et al., 2011). However, the inherent heterogeneity of these cells, complicated by the fact that the derived cardiomyocytes are largely immature (Mummery et al., 2010; Mummery et al., 2012), may result in erroneous index of how a putative drug may react in atrial or ventricular myocardium. These concerns underscore the need for attaining subtype-specific populations of cardiomyocytes. Previous work by others has tried to address this by inducing pluripotent stem cells to cardiac pacemaker-like cells with various pharmacological agents (Kleger et al., 2010; Müller et al., 2012; Wiese et al., 2011). Here, we demonstrate that SHOX2-mediated pacemaker cell potentiation leads to heightened automaticity in the EBs and that the SHOX2-EBs provide biological pacemaker function upon transplantation into the rat myocardium in vivo. Implantation of the SHOX2-EBs was performed without microsurgical excision of nonbeating areas of the EBs, further highlighting the intensified automaticity in the SHOX2-EBs. The long-term potential of ESC-derived EBs as durable biological pacemakers is an important step toward clinical realization (Jung et al., 2014). However, we do not offer the present findings as a direct prelude to long-term biological pacing tools, but rather as insights into the progression of pacemaker cell development as they are reflected in the EB system.

Because embryonic development of the SAN occurs concurrently with the looping of the linear heart tube (Christoffels et al., 2004), major signaling motifs may impart a unique signature on the developing SAN from the general myocardium. Wnt signaling is indispensable for embryonic heart development (Schneider and Mercola, 2001) and can be manipulated to enrich the cardiomyocyte population from human ESCs (Lian et al., 2012; Willems et al., 2011). Since canonical Wnt signaling is necessary for maintaining mesenchymal precursors that later form the sinus horn (Norden et al., 2011), we looked for differential expression of Wnt ligands and regulators in SHOX2-EBs. On day 6+4 expression of noncanonical Wnt, ligands are mostly suppressed, while that of Wnt inhibitors are higher in SHOX2-EBs compared with control (Figure S5A),

(E) Current density-voltage relationships of GFP (black, \(n = 4\)) and SHOX2 (red, \(n = 5\)) groups. *\(p < 0.05\).
(F) Representative APs of a GFP cell (top row) and a SHOX2 cell (bottom row) before (left) and after treatment with isoproterenol (Iso, 1 \(\mu M\), middle) or acetylcholine (ACh, 50 nM, right).
(G) Summary of beating rate responses before and after treatment with isoproterenol or acetylcholine. Data are represented as mean ± SEM. All experiments were performed on three independent biological replicates.
but the expression pattern reverses later at D6+14 (Figures S5B and S5C). Inhibition of endogenous Wnt generally potentiates cardiac differentiation of ESCs (Kattman et al., 2011; Paige et al., 2010). In contrast, the expression of classical Wnt inhibitors such as Dkk1, Sfrp4, and Wif1 is significantly downregulated in SHOX2-EBs at D6+4 (Figure S5C). The data point to antagonistic effects of Wnt signaling on cardiac myocyte subtype specification, manipulation of which may steer the ESCs to differentiate into a specific cardiac cell type.

**EXPERIMENTAL PROCEDURES**

**Mouse ESC Culture**

The mESC line, R1 (ATCC) was cultured in KnockOut Dulbecco’s modified Eagle’s medium supplemented with 15% KnockOut Serum Replacement, 2 mM l-glutamine, 50 units/ml penicillin, 50 μg/ml streptomycin, 1% MEM nonessential amino acids, and β-mercaptoethanol. The mESCs were kept undifferentiated by culturing them on confluent monolayers of mitomycin C-treated primary mouse embryonic fibroblasts (Millipore) and by adding purified recombinant mouse leukemia inhibitory factor (ESGRO, 1,000 units/ml; Millipore). Cells were maintained at 37°C in a humidified atmosphere of 5% CO2.

**Molecular Cloning and Adenovirus Purification**

The human SHOX2 gene with a C-terminal myc/FLAG tag was excised from pCMV-6-Tbx18 (Origene) by digestion with FseI and Sall and then subcloned into a Notl- and Xhol-digested lentiviral expression vector with the desired reporter gene, pLVX-IRES-ZsGreen1 (Clontech) to create pLV-Tbx18-IRES-ZsGreen. The recombinant target gene was then introduced into an adenovirus backbone by Gateway recombination cloning using Gateway-adapted vectors (Invitrogen). LR recombination reaction experiments were performed between the entry clone and the destination vector, pAd/CMV/V5-DEST, to generate the desired adenoviral expression construct, pAd-CMV-SHOX2-IRES-ZsGreen. Positive constructs were verified to have the correct target gene by DNA sequencing and the recombinant target gene was then introduced to an adenovirus expression vector with the desired reporter gene, pLVX-IRES-ZsGreen1 (Clontech) with the primary antibodies against HCN4 (Abcam), Connexin-45 (CX45; Invitrogen), Connexin-43 (CX43; Sigma-Aldrich), and Na⁺/Ca²⁺ exchanger (NCX1; Abcam). The primary antibodies were detected using horseradish peroxidase-conjugated secondary antibodies raised in appropriate species, followed by chemiluminescence detection (Pico Chemiluminescence Substrate; Pierce). Protein loading was controlled by reprobing the membranes with monoclonal anti-β-actin antibody (Sigma-Aldrich).

**Immunocytochemistry**

Whole-EBs were fixed using 4% paraformaldehyde, washed with PBS, and permeabilized with 0.1% Triton X-100. Fixed cells were blocked with 5% normal donkey serum overnight at 4°C. The EBs were then incubated with primary antibodies for HCN4 (Abcam) and a secondary antibody conjugated with Alexa Fluor 488.

**Western Blot Analysis**

Whole-cell lysates were harvested with RIPA Buffer (Thermo Scientific) containing protease inhibitors (HALT Protease Cocktail; Pierce). Protein concentrations were determined with bicinchoninic acid protein assay (MicroBCA Kit; Pierce). Samples were loaded onto 12% SDS-PAGE, and the separated proteins were transferred to a polyvinylidene fluoride membrane. Blots were incubated overnight at 4°C with the primary antibodies against HCN4 (Abcam), Connexin-43 (CX43; Sigma-Aldrich), and Na⁺/Ca²⁺ exchanger (NCX1; Abcam). The primary antibodies were detected using horseradish peroxidase-conjugated secondary antibodies raised in appropriate species, followed by chemiluminescence detection (Pico Chemiluminescence Substrate; Pierce). Protein loading was controlled by reprobing the membranes with monoclonal anti-β-actin antibody (Sigma-Aldrich).
at 1:500 dilution for 1 hr at room temperature. Nuclei were counterstained with 4′,6-diamidino-2-phenylindole (DAPI).

In Vivo Injection and Ex Vivo Optical Mapping
All animal procedures were reviewed and approved by the Institutional Animal Care and Use Committee of the Cedars-Sinai Medical Center. For testing of biological pacemaker function in animals implanted with the EBs in vivo, 10–12 whole SHOX2-EBs or GFP-EBs were randomly selected and injected with a 24G needle subepicardially into the left ventricular anterior wall of adult Sprague Dawley female rats upon thoracotomy. At 24 to 48 hr after injection, heart was harvested and retrogradely perfused with normal Tyrode’s solution containing 10 μM blebbistatin for 30 min in order to uncouple excitation-contraction, thereby minimizing motion artifacts (Fedorov et al., 2007). The heart was then perfused with di-4-ANEPPS (2 μM; Molecular Probes) for 15 min. Perfusion was made through the aorta, and temperature was continuously maintained at 37°C ± 1°C. During mapping, the heart was positioned in a transparent chamber filled with Tyrode’s solution containing the injected site facing the optical light path, and the optical signals were recorded from a 5 × 5 mm area at baseline (sinus rhythm) and after complete heart block. Heart block was achieved by mechanically excitating the SAN and the AV node. The fluorescences were recorded on a 496-diode array mapping system (WuTech).

Single-Cell Electrophysiology
To examine the electrophysiological properties of individual cardiomyocytes derived from mESC, EBs at D6+14 were dispersed into single cells with a protocol modified from a previous report (Zhang et al., 2002). EBs were digested with a nominally calcium-free solution (in mM: NaCl 140, KCl 5.4, KH₂PO₄ 1.2, MgCl₂ 0.5, HEPES 5, taurine 50, glucose 5.5 [pH = 6.9] with NaOH) containing collagenase B (Roche, 0.5 mg/ml) at 37°C for 50 min followed by digestion with Liberase (Roche, 75 μg/ml) at 35°C for 20 min. Single, whole-cell AP and ionic current measurements were carried out using standard microelectrode whole-cell, patch-clamp technique with an Axopatch 200B amplifier (Molecular Devices) with a sampling rate of 20 kHz and low-pass Bessel-filtered at 5 kHz. Experiments were performed at 33°C ± 1°C. Cells were perfused with a normal Tyrode’s solution containing (mM: NaCl 138, KCl 5, CaCl₂ 1.8, MgCl₂ 0.5, glucose 10, and HEPES 10 [pH = 7.4]) with NaOH. Pipette solution contained (mmol/l) K-glutamate 98, KCl 50, MgCl₂ 1.0, HEPES 10, EGTA 2, and K-ATP 5 (pH = 7.2) with KOH. Microelectrodes had tip resistances of 2–4 MΩ when filled with the internal recording solution. Spontaneous APs were recorded with I = 0 mode. Effects of adrenergic and cholinergic agonists on AP firing rate were tested by perfusing cells with Tyrode solution containing isoproterenol (1 μM, Sigma) or acetylcholine (50 nM; Sigma). Data were corrected for the estimated liquid junction potentials (~12.5 mV). The diastolic depolarization rate was determined from the slope of a 20-ms segment after the maximum diastolic potential. Funny currents (If) were recorded in a voltage-clamp mode with cells bathed in normal Tyrode’s solution containing 1 mM BaCl₂ in order to block contaminating inward rectifier K⁺ currents (Iₖ1). Holding potential was set at −35 mV, and a family of voltage steps from −135 mV to +35 mV for 1.5 s with 10 mV increment was applied to elicit If. The If was identified by their time-dependent activation and their sensitivity to ivabradine (10 μM; Sigma–Aldrich).

Similar to the criteria adopted in the human ESC-derived cardiomyocytes (He et al., 2003), the APs were designated ventricular-, atrial- and pacemaker-like cells based on the AP duration and the slope of spontaneous phase 4 depolarization rate. Ordinary ventricular cardiomyocytes exhibit prominent plateau phase, reflected by their slow early repolarization rate (i.e., long APD₈₀) and short APD₂₀/₈₀. Accordingly, cells with APD₂₀/₈₀ >3.0 were categorized to ventricular-like cells. Pacemaker-like APs were designated to cells with fast phase 4 diastolic depolarization rate (>0.04 V/s) and short APD₂₀/₈₀ ≤3.0. Atrial-like APs were designated to cells with short APD (APD₂₀/₈₀ ≤3.0) and slow phase 4 diastolic depolarization (<0.04 V/s).

Curve Fitting
The time course of endogenous Shox2 expression data was processed by nonlinear curve fitting (Figure 2A) with amplitude version of Gaussian peak function with an equation, \( y = y_0 + A \exp(-0.5 \times ((x - xc)/w)^2) \). Levenberg Marquardt algorithm was used for iteration. The final values for each parameter at the end of the iteration are provided in Table 2.

| Table 1. Primer Sets for Quantitative PCR |
|------------------------------------------|
| Catalog Identification | Interrogated Sequence (RefSeq) | NCBI Chromosome Location | Exon Boundary | Amplicon Length |
|--------------------------|---------------------------------|--------------------------|----------------|-----------------|
| Human SHOX2              | HS00243203_m1 NM_001163678.1   | chromosome 3: 157813800–157823952 | 2–3            | 129             |
| Mouse Shox2              | MM00443183_m1 NM_013665.1      | chromosome 3: 66973266–66981771 | 1–2            | 97              |
| Mouse Tbx3               | MM01195726_m1 NM_011535.3     | chromosome 5: 119670669–119684601 | 7–8            | 65              |
| Mouse Tbx18              | MM00470177_m1 NM_023814.4     | chromosome 9: 87702800–87731260 | 6–7            | 64              |
| Mouse Nkx2.5             | MM00657783_m1 NM_008700.2     | chromosome 17: 26838665–26841565 | 1–2            | 117             |
| Mouse Actc1              | MM0133821_m1 NM_009608.3      | chromosome 2: 114047289–114052811 | 3–4            | 62              |
| Mouse TnnT2              | MM01290256_m1 NM_001130174.2  | chromosome 1: 135836386–135852261 | 8–9            | 110             |
| Mouse Hmbs               | MM01143545_m1 NM_001110251.1 | chromosome 9: 44336348–44344228 | 6–7            | 81              |

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Table 2. Parameters for the Nonlinear Curve Fitting of the Data in Figure 2A

| Parameter                                         | Value    | SE       |
|---------------------------------------------------|----------|----------|
| \( y_0 \)                                         | 1.88621  | 0.12281  |
| \( x_c \)                                         | 5.0783   | 0.23033  |
| \( w \)                                           | 3.34034  | 0.3499   |
| \( A \)                                           | -1.904   | 0.13304  |
| Full width at half maximum                        | 7.86591  | 0.82396  |
| Area                                              | -15.9422 | 2.2425   |
| Number of points                                  | 10       |          |
| Degrees of freedom                                | 6        |          |
| Reduced chi squared                               | 1.28641  |          |
| Adjusted R square                                 | 0.96031  |          |

Statistical Analysis
All data are represented as mean ± SEM. Statistical significance was calculated with an unpaired Student’s t test. A confidence of \( p \leq 0.05 \) was considered significant.

SUPPLEMENTAL INFORMATION
Supplemental Information includes five figures, one table, and two movies and can be found with this article online at http://dx.doi.org/10.1016/j.stemcr.2014.11.004.

AUTHOR CONTRIBUTIONS
V.I. designed and carried out all experiments except the single-cell electrophysiology work. W.L. carried out all experiments that relate to the single-cell electrophysiology.

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