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**Regulation of sinus node pacemaking and atrioventricular node conduction
by HCN channels in health and disease**

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Abstract

The funny current, I_f , was first recorded in the heart 40 or more years ago by Dario DiFrancesco and others. Since then, we have learnt that I_f plays an important role in pacemaking in the sinus node, the innate pacemaker of the heart, and more recently evidence has accumulated to show that I_f may play an important role in action potential conduction through the atrioventricular (AV) node. Evidence has also accumulated to show that regulation of the transcription and translation of the underlying *Hcn* genes plays an important role in the regulation of sinus node pacemaking and AV node conduction under normal physiological conditions - in athletes, during the circadian rhythm, in pregnancy, and during postnatal development - as well as pathological states - ageing, heart failure, pulmonary hypertension, diabetes and atrial fibrillation. There may be yet more pathological conditions involving changes in the expression of the *Hcn* genes. Here, we review the role of I_f and the underlying HCN channels in physiological and pathological changes of the sinus and AV nodes and we begin to explore the signalling pathways (microRNAs, transcription factors, GIRK4, the autonomic nervous system and inflammation) involved in this regulation. This review is dedicated to Dario DiFrancesco on his retirement.

1. Introduction

The funny current, I_f , was first observed in the years from 1968 to 1982 by the groups at the University of Oxford and the National Institute for Physiological Sciences in Okazaki. It was first observed in the Purkinje fibres making up the ventricular conduction system (Noble & Tsien, 1968), where it was wrongly interpreted as a decaying outward current and referred to as $I_{K,2}$. Interestingly, Noble (Noble, 1960) had earlier postulated the presence of such a current in cardiac pacemaker tissue. It was later observed in the pacemaker of the heart, the sinus node (Brown & DiFrancesco, 1980; Yanagihara & Irisawa, 1980; Yanagihara *et al.*, 1980), where it was referred to as I_f or I_h (hyperpolarization-activated current). Finally, it was reported in the atrioventricular (AV) node, which is responsible for conduction of the action potential from the atria to the ventricles (Kokubun *et al.*, 1982). Therefore, I_f is present throughout the cardiac conduction system (sinus node, AV node and His-Purkinje system). The hyperpolarization-activated cyclic nucleotide-gated (HCN) ion channels responsible for I_f in the heart were identified ~20 years ago (Ludwig *et al.*, 1998; Ishii *et al.*, 1999; Ludwig *et al.*, 1999; Vaccari *et al.*, 1999) and since then they have been shown to be expressed throughout the cardiac conduction system. Since its discovery, I_f has never been far from controversy. Early, there was the confusion about the ionic nature of I_f : first, it was considered to be a K^+ current, $I_{K,2}$ (Noble & Tsien, 1968), but later DiFrancesco correctly identified it as a mixed Na^+/K^+ current (DiFrancesco, 1981). After this, there was a debate concerning the importance of I_f in pacemaking as compared to, first, background inward current (Noma *et al.*, 1983; DiFrancesco, 1991; Hagiwara *et al.*, 1992) and, secondly, the Ca^{2+} clock (Lakatta & DiFrancesco, 2009). The debate concerning I_f (part of the so-called membrane clock) and the Ca^{2+} clock continues.

This review concerns yet another debate. In 1880, the University of Cambridge physiologist Walter Holbrook Gaskell wrote that most physiologists attributed the heartbeat to “the action of certain ganglion cells situated in the heart itself, while the cardiac muscular tissue is credited with the purely subordinate role of responding to the impulses generated in these nerve cells” (Gaskell, 1880). In other words, at this time, most physiologists believed the heartbeat to be neurogenic like the contraction of skeletal muscle, but Gaskell went on to disprove this and prove that the heart beat is myogenic in origin by showing that the apex of the tortoise heart although devoid of

ganglion cells has the ability to beat rhythmically like other parts of the heart (Gaskell, 1883). ~20 years later in 1907, Keith and Flack discovered the natural pacemaker of the heart, the sinus node (Keith & Flack, 1907), and after a further ~60 years I_f was discovered. It can be argued that the discovery of I_f finally resolved the original neurogenic versus myogenic debate, which had been ongoing for ~1000 years – Galen, a physician, surgeon and philosopher in the Roman Empire, observed that the heart continued to beat after it had been excised and concluded that “the pulsative faculty of the heart has its source in its own substance” (Fye, 1987; Boyett & D’Souza, 2020). However, what about *changes* in heart rate? We know that short-term changes in heart rate such as *during* exercise, the vaso-vagal reflex or the diving reflex are ‘neurogenic’ and caused by the autonomic nervous system. However, there is a vigorous modern neurogenic versus myogenic debate concerning long-term changes in heart rate in the athlete and during the day-night cycle (Boyett & D’Souza, 2020). These changes are generally attributed to the vagus (i.e. they are neurogenic), but could they be myogenic, i.e. intrinsic to the heart? Long-term changes in heart rate occur in other circumstances as well, and what is responsible for them? This review shows an important role for myogenic mechanisms: an important role for HCN channels and I_f in long-term heart rate changes both under physiological conditions (in athletes as well as during the circadian rhythm, pregnancy and postnatal development) and in pathophysiological states (in ageing, heart failure, pulmonary hypertension, diabetes and atrial fibrillation - although ageing is not in itself a pathological state, it is associated with sinus node dysfunction). This work raises questions about transcriptional regulation of HCN channels and this review also discusses this newly emerging field of study. Finally, this review highlights a new role for HCN channels and I_f in atrioventricular (AV) node conduction. This review is dedicated to Dario DiFrancesco on the occasion of his retirement.

Although this review focusses on HCN channels, it does not mean that other ion channels and mechanisms are not involved, and some are mentioned here. In this review, proteins are written in capitals (e.g. HCN4) whereas mRNAs (transcripts) and genes are written in italics in lower case with an initial capital letter (e.g. *Hcn4*).

2. Expression of HCN channels in the sinus node and AV node

The sinus node is located at the junction of the superior vena cava with the right atrium. It is frequently shown in medical textbooks as a small nodule at this point, but is now known from the

work of Dobrzynski and others to extend from the junction down the crista terminalis (a thick bundle of atrial muscle) towards the inferior vena cava and is closely associated with the sinus node artery (Fig. 1A-D) (Dobrzynski *et al.*, 2005; Chandler *et al.*, 2011; Stephenson *et al.*, 2012; Stephenson *et al.*, 2017). There are four HCN channels. HCN1 channels have a more positive threshold for activation and faster activation kinetics. The cyclic nucleotide binding domain of HCN1 channels contains pre-bound cAMP (Lolicato *et al.*, 2011). This high affinity for cAMP of HCN1 channels renders HCN1-mediated I_f poorly sensitive to variations in intracellular cAMP concentration (Lolicato *et al.*, 2011). In contrast, HCN4 channels are slowly gating and have higher sensitivity to variations in cAMP level. Finally, HCN2 and HCN3 have intermediate properties between HCN1 and HCN4 (Santoro & Tibbs, 1999; Baruscotti *et al.*, 2005; Wahl-Schott & Biel, 2009). Interestingly, cAMP induces channel tetramerisation of HCN2 and HCN4 channels (Lolicato *et al.*, 2011). HCN4 is widely regarded as the most highly expressed isoform in the two nodes. For example, in the mouse sinus node, the abundance of the channel transcripts as determined by RNAseq is *Hcn4*>*Hcn1*>*Hcn2*>>*Hcn3* (Wang *et al.*, 2021) and this is typical for the two nodes. The expression of HCN4 (green signal) and Cx43 (red signal) proteins in the rat sinus node as determined by Yanni and Dobrzynski using immunohistochemistry is shown in Fig. 1E (Boyett, 2009). Whereas HCN4 is expressed exclusively (or almost exclusively) in the sinus node, Cx43 is expressed exclusively (or almost exclusively) in the surrounding atrial node. Expression of HCN4 protein in the AV node has been shown by us (Dobrzynski *et al.*, 2003) as well as others.

3. What HCN4 mutations tell us

Naturally occurring mutations in HCN4 in the human show the importance of the channel for both the sinus and AV nodes. Loss-of-function mutations in human HCN4 cause asymptomatic and symptomatic sinus bradycardia and chronotropic incompetence (Schulze-Bahr *et al.*, 2003; Milanesi *et al.*, 2006; Hategan *et al.*, 2017) and also AV block (Zhou *et al.*, 2014b), whereas gain-of-function mutation causes inappropriate sinus tachycardia (Baruscotti *et al.*, 2015). Interestingly, loss of function mutations in HCN4 also result in atrial fibrillation (AF) (Duhme *et al.*, 2013; Macri *et al.*, 2014). It is known that AF causes sinus node dysfunction by downregulating HCN4 (see below) and, therefore, the interaction between HCN4 and AF appears to be two-way.

4. Regulation of the HCN channels in health - resting bradycardia in athletes

It is well known that athletes have a low resting heart rate – a resting bradycardia (Fig. 2A) (D'Souza *et al.*, 2015). Despite this, the athlete's heart can still provide sufficient cardiac output at rest –athletes have enlarged hearts with a greater stroke volume (Maron Barry & Pelliccia, 2006) and this will help offset the effect of the lower heart rate. Elite cyclists can have resting heart rates of ~30 beats/min (D'Souza *et al.*, 2015) (see also Fig. 2A). This bradycardia is particularly marked at night (Fig. 2B) (Northcote *et al.*, 1989). At night, athletes can have nocturnal pauses, which have been documented to be as long as 15 s in veteran athletes (Northcote *et al.*, 1989). Sinus node dysfunction is more common in veteran athletes and they are more likely to need a pacemaker implanted (Baldesberger *et al.*, 2008). As stated in the Introduction, the resting bradycardia in athletes for many decades has been attributed to high vagal tone (Aubert *et al.*, 2003). This assertion is primarily based on measurement of heart rate variability (Aubert *et al.*, 2003). Heart rate variability is widely used as an indirect measure of autonomic tone to the heart (Aubert *et al.*, 2003). Athletes have a greater heart rate variability, and this is said to be evidence of an increase in vagal tone (Aubert *et al.*, 2003). However, following Zaza and colleagues (Zaza & Lombardi, 2001), we have shown that heart rate variability is primarily influenced by the heart rate and we have argued that the increase in heart rate variability in athletes is the result of the resting bradycardia in these individuals (i.e. the resting bradycardia is not a 'consequence' of the increase in heart rate variability or at least what is thought to be the underlying factor, an increase in vagal tone) (Monfredi *et al.*, 2014). Another way to test the role of the autonomic nervous system in the resting bradycardia resulting from exercise training is to pharmacologically block cardiac autonomic tone. This has been carried out many times in both human athletes as well as animal models (Boyett *et al.*, 2013). The majority of the studies show that a resting bradycardia is still present after complete autonomic blockade – for example, in the horse (Betros *et al.*, 2013). In human athletes, the relative bradycardia is greater after autonomic blockade (Katona *et al.*, 1982; Boyett *et al.*, 2013; D'Souza *et al.*, 2017). Bahrainy *et al.* (Bahrainy *et al.*, 2016) concluded that both parasympathetic (vagal) and sympathetic tone is unchanged in human subjects after six months of exercise training. This evidence is inconsistent with the high vagal tone hypothesis to explain the resting bradycardia in athletes.

Using rodent models of exercise training, we showed that the resting bradycardia is still present after complete autonomic blockade and, in addition, the intrinsic beating rate of the isolated (denervated) sinus node preparation taken from exercise trained animals is lower (D'Souza *et al.*, 2014). This points to an intrinsic mechanism being responsible, and quantitative PCR (qPCR) showed a downregulation of the transcripts for many ion channels, including the HCN channels, in the sinus node of exercise trained animals (D'Souza *et al.*, 2014). There is a downregulation of the principal HCN channel, HCN4, at both transcript and protein levels, and there is also a downregulation in the density of the corresponding funny current, I_f (Fig. 2C) (D'Souza *et al.*, 2014). Finally, we showed that block of HCN channels and I_f by Cs⁺ or ivabradine abolishes the difference in the intrinsic beating rate of the isolated sinus node taken from exercise trained animals and control sedentary animals, and the difference in the resting heart rate of conscious or anaesthetised exercise trained animals and control sedentary animals (D'Souza *et al.*, 2014). This suggests that the resting bradycardia in exercise trained animals is the result of the downregulation of HCN channels and I_f . The same may be true in human athletes: we showed that the lower the resting heart rate, the smaller the effect of ivabradine and this is consistent with a downregulation of I_f in human athletes (D'Souza *et al.*, 2017). However, other factors may also be involved – for example, D'Souza *et al.* (D'Souza *et al.*, 2014) observed a downregulation of other ion channel transcripts (apart from *Hcn4*) and Bidaud *et al.* (Bidaud *et al.*, 2020b) have reported a training-induced downregulation of L- and T-type Ca²⁺ currents, $I_{Ca,L}$ and $I_{Ca,T}$ (as well as I_f).

What is responsible for the downregulation of HCN4 and I_f following exercise training? In recent years, we have focused on epigenetic regulation by microRNAs, small non-coding RNAs that regulate gene expression by either targeting a mRNA for degradation or by inhibiting translation (D'Souza *et al.*, 2017). A screen of microRNAs in the mouse sinus node identified significant increases in 25 microRNAs, for example miR-423-5p (Fig. 2D), following exercise training and some of these were suggested by bioinformatics and *in vitro* luciferase reporter gene analysis to target HCN4 (D'Souza *et al.*, 2017). miR-423-5p was identified as the most likely microRNA to be targeting HCN4. An anti-miR targeting miR-423-5p given to mice *in vivo* prevented the exercise training-induced upregulation of miR-423-5p, downregulation of HCN4, and decrease

in heart rate (Fig. 2D) (D'Souza *et al.*, 2017). Further experiments suggested that miR-423-5p was under the control of the transcription factor, NKX2.5 (D'Souza *et al.*, 2017).

Although miR-423-5p-NKX2.5 interactions may be the immediate cause of the exercise training-induced downregulation of HCN4, D'Souza *et al.* (D'Souza *et al.*, 2017) did not identify the pathway upstream of the microRNA. A clue about the possible upstream pathway came from an unexpected direction. In the sinus node, ACh released from the vagus binds to the muscarinic M₂ receptor and activates an outward K⁺ current, $I_{K,ACh}$, carried by heteromultimeric channels comprised of Kir3.1 (GIRK1) and Kir3.4 (GIRK4); activation of $I_{K,ACh}$ results in an acute bradycardia, i.e. immediate slowing of heart rate (left hand side of Fig. 3A). Surprisingly, Mangoni and colleagues discovered that genetic ablation (i.e. knocking out) of Kir3.4 or pharmacologic block of $I_{K,ACh}$ by administration of the peptide blocker tertiapin-Q can rescue sinus node dysfunction and high-degree AV block caused by loss-of-function of inward current carrying ion channels, HCN4 and Ca_v1.3 (Mesirca *et al.*, 2014; Mesirca *et al.*, 2016; Bidaud *et al.*, 2020a). These findings were explained by the hypothesis that a decrease in inward current in diastole can be compensated for by decreasing an outward current, $I_{K,ACh}$, in diastole. Mesirca, Mangoni and colleagues asked the question whether knockout of Kir3.4 can reverse exercise training-induced bradycardia (Bidaud *et al.*, 2020b). Knockout of Kir3.4 did indeed reverse exercise training-induced bradycardia (Bidaud *et al.*, 2020b). However, D'Souza and colleagues showed that knockout of Kir3.4 prevented: (i) the upregulation of miR-423-5p (Fig. 3B) and other microRNAs likely to be targeting HCN4, (ii) the downregulation of HCN4 (Fig. 3C-E) and (iii) the downregulation of I_f density with exercise training (Bidaud *et al.*, 2020b). We tentatively suggest that the ACh-activated K⁺ channel may act as a signalling molecule to bring about the downregulation in HCN4 (Fig. 3A). However, there must be a stimulus acting on the ACh-activated K⁺ channel following exercise training to bring about the transcriptional remodelling. One possibility is high vagal tone in athletes (Fig. 3A), although Bidaud *et al.* (Bidaud *et al.*, 2020b) obtained no evidence of this.

Knockout of Kir3.4 not only prevented the training-induced downregulation of I_f , it also prevented a training-induced downregulation of L- and T-type Ca²⁺ currents in the sinus node as well as the training-induced prolongation of the PR interval and physiological hypertrophy (Fig. 3A)

(Bidaud *et al.*, 2020b). Clearly, more work is required to unravel the mechanisms and pathways involved.

5. Regulation of the HCN channels in health - circadian rhythm in heart rate

It has been known since the 1600's that there is a circadian rhythm in the heart rate (Lemmer, 2009) – the heart rate is higher during the awake period and lower during the sleep period. Fig. 2B shows an example from Northcote *et al.* (Northcote *et al.*, 1989) in human athletes and sedentary controls. The heart rate is presumably higher during the awake period to anticipate the increase in demand for cardiac output during the awake period. Although it is known that increased heart rate is a predictor of all-cause and cardiovascular mortality, in the study of Johansen *et al.* (Johansen *et al.*, 2013) of middle-aged subjects with no apparent heart disease, only night-time (not day-time or 24 h) heart rate was associated with adverse cardiovascular events after adjusting for cardiovascular risk factors. We have worked on the circadian rhythm in heart rate for about seven years and it has proved to be the most difficult project we have worked on. Partly, this was because the circadian rhythm in heart rate is complex and multifactorial and involves many systems (not just the heart) - it is an excellent example of integrative whole animal physiology. However, partly, it was because the circadian rhythm in heart rate had already been attributed to a circadian rhythm in cardiac vagal tone for many decades (Boas & Weiss, 1929; Sutherland, 1929; Bexton *et al.*, 1986; Black *et al.*, 2019) and, therefore, the work proved controversial and it provokes strong opinions from reviewers and others.

The commonly held assumption is that vagal tone is high during sleep and this results in greater release of ACh, which via the muscarinic M₂ receptor, results in a greater activation of $I_{K,ACh}$ and possibly a lower basal intracellular cAMP concentration leading to a slower heart rate through the workings of the coupled clock system (Monfredi *et al.*, 2013). Heart rate variability has been used as one line of evidence to assert that the circadian rhythm in heart rate is the result of high vagal tone during sleep. Heart rate variability is high during sleep when heart rate is low (Vandewalle *et al.*, 2007). Once again, we argue that the heart rate variability may be high because the heart rate is low (and not vice versa). Another test used is complete autonomic blockade using pharmacological blockers. The data obtained are variable with some studies showing that the circadian rhythm in heart rate is unaffected by complete autonomic blockade and

others showing that it is affected (Black *et al.*, 2019). We have previously reviewed the effect of complete autonomic blockade on the circadian rhythm in heart rate and tentatively conclude that acute autonomic blockade does not block the circadian rhythm in heart rate (Black *et al.*, 2019). The circadian rhythm in heart rate also persists after chronic functional autonomic blockade: (i) knockout of the muscarinic M₂ ACh receptor or knockout of the β_1 , β_2 and β_3 receptors mediating the effects of ACh and catecholamines released by the autonomic nervous system on the heart does not block the circadian rhythm in heart rate (although this does not rule out a role for neuropeptides released from vagal nerve endings) (Swoap *et al.*, 2008); and (ii) heart transplant patients with denervated hearts show a circadian rhythm in heart rate (although this does not rule out a role for a circadian variation in the level of circulating catecholamines) (Idema *et al.*, 1994; Kotsis *et al.*, 2005). However, the effects of chronic intervention should be viewed cautiously, because chronic intervention may lead to compensatory transcriptional remodelling. One problem has been that, in both the case of athletic bradycardia and the circadian rhythm in heart rate, imperfect surrogates of cardiac autonomic tone have been measured rather than autonomic tone itself. However, Bussey (Bussey, 2019) has recently directly recorded cardiac sympathetic and parasympathetic (vagal) nerve activity in the rat and observed no evidence of a circadian variation.

Our work has focussed on the mouse. We confirmed that there is a circadian rhythm in heart rate *in vivo*, and *in vivo* the circadian rhythm in heart rate persists after acute pharmacological autonomic blockade and on right cervical vagotomy (in rats) (D'Souza *et al.*, 2021). There is also a circadian rhythm in the intrinsic beating rate of the isolated and therefore denervated sinus node (D'Souza *et al.*, 2021). This work together with the work of others reviewed above suggests that there is an intrinsic circadian rhythm in sinus node pacemaking. There are circadian rhythms of many physiological systems and, ultimately, the majority, if not all of these, are the result of a molecular circadian clock (Patke *et al.*, 2020). There is a master circadian clock in the suprachiasmatic nucleus in the hypothalamus and there are peripheral clocks in many if not all peripheral tissues (Mohawk *et al.*, 2012). There is known to be a local circadian clock in the heart (Durgan & Young, 2010). Measurement of selected transcripts using qPCR by D'Souza *et al.* (D'Souza *et al.*, 2021) showed that there is a functioning local circadian clock in the sinus node (Fig. 4A); this was confirmed by coupling promoter activity of the clock gene *Period* to a

bioluminescent reporter. qPCR, western blot and patch clamp showed that there is a circadian rhythm in HCN4 transcript and protein and the density of I_f (Fig. 4B-D) (D'Souza *et al.*, 2021). Is the circadian rhythm in HCN4 and I_f density responsible for the circadian rhythm in heart rate? Block of HCN channels and I_f *in vivo* using ivabradine (Fig. 4E) or *in vitro* (in the isolated sinus node) using 2 mM Cs⁺ abolished the circadian rhythm in heart rate and intrinsic beating rate, respectively, and this suggests that the circadian rhythm in HCN4 and I_f density is involved (D'Souza *et al.*, 2021).

In a subsequent study, we showed that ~44% of the sinus node transcriptome (7,134 of 16,387 transcripts) measured using RNA-seq exhibits a circadian rhythm (Wang *et al.*, 2021). Consistent with the previous study, *Hcn4* tended to show a circadian rhythm, but in addition, *Hcn1* and *Hcn2* showed significant circadian rhythms (Wang *et al.*, 2021). Regulators of HCN4 - TRPM7, a divalent-permeant channel-kinase, AMP kinase, and phosphoinositide 3-kinase (Sah *et al.*, 2013; Yavari *et al.*, 2017; Lin *et al.*, 2019) - also showed a circadian rhythm (Wang *et al.*, 2021). However, other pacemaker transcripts (for example Ca²⁺ clock transcripts) showed a circadian rhythm (Wang *et al.*, 2021). Therefore, I_f may not be the only pacemaker mechanism involved in the circadian rhythm in pacemaking. Transcripts responsible for receptors and signalling pathways known to control pacemaking, transcripts from genes identified by GWAS as determinants of resting heart rate, and transcripts from genes responsible for familial and acquired sick sinus syndrome all exhibited a circadian rhythm (Wang *et al.*, 2021).

In conclusion, based on the information presented above, there is little or no evidence that the circadian rhythm in heart rate is the result of the autonomic nervous system and *acute* regulation of ionic conductances as previously thought. Instead, there is evidence that the circadian rhythm in heart rate is the result of transcriptional regulation of ion channel expression. What is responsible for the circadian rhythm in transcripts? There are three possibilities:

(i) *The local circadian clock in the sinus node.* BMAL1 and CLOCK are important circadian clock transcription factors that exert transcriptional control over clock-controlled genes by forming a heterodimer and binding to enhancer (E-box) elements (Monfredi & Lakatta, 2019). On the basis of computational predictions, we identified eight E-box binding regions on the *Hcn4* gene; a ChIP assay confirmed that BMAL1 can bind to two specific intronic regions of the *Hcn4* gene (D'Souza *et al.*, 2021). It is therefore possible that the local circadian clock in the sinus node is involved in

Hcn4 transcription. However, current understanding of clock-controlled gene regulation is based on a co-operative action between core clock transcription factors and local, tissue-specific transcription factors (Beytebiere *et al.*, 2019). Therefore, it is likely that candidates among the 347 transcription factors that we have identified to show a circadian rhythm in the sinus node (Wang *et al.*, 2021) are involved. microRNAs can also regulate expression as discussed above and Anderson *et al.* (Anderson *et al.*, 2019) have shown a circadian rhythm in 74 microRNAs. We are exploring specific targeting of *Hcn4* by rhythmic microRNAs.

After cardiomyocyte-specific knock out of the key circadian clock gene, *Bmal1*, in the mouse, Schroder *et al.* (Schroder *et al.*, 2013) have shown that the circadian rhythm in heart rate continues almost unchanged. At face value, this is evidence that the local circadian clock in the heart does not play a major role in the circadian rhythm in heart rate; a contemporary review on the subject has also arrived at this conclusion (Rana *et al.*, 2020). However, Anderson, Boyett and D'Souza using RNAseq (Wang *et al.*, 2021) have shown that in the sinus node of a cardiomyocyte-specific *Bmal1* knockout mouse (D'Souza *et al.*, 2021), *Bmal1* is not knocked out but only marginally depressed and the other clock genes continue to oscillate almost unchanged (transcripts measured in n=3 knockout mice and n=3 wild-type mice at six time points over 24 h). Therefore, the continuing circadian rhythm in heart rate in the cardiac-specific *Bmal1* knockout mouse does not necessarily rule out the involvement of the local circadian clock in the sinus node. This uncertainty needs to be resolved. The circadian rhythm in heart rate also continues almost unchanged in a cardiac-specific *Clock* dominant negative mutant mouse (Bray *et al.*, 2008). Is this evidence against the involvement of the local circadian clock in the sinus node in the circadian rhythm in heart rate? Bearing in mind the experience of the *Bmal1* knockout mouse, it needs to be confirmed that the dominant negative *Clock* mutant does indeed abolish the local circadian clock in the sinus node myocytes. It may also be relevant that both *Bmal1* and *Clock* have paralogs (*Bmal2* and *Npas2*) that can substitute for *Bmal1* and *Clock* (Shi *et al.*, 2010; Landgraf *et al.*, 2016).

(ii) *The master clock in the suprachiasmatic nucleus.* Tong *et al.* (Tong *et al.*, 2013) have shown a circadian rhythm in various K⁺ channels in mouse atria and ventricles and the circadian rhythm was abolished by *chronic* pharmacological blockade of the autonomic nervous system; they reported similar findings for connexins (Tong *et al.*, 2016). Tong *et al.* (Tong *et al.*, 2013)

concluded that the master circadian clock in the suprachiasmatic nucleus is responsible for the circadian rhythm in the expression of the ion channels in the atria and ventricles. Tong *et al.* (Tong *et al.*, 2013) also reported that *chronic* pharmacological blockade of the autonomic nervous system abolished the circadian rhythm in heart rate. Therefore, it is possible that the circadian rhythm in heart rate involves the autonomic nervous system and transcriptional regulation of ion channels.

In favour of master clock control are the findings that lesioning the suprachiasmatic nucleus completely abolishes the circadian rhythm in heart rate (as well as body temperature and physical activity rhythms), chronic autonomic blockade can abolish the circadian rhythm in rhythmic cardiac ion channel gene transcription, and the presence of an anatomical connection between the suprachiasmatic nucleus and the stellate ganglion - the main sympathetic ganglion innervating the heart (Ueyama *et al.*, 1999; Scheer *et al.*, 2003; Tong *et al.*, 2013; Tong *et al.*, 2016). Interestingly, depletion of peripheral catecholamine content with guanethidine abolished the circadian rhythm in heart rate specifically (body temperature and physical activity were unaffected) in the work of Warren *et al.* (Warren *et al.*, 1994), although this conclusion is disputed (Makino *et al.*, 1997; Oosting *et al.*, 1997). These data suggest that the master clock may signal to the sinus node via the sympathetic nervous system to bring about changes in gene transcription (Warren *et al.*, 1994).

(iii) The master clock in the suprachiasmatic nucleus acting via the local circadian clock in the sinus node. There are two ways by which the master clock in the suprachiasmatic nucleus may be generating circadian rhythms in transcripts in the sinus node. The autonomic nervous system may be directly controlling cardiac gene transcription, but alternatively the function of the autonomic nervous system may be to entrain the local circadian clock in the sinus node to the master circadian clock in the suprachiasmatic nucleus and it is the local clock that controls gene transcription. For example, it is known that β -agonist increases PER2 circadian rhythms in cultured cardiac ventricular tissue (Beesley *et al.*, 2016).

6. Regulation of the HCN channels in health - increase in heart rate in pregnancy

A variety of changes in the cardiovascular system occur during normal pregnancy in the human, including an increase in heart rate (Fig. 5A), stroke volume and cardiac output (Hall *et al.*, 2011). The increase in cardiac output is necessary to meet the increased metabolic demands of tissues and this is achieved by the increases in heart rate and stroke volume (Hall *et al.*, 2011). During

pregnancy, there is an increased risk of arrhythmia, and a higher resting heart rate is a known risk factor for arrhythmias (El Khoury *et al.*, 2013). El Khoury *et al.* (El Khoury *et al.*, 2013) observed a faster heart rate in the pregnant mouse and this persisted in the absence of autonomic nervous innervation: in the Langendorff-perfused heart and the isolated sinus node cell. Pregnancy increased the density of I_f (Fig. 5C) and, although there was no change in the expression of HCN4, there was an increase in the expression of HCN2 (El Khoury *et al.*, 2013). El Khoury *et al.* (El Khoury *et al.*, 2013) concluded that the increase in I_f density contributes to the increase in heart rate in pregnancy. The increase in I_f during pregnancy is caused by 17β -estradiol (Long & Fiset, 2020).

7. Regulation of the HCN channels in health - postnatal development

The heart rate of the human and other large mammals decreases postnatally. In the human, it decreases from ~140 to 70 beats/min (Fig. 5B). In the rabbit, we showed that there is a decrease in the intrinsic heart rate (measured in the isolated sinus node) from the neonate to the adult (Abd Allah *et al.*, 2011). During postnatal development, qPCR revealed a significant decline in the sinus node of *Hcn1* and *Hcn4* mRNAs as well as other ion channel transcripts expected to impact pacemaking (Nav1.5, Cav1.3, *Slc8a1/NCX1*, Kv1.5, KvLQT1, minK and ERG; immunohistochemistry also showed complex changes in the expression of Ca^{2+} -handling proteins) (Abd Allah *et al.*, 2011). In the adult rabbit as compared to the newborn rabbit, Accili *et al.* (Accili *et al.*, 1997) observed a decrease in the maximal conductance of I_f consistent with the findings of Abd Allah *et al.* (Abd Allah *et al.*, 2011). Accili *et al.* (Accili *et al.*, 1997) also observed a steeper dependence of activation of I_f on membrane potential. The changes in *Hcn1*, *Hcn4* and I_f could contribute to the decreased heart rate in the adult and this was confirmed by Zhang and colleagues using biophysically-detailed computer modelling (Alghamdi *et al.*, 2020b). However, this is unlikely to be the only factor involved: Baruscotti *et al.* (Baruscotti *et al.*, 1996) showed that in the rabbit the density and frequency of occurrence of the Na^+ current, I_{Na} , decreased during postnatal development and, whereas block of I_{Na} by TTX decreased the spontaneous rate of sinus node cells from newborn rabbits by 63%, it had no effect on cells from adult animals. There is also a postnatal decrease in the density of I_{Na} in the dog (Protas *et al.*). This is perhaps consistent with the postnatal decrease in Nav1.5 mRNA described above, although sinus node cells also express

neuronal type Na⁺ channels (Protas *et al.*; Baruscotti *et al.*, 1997). There is also a postnatal decrease in the density of $I_{Ca,L}$ in the rabbit, although changes in the voltage-dependence of the current predisposes towards an increase rather than decrease in the contribution of $I_{Ca,L}$ to pacemaking (Protas *et al.*, 2001).

Interestingly, the heart rate of small mammals increases rather than decreases postnatally. Adachi *et al.* (Adachi *et al.*, 2013) reported that in the mouse the heart rate increases from ~320 beats/min at birth to ~690 beats/min at postnatal day 14. In this case, the change was not associated with any change in I_f . Adachi *et al.* (Adachi *et al.*, 2013) concluded that the postnatal increase in heart rate is in part the result of an increase in sympathetic tone and in part an increase in the intrinsic heart rate (measured *in vivo* after autonomic blockade or *in vitro* in the isolated sinus node). In patch clamp experiments, there was an increase in the density of $I_{Ca,L}$ and a hyperpolarizing shift of the $I_{Ca,L}$ activation curve and this could be responsible for the postnatal increase in the intrinsic heart rate (Adachi *et al.*, 2013).

8. Regulation of the HCN channels in disease - ageing

Sinus node dysfunction is primarily a disease of ageing and it increases in an exponential-like manner with age (Fig. 6C) (Benditt *et al.*, 1995); AV node dysfunction increases in a similar fashion (Penton *et al.*, 1956). For example, pacemakers are mainly implanted in the elderly (<https://www.statista.com/statistics/982630/number-of-new-pacemaker-implants-in-sweden-by-gender-and-age/>). Although the resting heart rate in the human changes little with age after adulthood is achieved (Fig. 6A) (Kuga *et al.*, 1993; Ostchega *et al.*, 2011; Avram *et al.*, 2019), the heart rate *in vivo* is determined by the intrinsic properties of the sinus node together with the autonomic nervous system. Jose and Collison (Jose & Collison, 1970) measured the intrinsic heart rate after complete autonomic blockade in 432 human subjects and unlike the normal heart rate there was a steady decline of the intrinsic heart rate with age; Kuga *et al.* (Kuga *et al.*, 1993) obtained similar results (Fig. 6B). In addition, there is an age-dependent increase in the sinus node conduction time (time taken for the action potential, once initiated, to exit the sinus node) (Kuga *et al.*, 1993). This suggests that there is a decline in intrinsic sinus node function with age. This age-dependent decline has been the focus of various studies from us and others and the results have been varying. The oldest explanation is that age-dependent sinus node dysfunction is the result of

fibrosis (i.e. a proliferation of the extracellular matrix). For example, interstitial collagen deposition and an increase in fibroblast area has been reported in the ageing mouse (Hao *et al.*, 2011; Moghtadaei *et al.*, 2016). The case for age-dependent sinus node fibrosis has been recently reviewed by Csepe *et al.* (Csepe *et al.*, 2015). However, Alings *et al.* (Alings *et al.*, 1995) investigated the possibility of age-dependent fibrosis in 41 human and 21 cat hearts and concluded that there is no age-dependent change in collagen content (although there is a change in collagen organisation). In the ageing rat, Yanni *et al.* (Yanni *et al.*, 2010) observed no evidence of age-dependent fibrosis. For example, using qPCR, they observed a ~79% downregulation of mRNA for collagens 1 and 3 and a ~52% downregulation of mRNA for elastin (Yanni *et al.*, 2010). In contrast, an age-dependent increase in the interstitium and a loss of nodal cells has been reported in the rat (de Melo *et al.*, 2002).

The action potential in the centre of the sinus node has a slow upstroke because it is generated by the relatively small and slow L-type Ca^{2+} current, $I_{\text{Ca,L}}$, rather than the much larger and faster Na^+ current as in the atrial and ventricular working myocardium. Alings and Bouman (Alings & Bouman, 1993) investigated the ageing rabbit and cat sinus node and showed that there is an enlargement of the area with a slow action potential. This is consistent with the loss of Na^+ channels and I_{Na} from the sinus node - although Na^+ channels and I_{Na} are absent from the centre of the sinus node, they are present in the periphery (Tellez *et al.*, 2006). Consistent with this, an age-dependent loss of mRNA for the cardiac Na^+ channel, Nav1.5, has been observed in the mouse sinus node (Hao *et al.*, 2011); an age-dependent loss of mRNA for other Na^+ channel isoforms has also been reported from the rat sinus node (Huang *et al.*, 2015). Zhang *et al.* (Zhang *et al.*, 1998) have shown using biophysically-detailed computer modelling that a decrease in I_{Na} in the periphery of the sinus node would indeed lead to a slowing of pacemaking and an increase in the sinus node conduction time. This is supported by the fact that loss-of-function mutations of Nav1.5 are associated with sinus node dysfunction (Butters *et al.*, 2010). In the ageing rat, although we did not observe a decrease in Nav1.5 mRNA in the sinus node measured using qPCR (Tellez *et al.*, 2011), using immunohistochemistry, we did observe an expansion of the Nav1.5-negative area of the sinus node (Yanni *et al.*, 2010).

In studies of the ageing guinea-pig, using western blot, we observed a downregulation of protein for the gap junction channel, Cx43, and the L-type Ca^{2+} channel, Cav1.2, in the sinus node; there was also an age-dependent increase in the sensitivity to Ca^{2+} channel block by nifedipine consistent with a downregulation of Ca^{2+} channels (Jones *et al.*, 2004; Jones *et al.*, 2007). However, in the ageing rat (Tellez *et al.*, 2011), we observed no changes in Cx43 and Cav1.2 mRNA measured by qPCR, but we did observe a significant downregulation of mRNA for the ryanodine receptor, RyR2, which is known to play a central role in the Ca^{2+} clock mechanism of pacemaking (Lakatta *et al.*, 2010).

In the ageing rat, we observed a large significant downregulation of *Hcn1* mRNA, but not of other *Hcn* mRNAs (Tellez *et al.*, 2011), and, in the ageing mouse, we observed a significant downregulation of *Hcn1* and *Hcn2* mRNAs (Hao *et al.*, 2011). In the ageing rat, Huang *et al.* (Huang *et al.*, 2007) observed a downregulation of *Hcn2* and *Hcn4* mRNAs. One of the most interesting studies of the ageing sinus node was carried out on the mouse by Larson *et al.* (Larson *et al.*, 2013). Using isolated sinus node myocytes, Larson *et al.* (Larson *et al.*, 2013) showed an age-dependent decrease in the density of $I_{\text{Ca,L}}$, $I_{\text{Ca,T}}$ and I_f as well as a hyperpolarizing shift of the voltage-dependence of I_f ; the decrease in I_f density is shown in Fig. 6D,E. Interestingly, Sharpe *et al.* (Sharpe *et al.*, 2017) showed that, in isolated sinus node cells from mice, the effects of ageing were abolished by a high concentration of exogenous cAMP, which restored the beating rate and I_f of sinus node cells from old mice to the level seen in cells from young mice.

In conclusion, age-dependent sinus node dysfunction is likely to be the result of sinus node remodelling including downregulation of HCN channels and I_f . However, disparate results have been obtained in different studies and the reason for this is unclear. One explanation for the variability amongst studies may be the presence of comorbidities and as a result the remodelling can take different forms. For example, our study of the ageing rat was carried out on males, and the male rats became obese with age (Yanni *et al.*, 2010). Moghtadaei *et al.* (Moghtadaei *et al.*, 2016) studied the effect of ageing in the mouse and noted that sinus node dysfunction is correlated with frailty (accumulation of health deficits), although the R^2 value was generally low and therefore frailty is a relatively poor indicator (for example, for *in vivo* heart rate versus frailty, $R^2=0.09$). Using a biophysically-detailed model of the rat sinus node action potential, Alghamdi *et al.* (Alghamdi *et*

et al., 2020a) examined two different patterns of ion channel remodelling that have been reported in the aged rat sinus node and concluded that both patterns result in bradycardia; this work suggested that in each case it is the change in $I_{Ca,L}$ that plays the most important role and I_f plays little or no role. However, there is experimental evidence that the downregulation of I_f does play a role: Huang *et al.* (Huang *et al.*, 2007) reported that the intrinsic heart rate of the rat (measured *in vivo* after autonomic blockade decreases by 55 beats/min (from ~310 to ~255 beats/min) from the adult to the senescent animal, and block of I_f by 3 μ M ivabradine prolonged the cycle length of the isolated sinus node from adult and senescent animals by ~26 and ~13%. This suggests that after partial block of I_f (3 μ M ivabradine causes ~50% block) the heart rate decreases by ~64 beats/min in the adult animal and only ~29 beats/min in the senescent animal, i.e. the age-dependent downregulation of I_f does contribute to the age-dependent decrease in heart rate.

Clearly, further studies are required to resolve this confusing picture and D'Souza, Boyett and Smith have recently used RNAseq (Wang *et al.*, 2021) to study the transcriptome of the sinus node in ~2 and ~24 month-old male C57BL/6J mice (n=8/8). 55,401 transcripts were detected and there were significant changes in 7,206 of them. Fig. 6F shows a significant downregulation of transcripts underlying I_f (*Hcn1*, *Hcn2*, *Hcn4*), $I_{Ca,L}$ (*Cacna1d*), $I_{Ca,T}$ (*Cacna1g*, *Cacna1h*) and the Ca^{2+} clock (*Ryr2*, *Slc8a1/NCX1*), consistent with some of the studies above. Interestingly, there was evidence of activation of the immune system, for example an upregulation of the transcripts responsible for the major histocompatibility complex class 2 (Fig. 6F). This may be important as discussed below.

There have been two other recent reviews on age-dependent sinus node dysfunction (Monfredi & Boyett, 2015; Peters *et al.*, 2020).

9. Regulation of the HCN channels in disease - heart failure

Although chronic heart failure patients can exhibit heart rates greater than 70 beats/min (example shown in Fig. 7A) (Crespo-Leiro *et al.*, 2016), because of an activation of the sympathetic nervous system to support the failing heart (Hasking *et al.*, 1986; Parati & Esler, 2012), there is evidence of underlying sinus node dysfunction in heart failure patients: (i) Jose *et al.* (Jose & Taylor, 1969) showed that there is a decrease in the *intrinsic heart rate* (measured after complete autonomic blockade), which worsened with the severity of heart failure (Fig. 7B); (ii) Sanders *et al.* (Sanders

et al., 2004) showed functional sinus node remodelling, with a prolonged intrinsic sinus node cycle length, corrected sinus node recovery time and sinoatrial conduction time; (iii) in the CARSIMA study of post-myocardial infarction heart failure patients (Bloch Thomsen *et al.*, 2010), sinus bradycardia was observed in 6.7% of the patients over a two year period (Fig. 7C); and (iv) ~70% of heart failure patients (Roche *et al.*, 2001) show chronotropic incompetence, the inability of the heart rate to appropriately rise with exertion perhaps as a result of sinus node dysfunction (Sanders *et al.*, 2004; Brubaker & Kitzman, 2011). Evidence suggests that the sinus node dysfunction impacts heart failure patients: in the CARISMA study, sinus bradycardia was a more significant predictor of mortality than non-sustained ventricular tachycardia (Fig. 7D); there is a J-shaped relationship between mortality and heart rate in chronic heart disease and, although there is an obvious association of mortality with a higher heart rate, there is also an association with a lower heart rate (Kollock *et al.*, 2008; Parodi *et al.*, 2010); and a significant proportion of heart failure patients (27.6% – 62%) are profoundly bradycardic at the point of sudden death (Luu *et al.*, 1989; Schoeller *et al.*, 1993; Stevenson *et al.*, 1993; Faggiano *et al.*, 2001).

Could bradyarrhythmias cause heart failure? Iwataki *et al.* (Iwataki *et al.*, 2015) compared 39 patients with a mean heart rate of 84 ± 17 beats/min and heart failure, which they attributed to left ventricular pump failure, with 24 patients with a mean heart rate of 39 ± 5 beats/min and heart failure, which they attributed to the bradyarrhythmia; in both groups there was a decrease in cardiac output and increase in left ventricle filling pressure (the latter was only modest in the bradyarrhythmic patients). However, the study of Iwataki *et al.* (Iwataki *et al.*, 2015) is inconclusive: although Iwataki *et al.* (Iwataki *et al.*, 2015) attributed the heart failure in the bradycardic patients to the bradyarrhythmia, it is also possible that the bradyarrhythmia is a consequence of the heart failure. Penton *et al.* (Penton *et al.*, 1956) studied 251 AV (i.e. heart) block patients and observed congestive heart failure in 40% of the patients. They reported that the congestive heart failure could “precede, accompany, or follow the onset of complete AV block”; in patients in which the congestive heart failure followed the onset of complete AV block, the congestive heart failure could have been caused by the bradyarrhythmia. Alboni *et al.* (Alboni *et al.*, 1999) pointed out that improvement in symptoms of heart failure, with or without the addition of digitalis, has been reported after pacemaker implantation in patients with sick sinus syndrome, and pacing is

commonly considered an effective treatment for patients with sinus bradycardia and heart failure. In the randomised THEOPACE trial involving 107 patients with symptomatic sinus bradycardia (sinus rate <50 beats/min) from the same authors, an increase in heart rate, induced by DDD pacing or oral theophylline, significantly reduced the incidence of overt heart failure (Alboni *et al.*, 1997; Alboni *et al.*, 1999; Alboni *et al.*, 2001); the authors concluded that sinus bradycardia appears to play a role in the genesis of heart failure. Case reports support the concept that bradycardia can lead to new symptoms of heart failure and decompensation of pre-existing heart failure (Berczeller, 1994; Ntalianis & Nanas, 2006; Senga *et al.*, 2007; Caliskan *et al.*, 2010; Aoun & Tabbah, 2016; Nagatomo *et al.*, 2020), but the anecdotal evidence of case reports has to be treated cautiously. Two studies relating to HCN4 and I_f will be highlighted: Milano *et al.* (Milano *et al.*, 2014) showed that, in four families, HCN4 mutations linked to bradycardia are associated with left ventricular noncompaction cardiomyopathy, whereas Romero-León *et al.* (Romero-Leon *et al.*, 2016) reported that the blocker of HCN4 and I_f , ivabradine, induced heart failure in a patient receiving antiviral therapy, and when ivabradine was withdrawn symptoms disappeared. Once again, the publication of Romero-León *et al.* (Romero-Leon *et al.*, 2016) is a case report and as such has to be treated cautiously. In conclusion, there is clinical evidence that bradyarrhythmias, in conjunction with pre-existing disease, may contribute to the symptoms and signs of heart failure. However, the authors know that this concept is controversial and not widely accepted in the clinical community; clearly, there is a need for further clinical studies.

Dysfunction of the sinus node has been observed in a rabbit model of pressure and volume overload-induced heart failure, a dog ventricular tachypacing-induced heart failure model, a rat model of volume overload-induced heart failure, and a mouse model of pressure overload-induced heart failure (Opthof *et al.*, 2000; Verkerk *et al.*, 2003; Zicha *et al.*, 2005; Du *et al.*, 2016; Yanni *et al.*, 2020). These studies have shown that the heart rate measured *in vivo* in the conscious animal can be slowed, the intrinsic heart rate measured *in vivo* after complete autonomic blockade is slowed, the intrinsic pacemaker activity of the sinus node *in vitro* is slowed, HCN4 mRNA and protein is downregulated, and I_f is downregulated. What is the underlying mechanism? Yanni *et al.* (Yanni *et al.*, 2020) screened 754 microRNAs in the sinus node using qPCR and observed significant changes in 44 of them (some upregulated and others downregulated) in the mouse

model of pressure overload-induced heart failure. miR-370-3p and miR-139-3p were upregulated (miR-370-3p was shown to be also upregulated in the human sinus node in heart failure) and they were identified by Ingenuity Pathway Analysis software as potentially targeting HCN4 (Yanni *et al.*, 2020). RNA22 software predicted that *Hcn4* mRNA has multiple binding sites for both microRNAs and luciferase reporter gene assays confirmed that the two microRNAs can bind to and downregulate *Hcn4* mRNA (Yanni *et al.*, 2020). Exogenous expression of the two microRNAs in the isolated sinus node caused a downregulation of HCN4 protein and a decrease in the intrinsic pacemaker activity (Yanni *et al.*, 2020). *In vivo*, silencing of miR-370-3p by an intraperitoneal injection of a suitable anti-microRNA prevented the upregulation of miR-370-3p, prevented the downregulation of HCN4 mRNA and protein and blunted the decrease in heart rate (Fig. 8A) (Yanni *et al.*, 2020). Fascinatingly, Yanni *et al.* (Yanni *et al.*, 2020) showed that the anti-miR-370-3p reduced cardiac hypertrophy and most importantly reduced mortality. This is consistent with the decrease in heart rate worsening heart failure and mortality - the anti-microRNA by blunting the decrease in heart rate ultimately blunts mortality. There are case reports of heart failure patients in whom heart failure symptoms were stabilised, reduced or even reversed by cessation of ivabradine treatment (Romero-Leon *et al.*, 2016) or implantation of a pacemaker (Senga *et al.*, 2007; Caliskan *et al.*, 2010; Nagatomo *et al.*, 2020). What upstream pathway is responsible for the microRNA changes? As already mentioned, there is well known to be an activation the sympathetic nervous system to support the failing heart (Hasking *et al.*, 1986; Parati & Esler, 2012). Du *et al.* (Du *et al.*, 2016) have reported that treatment of a rat model of volume overload-induced heart failure with the beta-blocker, bisoprolol, prevented the heart failure-induced downregulation of *Hcn4* mRNA, decrease in the intrinsic heart rate, and the increase in the sinus node recovery time (Fig. 8B). This suggests that the sinus node remodelling in heart failure may be ultimately due to the hyperadrenergic state. This deserves further investigation, but of course beta-blockers are already a mainstream therapy used to treat heart failure.

Fig. 8C attempts to present a synthesis of this information. The inner loop in black is well known and accepted: during heart failure there is activation of the sympathetic nervous system, which results is an inappropriately fast heart rate; this stresses the heart and ultimately worsens the condition of heart failure. The outer loop in red is more speculative and summarises the

information presented here. The activation of the sympathetic nervous system in heart failure or perhaps the activation of the immune system in heart failure (see below) causes a remodelling of the sinus node: there is an upregulation of some microRNAs targeting *Hcn4* resulting in a downregulation of HCN4 and I_f and consequently sinus node dysfunction. It is well known that heart failure patients suffer chronotropic incompetence (an inability of the heart rate to increase sufficiently on exercise) (Brubaker & Kitzman, 2011) and this could be the result of the sinus node dysfunction. The resulting relative sinus bradycardia could worsen the condition of heart failure.

A common cause of heart failure is myocardial infarction and a rat model of myocardial infarction-induced heart failure showed sinus node dysfunction: the intrinsic heart rate was reduced and the corrected sinus node recovery time increased (Yanni *et al.*, 2011). qPCR showed an increase in the expression of ERG, KvLQT1, Kir2.4, TASK1, TWIK1, TWIK2, calsequestrin 2 and A1 adenosine receptor transcripts in the sinus node that could explain the slowing of the intrinsic heart rate (Yanni *et al.*, 2011). In this rat model, HCN channels were not downregulated: *Hcn2* and *Hcn4* were upregulated in the sinus node in heart failure (Yanni *et al.*, 2011). Therefore, as with ageing, the remodelling of the sinus node in heart failure can take different forms.

10. Regulation of the HCN channels in disease – pulmonary hypertension

Pulmonary hypertension (pulmonary artery pressure >25 mmHg) is a disease characterised by raised pulmonary vascular resistance. It has a poor prognosis and typically results in progressive right ventricular failure and death. The incidence of arrhythmias in patients with pulmonary hypertension is high (Temple *et al.*, 2016). For example, in patients with pulmonary hypertension, sinus tachycardia, sinus bradycardia and first-degree AV block occurred in 70% of the patients, whereas ventricular arrhythmias were rare (Kanemoto & Sasamoto, 1979; Rajdev *et al.*, 2012). In a rat model of monocrotaline-induced pulmonary hypertension, there was a decrease of the intrinsic heart rate (measured in the isolated sinus node) as well as the normal heart rate, evidence of sinus node dysfunction (Yamanushi *et al.*, 2010). qPCR and immunohistochemistry showed a remodelling of ion channel, Ca^{2+} -handling and fibrosis genes in the sinus node which was likely to be responsible for the sinus node dysfunction (Yamanushi *et al.*, 2010). This included a downregulation of *Hcn1* and *Hcn4* (Fig. 9A,B) (Yamanushi *et al.*, 2010).

11. Regulation of the HCN channels in disease – diabetes mellitus

The major cause of morbidity and mortality in diabetic patients are cardiovascular complications. Bradyarrhythmias (Grimm *et al.*, 1990) and AV block (Rubler *et al.*, 1975) are significant problems in diabetes mellitus. Diabetic patients are more likely to need implantation of an electronic pacemaker. Data from 688 elderly patients (79% aged over 65 years) who had undergone electronic pacemaker implantation were compared to data from a control group (Lear *et al.*, 1996): the relative risk of needing an electronic pacemaker was 1.34 for the elderly diabetic patients. In a large study, 416,247 patients with type 2 diabetes mellitus from the Swedish National Diabetes Registry were compared with >2,000,000 matched control subjects – for diabetic patients, the relative risk of needing an electronic pacemaker was 1.65 (Rautio *et al.*, 2018; Rautio *et al.*, 2020).

Dobrzynski and Howarth have studied nodal function in streptozotocin-induced type 1 diabetic rats: there is a decrease in the heart rate *in vivo* (Howarth *et al.*, 2005a; Howarth *et al.*, 2005b) and *in vitro* there is a decrease of the beating rate of the isolated (and denervated) sinus node preparation (Zhang *et al.*, 2019). Huang *et al.* (Huang *et al.*, 2016) have similarly reported a decrease in heart rate *in vivo* and beating rate *in vitro*, but in addition a lengthened sinoatrial conduction time and rate-corrected maximal sinus node recovery time *in vivo* in the streptozotocin-induced type 1 diabetic rat. Ferdous *et al.* (Ferdous *et al.*, 2016) reported changes in various transcripts in the sinus node in streptozotocin-induced type 1 diabetic rat, but no change in *Hcn4* mRNA. However, there is doubt about this conclusion, because Ferdous *et al.* (Ferdous *et al.*, 2016) reported *Hcn4* mRNA to be higher in the right atrial muscle than in the sinus node of the control animals and this contradicts many previous reports, e.g. Tellez *et al.* (Tellez *et al.*, 2006). Furthermore, Huang *et al.* (Huang *et al.*, 2016) reported a downregulation on HCN2 and HCN4 mRNA and protein in the sinus node of the streptozotocin-induced type 1 diabetic rat; they also reported that blockade of HCN channels by 3 μ M ivabradine prolonged the spontaneous cycle length by 18% in Langendorff hearts from diabetic rats and 26% from control rats, consistent with a downregulation of I_f in the diabetic rats. This is likely to be correct, because Zhang *et al.* (Zhang *et al.*, 2019) - from the same team as the paper by Ferdous *et al.* (Ferdous *et al.*, 2016) - showed using western blot that HCN4 protein is downregulated in the sinus node of streptozotocin-induced type 1 diabetic rats. Zhang *et al.* (Zhang *et al.*, 2019) also showed a downregulation of other key proteins involved in pacemaking (Cav1.3, Cav3.1, Cx45 and NCX1).

12. Regulation of the HCN channels in disease – atrial fibrillation

Sinus node dysfunction is frequently associated with AF resulting in the “tachy-brady syndrome” (Semelka *et al.*, 2013). AF is responsible for the tachycardia and when in sinus rhythm the patient is bradycardic. Sick sinus syndrome after termination of AF can cause syncope and require pacemaker implantation (Yeh *et al.*, 2009). In the dog, Elvan *et al.* (Elvan *et al.*, 1996) reported that after 2-6 weeks of atrial tachypacing to induce AF, there was sinus node dysfunction: the maximal and intrinsic heart rates were decreased and the corrected sinus node recovery time was prolonged. Yeh *et al.* (Yeh *et al.*, 2009) studied sinus node dysfunction in the dog resulting from seven day atrial tachypacing. In the sinus node, *Hcn2* and *Hcn4* mRNAs as determined by qPCR were downregulated by >50% (Fig. 10A) and mRNA for minK (an accessory subunit for KvLQT1 responsible for the slow delayed rectifier K⁺ current, $I_{K,s}$) was downregulated by ~42%. Patch clamp experiments showed a downregulation of the corresponding currents, I_f and $I_{K,s}$, respectively (Yeh *et al.*, 2009); data for I_f are shown in Fig. 10B. Yeh *et al.* (Yeh *et al.*, 2009) concluded that the downregulation of I_f in particular may be responsible for the sinus node dysfunction.

13. Other bradycardias – other HCN problems?

A series of publications report bradycardia and bradyarrhythmias in COVID-19 patients (Amaratunga *et al.*, 2020; Babapoor-Farrokhran *et al.*, 2020; Beyls *et al.*, 2020; Bhatla *et al.*, 2020; Capoferri *et al.*, 2020; Cimino *et al.*, 2020; Hiraiwa *et al.*, 2020; Hu *et al.*, 2020; Ikeuchi *et al.*, 2020; Manolis *et al.*, 2020; Peigh *et al.*, 2020). It has been reported: relative bradycardia is a frequent clinical feature of COVID-19, occurring in 56% of febrile hospitalised patients (Capoferri *et al.*, 2020); about a third of the patients with severe illness develop sinus bradycardia (Hu *et al.*, 2020); and one of the most common arrhythmias in relation to COVID-19 is sinus bradycardia (Babapoor-Farrokhran *et al.*, 2020). There is a high mortality of patients with chronic kidney disease undergoing haemodialysis and 25% of deaths are the result of sudden cardiac death (Wong *et al.*, 2015a). In 50 of these patients, bradycardia was recorded in 30%, sinus arrest in 28% and second-degree AV block in 8%; 16% of the patients died of sudden cardiac death and in each case there was severe bradycardia with asystole (Wong *et al.*, 2015b). Anorexia nervosa is an eating disorder with a significant risk for sudden death (5-20%) due to severe cardiovascular complications. Anorexia nervosa is associated with bradycardia - in a study of 20 female patients, ~70% had a

heart rate of <50 beats/min and the mean lowest heart rate was 44 beats/min (Yahalom *et al.*, 2013). There was a significant correlation between heart rate and body mass index (Yahalom *et al.*, 2013). Similar findings have been reported by others (Kollai *et al.*, 1994; Vanderdonckt *et al.*, 2001; Portilla, 2011). Although the cause of sinus bradycardia in these cases is not known, a transcriptional remodelling of the sinus node, including of HCN channels, perhaps as a result of inflammation, must be one possible cause. In the case of COVID-19 there is some evidence for this: miR-486-3p is highly expressed in the human sinus node and inhibits HCN4 expression (Petkova *et al.*, 2020; Aminu *et al.*, 2021) and circulating miR-486-3p is upregulated in COVID-19 patients (Tang *et al.*, 2020); sinus bradycardia in COVID-19 patients has also been attributed to inflammatory damage of sinus node cells (Amaratunga *et al.*, 2020).

14. AV node and HCN channels in health and disease

Most studies on the nodes in health and disease focus on the sinus node and this review reflects this bias. However, there are studies of the HCN channels in the AV node in health and disease. HCN channels are considered to be pacemaking ion channels. The primary function of the AV node is to conduct the action potential from the atria to the ventricles, although it is also a back-up pacemaker in case of failure of the sinus node (Dobrzynski *et al.*, 2003). As in the case of the sinus node, the HCN channels of the AV node are responsible for I_f , which is involved in AV node pacemaking (Liu *et al.*, 2008; Marger *et al.*, 2011; Mesirca *et al.*, 2014). However, there is increasing evidence that I_f is involved in AV node conduction:

(i) HCN4 mutations have been associated with AV block in humans (Zhou *et al.*, 2014a).

(ii) Baruscotti *et al.* (Baruscotti *et al.*, 2011) demonstrated that inducible cardiac-specific knockout of HCN4 in mice is lethal because of the development of complete AV block. Similarly, Mesirca *et al.* (Mesirca *et al.*, 2014) showed that inducible cardiac-specific silencing of f-channel conductance after expression of dominant-negative non-conducting HCN4 in mice resulted in a high incidence of types 1 and 2 second-degree AV block, as well as a reduction of automaticity of AV node myocytes.

(iii) The I_f blocking agent, zatebradine, has been shown to increase the A-H interval, AV node effective refractory period, and Wenckebach cycle length in humans (Chiamvimonvat *et al.*,

1998); similarly, in the rat, I_f block by ivabradine prolongs the A-H interval, AV node effective refractory period, and Wenckebach cycle length (Saeed *et al.*, 2018).

(iv) Verrier *et al.* (Verrier *et al.*, 2014) reported that ivabradine, at clinically safe concentrations, reduces ventricular rate during AF in the guinea-pig by slowing AV node conduction. Consistent with this, there are various reports that ivabradine improves ventricular rate control in patients with AF (Caminiti *et al.*, 2016; Wongcharoen *et al.*, 2016; Fontenla *et al.*, 2017).

We suggest that downregulation of I_f may slow AV node conduction by decreasing cell excitability (Li *et al.*, 2014). In this respect, previous work on the hippocampus by Maccaferri *et al.* (Maccaferri *et al.*, 1993) has shown that I_h (I_f) positively regulates neuronal firing by providing a depolarization reserve at resting potentials from and negative to -50 mV. A similar mechanism may be operating in the AV node to facilitate action potential conduction. Proenza and Yellen (Proenza & Yellen, 2006) reported that, on hyperpolarization, HCN channels may carry an instantaneous, time-independent current as well as a time-dependent current. Perhaps as an example of this, Fig. 3 of Kozasa *et al.* (Kozasa *et al.*, 2018) shows comparable changes of both time-independent and time-dependent currents as the HCN4 expression level was varied. Such an instantaneous, time-independent current, by mimicking a background inward current, could facilitate AV node conduction by I_f .

Athletic training. AV node dysfunction is a common occurrence in athletes, manifesting as a longer PR interval (first-degree AV block, i.e. slowed AV node conduction), a prolonged Wenckebach cycle length (minimum cycle length at which the AV node fails to conduct in a 1:1 manner) and second-degree AV block (intermittent block of conduction through the AV node) (Viitasalo *et al.*, 1982; Stein *et al.*, 2002; Crouse *et al.*, 2009). AV block has been correlated to the intensity and length of the training period in athletes (Hoogsteen *et al.*, 2004). The prevalence of first- and second-degree AV block in veteran endurance athletes has been reported to be 28–45% and 15–40% (Talan *et al.*, 1982) in contrast to 0.60% and 0.03% in the general population (Hiss & Lamb, 1962). The AV block likely contributes to the increased incidence of electronic pacemaker implantation in veteran athletes (Hood & Northcote, 1999; Luthi *et al.*, 2008). Like the resting bradycardia in athletes, the AV block is attributed to high vagal tone (D'Souza *et al.*, 2019). However, Stein *et al.* (Stein *et al.*, 2002) reported that the Wenckebach cycle length and

anterograde AV node effective refractory period are prolonged in human athletes, regardless of the presence of autonomic blockade. Similarly, Yamaya *et al.* (Yamaya *et al.*, 1997) reported that slower AV conduction, prolonged Wenckebach conduction and higher refractoriness in horses with AV block (*versus* horses without AV block) was maintained under complete autonomic block. Mesirca *et al.* (Mesirca *et al.*, 2021) reported that, as compared to sedentary animals, exercise-trained horses presented with a prolonged PR interval and exercise-trained mice also presented with a prolonged PR interval (*in vivo* and *ex vivo*) as well as a prolonged Wenckebach cycle length and AV node refractory period; the prolongation of the PR interval persisted after complete autonomic blockade in both species. In the exercise-trained mice, there was a downregulation of Cav1.2 and HCN4 mRNA (qPCR) and protein (immunohistochemistry and western blot) in the AV node and there was a concomitant decrease in the density of $I_{Ca,L}$ and I_f (patch clamp) (Mesirca *et al.*, 2021). There was a similar downregulation of Cav1.2 and HCN4 proteins in the exercise-trained horses. In the exercise-trained mice, a downregulation of other ion channel transcripts was also observed (Mesirca *et al.*, 2021). microRNA profiling revealed an upregulation of miR-211-5p and miR-432 in the AV node of the exercise-trained mice and evidence of a similar upregulation in the exercise-trained horses, and *in vitro* studies showed the two microRNAs to be direct regulators of Cav1.2 and HCN4 (Mesirca *et al.*, 2021). In the mouse, *in vivo* suppression of the microRNAs reversed training-induced PR prolongation and ion channel remodelling (Mesirca *et al.*, 2021).

Circadian rhythm. In the human and the mouse, there is a circadian rhythm in the PR interval, which is longer (i.e. AV node conduction is slower) during the sleep period (Dilaveris *et al.*, 2001; Black *et al.*, 2018). Without direct evidence, the circadian rhythm has again been attributed to the autonomic nervous system (principally, high vagal tone during sleep) (Verrier & Josephson, 2009). However, as in the case of the sinus node, qPCR has shown a circadian rhythm in the expression of circadian clock and ion channel transcripts in the AV node of young male C56BL/6J mice (Sunil Jit Logantha and M.R. Boyett); see D'Souza *et al.* (D'Souza *et al.*, 2021) for details of methods. The circadian rhythm in *Hcn4* is shown in Fig. 11A and it can be seen to be similar in phase with the circadian rhythm in *Hcn4* in the sinus node (Fig. 4B).

Heart failure and pulmonary hypertension. Heart failure is not only associated with sinus node dysfunction, evidence suggests that it is also associated with AV node dysfunction. Among

patients with heart failure, first-degree AV block is present in 15-51% of patients as compared to a prevalence of ~4% in the general population (Nikolaidou *et al.*, 2016). In heart failure patients, first-degree AV block is associated with an increased risk of mortality and heart failure hospitalisation, and optimisation of AV delay in patients by means of cardiac resynchronisation therapy is an important therapy (Nikolaidou *et al.*, 2016). AV node dysfunction has been observed in animal models of heart failure. Muir-Nisbet *et al.* (Muir-Nisbet, 2008) observed an increase in the PQ interval (equivalent to first-degree AV block) in a rabbit model of ischaemic cardiomyopathy (resulting from left ventricular myocardial infarction), which they attributed to increased fibrosis and gap junction (Cx43 and Cx40) remodelling. We have observed a prolongation of the PR interval (equivalent to first-degree AV block) in a rabbit model of pressure and volume overload-induced heart failure caused by rupture of the aortic valve and banding of the abdominal aorta (Nikolaidou *et al.*, 2015). An increase in the PR interval results from either slower conduction through the AV node or an increase in the length of the conduction pathway. In the rabbit heart failure model, there was a downregulation of HCN1 as measured by qPCR in the AV junction that could result in a slowing of conduction (Nikolaidou *et al.*, 2015). However, there was also a downregulation of Cav1.3, Cx40 and Cx43 mRNAs, which again could result in a slowing of conduction, as well as an enlargement of the AV junction (and the rest of the heart) as measured by micro-CT, which could result in an increase in the length of the conduction pathway (Nikolaidou *et al.*, 2015). In the work of Muir-Nisbet *et al.* (Muir-Nisbet, 2008) and Nikolaidou *et al.* (Nikolaidou *et al.*, 2015), the initial insult was to the left side of the heart. We have also studied the rat model of monocrotaline-induced pulmonary hypertension (Temple *et al.*, 2016). There is evidence of AV node dysfunction in pulmonary hypertension with a 14% incidence of first-degree heart block (Bossone *et al.*, 2002) compared with 2.1% in the general population (Aro *et al.*, 2014), a mean PR interval of ~180 ms (Bossone *et al.*, 2002) compared with ~160 ms for men and ~153 ms for women in the general population (Aro *et al.*, 2014), and 2% of patients requiring a pacemaker for high-degree heart block on initial screening of pulmonary hypertension patients (Bossone *et al.*, 2002). Sleep apnoea causes pulmonary hypertension (Laks *et al.*, 1995) and is associated with heart block in $\leq 10\%$ of patients with obstructive sleep apnoea (Koehler *et al.*, 1998). In the rat model of monocrotaline-induced pulmonary hypertension, Temple *et al.* (Temple *et al.*, 2016) showed that there was a 50%

incidence of heart block in isolated AV node preparations and a widespread downregulation of ion channel and related genes in the AV node. For example, there was a >50% downregulation of *Hcn1/2/4* and *Cav1.2* and *Cav1.3* mRNAs (Fig. 11B); biophysically-detailed computer modelling by Zhang and colleagues predicted that if the changes in mRNA are translated into protein and function they would result in heart block (Temple *et al.*, 2016).

Finally, in the mouse model of pressure overload-induced heart failure caused by banding of the aorta, there is a prolongation of the PR interval (Yanni *et al.*, 2020) and in this model we (Wilson and Boyett) have used RNAseq to study the transcriptome of the AV node. Biopsies from nine heart failure and nine sham-operated control mice (young male C57BL/6J mice) each divided into three groups were used; see Yanni *et al.* (Yanni *et al.*, 2020) and Wang *et al.* (Wang *et al.*, 2021) for details of methods. There were widespread changes in the transcriptome including a downregulation of Ca^{2+} and K^{+} channel transcripts, although there were no changes in *Hcn* transcripts. The data also showed evidence of an activation of the immune system and either an infiltration of the AV node by different classes of inflammatory cells or a proliferation of the cells in the AV node. This is of interest because heart failure is characterised by inflammation (Martini *et al.*, 2019) and inflammation can cause heart failure: myocardial inflammation and T-cells can lead to lethal acute or chronic heart failure (Blanton *et al.*, 2019; Strassheim *et al.*, 2019). In the same mouse model of pressure overload-induced heart failure, knockout of the class II major histocompatibility complex molecule or knockout of *Tcra* (T-cell receptor alpha locus) resulted in the nearly complete inhibition of left ventricular hypertrophy, and, in the case of knockout of *Tcra*, maladaptive changes in gene expression were prevented (Laroumanie *et al.*, 2014; Blanton *et al.*, 2019). The possibility that the remodelling of the nodes in heart failure is caused by inflammation is incorporated in Fig. 8C.

15. Biopacemaking

Currently, the only treatment for nodal dysfunction is the implantation of an electronic pacemaker, a treatment that has been in use for ~62 years (Aquilina, 2006). However, implanted electronic pacemakers have significant problems, for example, a limited battery life (Morris & Boyett, 2009). This has sparked the development of a 'biopacemaker' (an artificial biological pacemaker) as a replacement for the electronic pacemaker - authoritative reviews on biopacemakers have already

been published (Rosen *et al.*, 2007; Morris & Boyett, 2009) and the work will not be reviewed in detail here. However, it is relevant to this review that many efforts to generate a biopacemaker have focussed on the HCN channels (Rosen *et al.*, 2007). Most studies have focussed on a *de novo* pacemaker in the working myocardium (Rosen *et al.*, 2007). However, this may not be satisfactory – it is known that electronic pacemaking in the right ventricle can lead to pacing-induced cardiomyopathy because it does not replicate the normal activation sequence of the heart (Merchant & Mittal, 2020). It is, therefore, important to retain the normal activation sequence of the heart. In addition, most studies attempting to develop a biopacemaker focus on changing one or two genes, whereas it is known that there are 100s of differences in gene expression between the sinus node and atrial muscle (Linscheid *et al.*, 2019). We have argued that it may be better to ‘repair’ the existing nodal tissues using gene therapy if the nature of the problem is known (Morris *et al.*, 2013; Choudhury *et al.*, 2018). Sinus node tissue is extensive in the right atrium and it is the superior tissue close to the superior vena cava which is the dominant pacemaker (showing the fastest pacemaking) – see also Brennan *et al.* (Brennan *et al.*, 2020). We have worked with the isolated inferior part of the sinus node and shown that pacemaking can be accelerated by transducing the tissue with a HCN chimeric channel, HCN212 (Morris *et al.*, 2013) and TBX18 (Choudhury *et al.*, 2018). An important problem yet to be overcome is how nodal tissue can be selectively transduced, i.e. how one of the nodes can be genetically modified without affecting any other tissue in the heart or body (Stuart, 2021).

16. Purkinje fibres – an afterthought

This review focusses on the role of HCN channels in the sinus and AV nodes in health and disease, but what about the final part of the cardiac conduction system, the Purkinje fibres? Paradoxically, although I_f was first recorded in Purkinje fibres (Noble & Tsien, 1968), less is known about the current in Purkinje fibres. It is attributed to HCN channels and is thought to play a role in pacemaking (Boyden *et al.*, 2010; Dobrzynski *et al.*, 2013). Purkinje fibres are involved in a variety of arrhythmias. For example, Purkinje fibre dysfunction can result in bundle branch block, the incidence of which is higher in athletes (incomplete right bundle branch block), the elderly and heart failure patients (Dobrzynski *et al.*, 2013; Scharhag *et al.*, 2013). However, there is no evidence that I_f is involved in Purkinje fibre dysfunction, although *Hcn4* mRNA is downregulated in

left ventricular Purkinje fibres in a rabbit model of pressure and volume overload-induced heart failure (Logantha *et al.*, 2021).

17. Conclusions

There are changes in the base line (i.e. long term) heart rate set by the sinus node and also AV node conduction in many different physiological and pathophysiological conditions. Under physiological conditions, the changes adapt the heart to the changing need for cardiac output. However, under pathophysiological conditions the changes can be maladaptive. Previously, a lack of information and understanding of the two nodes meant that changes were attributed to high vagal tone or fibrosis, because at the time these were the only factors thought to affect the nodes. However, as the knowledge and understanding of the nodes increases further factors that could be involved have come to light and deserve investigation. This review has focussed on a role for the important pacemaker HCN ion channels and it has been shown that transcriptional control of the channels and consequently I_f density is occurring in many different physiological and pathophysiological circumstances (Fig. 12A) through a variety of mechanisms (Fig. 12B) and could either be responsible for or contributing to a change in heart rate and AV node conduction. It is important to stress that, although this review focusses on the HCN channels, it does not mean that other factors such as the Ca^{2+} clock are not involved. *Hcn4* mutations are associated with sinus node dysfunction and other diseases and the *Genomics England* website states that *Hcn4* should be analysed when investigating 'Progressive cardiac conduction disease' (which includes sick sinus syndrome) and 'Cardiomyopathies - including childhood onset' (<https://panelapp.genomicsengland.co.uk/panels/entities/HCN4>).

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References

- Abd Allah ESH, Tellez JO, Nelson T, Monfredi O, Boyett MR & Dobrzynski H. (2011). Changes in the expression of ion channels, connexins and Ca²⁺-handling proteins in the sinoatrial node during postnatal development. *Experimental Physiology* **96**, 426-438.
- Accili EA, Robinson RB & DiFrancesco D. (1997). Properties and modulation of I_f in newborn versus adult cardiac SA node *American Journal of Physiology* **272** H1549 - H1552
- Adachi T, Shibata S, Okamoto Y, Sato S, Fujisawa S, Ohba T & Ono K. (2013). The mechanism of increased postnatal heart rate and sinoatrial node pacemaker activity in mice. *Journal of Physiological Sciences* **63**, 133-146.
- Alboni P, Brignole M, Menozzi C & Scarfo S. (1999). Is sinus bradycardia a factor facilitating overt heart failure? *European Journal of Heart Failure* **20**, 252-255.
- Alboni P, Menozzi C, Brignole M, Paparella N, Gaggioli G, Lolli G & Cappato R. (1997). Effects of permanent pacemaker and oral theophylline in sick sinus syndrome the THEOPACE study: a randomized controlled trial. *Circulation* **96**, 260-266.
- Alboni P, Scarfo S & Fuca G. (2001). Development of heart failure in bradycardic sick sinus syndrome. *Italian Heart Journal* **2**, 9-12.
- Alghamdi AM, Boyett MR, Hancox JC & Zhang H. (2020a). Cardiac pacemaker dysfunction arising from different studies of ion channel remodeling in the aging rat heart. *Frontiers in Physiology* **11**.
- Alghamdi AM, Testrow CP, Whittaker DG, Boyett MR, Hancox JC & Zhang H. (2020b). Mechanistic insights into the reduced pacemaking rate of the rabbit sinoatrial node during postnatal development: a simulation study. *Frontiers in Physiology* **11**, 1516.

- Alings AM, Abbas RF & Bouman LN. (1995). Age-related changes in structure and relative collagen content of the human and feline sinoatrial node. A comparative study. *European Heart Journal* **16**, 1655-1667.
- Alings AMW & Bouman LN. (1993). Electrophysiology of the ageing rabbit and cat sinoatrial node - a comparative study. *European Heart Journal* **14**, 1278-1288.
- Amaratunga EA, Corwin DS, Moran L & Snyder R. (2020). Bradycardia in patients with COVID-19: a calm before the storm? *Cureus* **12**, e8599-e8599.
- Aminu AJ, Petkova M, Atkinson AJ, Yanni J, Morris AD, Simms RT, Chen W, Yin Z, Kuniewicz M, Holda MK, Kuzmin VS, Perde F, Molenaar P & Dobrzynski H. (2021). Further insights into the molecular complexity of the human sinus node – the role of ‘novel’ transcription factors and microRNAs. *Progress in Biophysics and Molecular Biology* (in press).
- Anderson C, Forte G, Wilson C, Oceandy D, Boyett MR & D’Souza A. (2019). MicroRNA control of the circadian rhythm in heart rate. *Proceedings of the Physiological Society* **45**, C06.
- Aoun M & Tabbah R. (2016). Case report: severe bradycardia, a reversible cause of “Cardio-Renal-Cerebral Syndrome”. *BMC Nephrology* **17**, 162.
- Aquilina O. (2006). A brief history of cardiac pacing. *Images in Paediatric Cardiology* **8**, 17-81.
- Aro AL, Anttonen O, Kerola T, Junttila MJ, Tikkanen JT, Rissanen HA, Reunanen A & Huikuri HV. (2014). Prognostic significance of prolonged PR interval in the general population. *European Heart Journal* **35**, 123-129.

- Aubert AE, Seps B & Beckers F. (2003). Heart rate variability in athletes. *Sports Medicine* **33**, 889-919.
- Avram R, Tison GH, Aschbacher K, Kuhar P, Vittinghoff E, Butzner M, Runge R, Wu N, Pletcher MJ, Marcus GM & Olgin J. (2019). Real-world heart rate norms in the Health eHeart study. *npj Digital Medicine* **2**, 58.
- Babapoor-Farrokhran S, Rasekhi RT, Gill D, Babapoor S & Amanullah A. (2020). Arrhythmia in COVID-19. *SN Comprehensive Clinical Medicine*, 1-6.
- Bahrainy S, Levy WC, Busey JM, Caldwell JH & Stratton JR. (2016). Exercise training bradycardia is largely explained by reduced intrinsic heart rate. *International Journal of Cardiology* **222**, 213-216.
- Baldesberger S, Bauersfeld U, Candinas R, Seifert B, Zuber M, Ritter M, Jenni R, Oechslin E, Luthi P, Scharf C, Marti B & Attenhofer Jost CH. (2008). Sinus node disease and arrhythmias in the long-term follow-up of former professional cyclists. *European Heart Journal* **29**, 71-78.
- Baruscotti M, Bucchi A & DiFrancesco D. (2005). Physiology and pharmacology of the cardiac pacemaker ("funny") current. *Pharmacology & Therapeutics* **107**, 59-79.
- Baruscotti M, Bucchi A, Milanesi R, Paina M, Barbuti A, Gneccchi-Ruscione T, Bianco E, Vitali-Serdoz L, Cappato R & DiFrancesco D. (2015). A gain-of-function mutation in the cardiac pacemaker HCN4 channel increasing cAMP sensitivity is associated with familial inappropriate sinus tachycardia. *European Heart Journal* **38**, 280-288.
- Baruscotti M, Bucchi A, Viscomi C, Mandelli G, Consalez G, Gneccchi-Rusconi T, Montano N, Casali KR, Micheloni S, Barbuti A & DiFrancesco D. (2011). Deep bradycardia and heart

block caused by inducible cardiac-specific knockout of the pacemaker channel gene Hcn4. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 1705-1710.

Baruscotti M, DiFrancesco D & Robinson RB. (1996). A TTX-sensitive inward sodium current contributes to spontaneous activity in newborn rabbit sino-atrial node cells. *Journal of Physiology* **492**, 21-30.

Baruscotti M, Westenbroek R, Catterall WA, DiFrancesco D & Robinson RB. (1997). The newborn rabbit sino-atrial node expresses a neuronal type I-like Na⁺ channel. *Journal of Physiology* **498**, 641-648.

Beesley S, Noguchi T & Welsh DK. (2016). Cardiomyocyte circadian oscillations are cell-autonomous, amplified by β -adrenergic signaling, and synchronized in cardiac ventricle tissue. *PLoS One* **11**, e0159618-e0159618.

Benditt DG, Sakaguchi S, Goldstein MA, Lurie KG, Gornick CC, Adler SW, Zipes DP & Jalife J. (1995). Sinus node dysfunction: pathophysiology, clinical features, evaluation, and treatment. In *Cardiac Electrophysiology: From Cell to Bedside*, 2nd edn, pp. 1215-1247. W.B. Saunders Company, Philadelphia.

Berczeller PH. (1994). 'Congestive heart failure' and bradycardia. *Hospital Practice* **29**, 111-114.

Betros CL, McKeever NM, Manso Filho H, Malinowski K & McKeever K. (2013). Effect of training on intrinsic and resting heart rate and plasma volume in young and old horses. *Comparative Exercise Physiology* **9**, 43-50.

Bexton RS, Vallin HO & Camm AJ. (1986). Diurnal variation of the QT interval - influence of the autonomic nervous system. *British Heart Journal* **55**, 253-258.

- Beyls C, Martin N, Hermida A, Abou-Arab O & Mahjoub Y. (2020). Lopinavir-ritonavir treatment for COVID-19 infection in intensive care unit: risk of bradycardia. *Circulation: Arrhythmia and Electrophysiology* **13**, e008798.
- Beytebiere J, Trott A, Greenwell B, Osborne C, Vitet H, Spence J, Yoo S-H, Chen Z, Takahashi J, Ghaffari N & Menet J. (2019). Tissue-specific BMAL1 cisomes reveal that rhythmic transcription is associated with rhythmic enhancer–enhancer interactions. *Genes & Development* **33**.
- Bhatla A, Mayer MM, Adusumalli S, Hyman MC, Oh E, Tierney A, Moss J, Chahal AA, Anesi G, Denduluri S, Domenico CM, Arkles J, Abella BS, Bullinga JR, Callans DJ, Dixit S, Epstein AE, Frankel DS, Garcia FC, Kumareswaram R, Nazarian S, Riley MP, Santangeli P, Schaller RD, Supple GE, Lin D, Marchlinski F & Deo R. (2020). COVID-19 and cardiac arrhythmias. *Heart Rhythm* **17**, 1439-1444.
- Bidaud I, Chong ACY, Carcouet A, Waard S, Charpentier F, Ronjat M, Waard M, Isbrandt D, Wickman K, Vincent A, Mangoni ME & Mesirca P. (2020a). Inhibition of G protein-gated K⁺ channels by tertiapin-Q rescues sinus node dysfunction and atrioventricular conduction in mouse models of primary bradycardia. *Scientific Reports* **10**, 9835.
- Bidaud I, D'Souza A, Forte G, Torre E, Gruet D, Thirard S, Chong ACY, Torrente A-G, Roussel J, Wickman K, Boyett MR, Mangoni ME & Mesirca P. (2020b). Genetic ablation of G protein-gated inwardly rectifying K⁺ (GIRK4) channels prevents training-induced sinus bradycardia. *Frontiers in Physiology* **11**, 1798.
- Black N, D'Souza A, Wang Y, Piggins H, Dobrzynski H, Morris G & Boyett MR. (2019). Circadian rhythm of cardiac electrophysiology, arrhythmogenesis, and the underlying mechanisms. *Heart Rhythm* **16**, 298-307.

- Black N, D'Souza A, Wang Y, Piggins H, Dobrzynski H, Morris G & Boyett MR. (2018). Circadian rhythm of cardiac electrophysiology, arrhythmogenesis, and the underlying mechanisms. *Heart Rhythm* **16**, 298-307.
- Blanton RM, Carrillo-Salinas FJ & Alcaide P. (2019). T-cell recruitment to the heart: friendly guests or unwelcome visitors? *American Journal of Physiology - Heart and Circulatory Physiology* **317**, H124-H140.
- Bloch Thomsen PE, Jons C, Raatikainen MJ, Moerch Joergensen R, Hartikainen J, Virtanen V, Boland J, Anttonen O, Gang UJ, Hoest N, Boersma LV, Platou ES, Becker D, Messier MD & Huikuri HV. (2010). Long-term recording of cardiac arrhythmias with an implantable cardiac monitor in patients with reduced ejection fraction after acute myocardial infarction: the Cardiac Arrhythmias and Risk Stratification After Acute Myocardial Infarction (CARISMA) study. *Circulation* **122**, 1258-1264.
- Boas EP & Weiss MM. (1929). The heart rate during sleep as determined by the cardi tachometer: its clinical significance. *Journal of the American Medical Association* **92**, 2162-2168.
- Bossone E, Paciocco G, Iarussi D, Agretto A, Iacono A, Gillespie BW & Rubenfire M. (2002). The prognostic role of the ECG in primary pulmonary hypertension. *Chest* **121**, 513-518.
- Boyden PA, Hirose M & Dun W. (2010). Cardiac Purkinje cells. *Heart Rhythm* **7**, 127-135.
- Boyett MR. (2009). 'And the beat goes on'. The cardiac conduction system: the wiring system of the heart. *Experimental Physiology* **94**, 1035-1049.
- Boyett MR & D'Souza A. (2020). Are you ruled by your head or your heart? Neurogenic versus myogenic debate on origin of the heart beat. *Physiology News* **120**, 18-21.

- Boyett MR, D'Souza A, Zhang H, Morris GM, Dobrzynski H & Monfredi O. (2013). Viewpoint: Is the resting bradycardia in athletes the result of remodelling of the sinoatrial node rather than high vagal tone? *Journal of Applied Physiology* **114**, 1351-1355.
- Bray MS, Shaw CA, Moore MW, Garcia RA, Zanquetta MM, Durgan DJ, Jeong WJ, Tsai JY, Bugger H, Zhang D, Rohrwasser A, Rennison JH, Dyck JR, Litwin SE, Hardin PE, Chow CW, Chandler MP, Abel ED & Young ME. (2008). Disruption of the circadian clock within the cardiomyocyte influences myocardial contractile function, metabolism, and gene expression. *American Journal of Physiology-Heart and Circulatory Physiology* **294**, H1036-1047.
- Brennan JA, Chen Q, Gams A, Dyavanapalli J, Mendelowitz D, Peng W & Efimov IR. (2020). Evidence of superior and inferior sinoatrial nodes in the mammalian heart. *JACC: Clinical Electrophysiology* **6**, 1827-1840.
- Brown HF & DiFrancesco D. (1980). Voltage-clamp investigations of membrane currents underlying pace-maker activity in rabbit sino-atrial node. *Journal of Physiology* **308**, 331-351.
- Brubaker PH & Kitzman DW. (2011). Chronotropic incompetence: causes, consequences, and management. *Circulation* **123**, 1010-1020.
- Bussey CT. (2019). Direct recordings of cardiac sympathetic and vagal parasympathetic nerve activity to clarify the underlying mechanisms of circadian heart rhythm. *Proceedings of the Physiological Society* **43**, SA034.

- Butters TD, Aslanidi OV, Inada S, Boyett MR, Hancox JC, Lei M & Zhang H. (2010). Mechanistic links between Na⁺ channel (SCN5A) mutations and impaired cardiac pacemaking in sick sinus syndrome. *Circulation Research* **107**, 126-137.
- Caliskan K, Balk AH, Jordaens L & Szili-Torok T. (2010). Bradycardiomyopathy: the case for a causative relationship between severe sinus bradycardia and heart failure. *Journal of Cardiovascular Electrophysiology* **21**, 822-824.
- Caminiti G, Fossati C, Rosano G & Volterrani M. (2016). Addition of ivabradine to betablockers in patients with atrial fibrillation: effects on heart rate and exercise tolerance. *International Journal of Cardiology* **202**, 73-74.
- Capoferri G, Osthoff M, Egli A, Stoeckle M & Bassetti S. (2020). Relative bradycardia in patients with COVID-19. *Clinical Microbiology and Infection*.
- Chandler N, Aslanidi O, Buckley D, Inada S, Birchall S, Atkinson A, Kirk D, Monfredi O, Molenaar P, Anderson R, Sharma V, Sigg D, Zhang H, Boyett M & Dobrzynski H. (2011). Computer three-dimensional anatomical reconstruction of the human sinus node and a novel paranodal area. *Anatomical Record* **294**, 970-979.
- Chiamvimonvat V, Newman D, Tang A, Green M, Mitchell J, Wulffhart Z & Dorian P. (1998). A double-blind placebo-controlled evaluation of the human electrophysiologic effects of zatebradine, a sinus node inhibitor. *Journal of Cardiovascular Pharmacology* **32**, 516-520.
- Choudhury M, Black N, Alghamdi A, D'Souza A, Wang R, Yanni J, Dobrzynski H, Kingston PA, Zhang H, Boyett MR & Morris GM. (2018). TBX18 overexpression enhances pacemaker function in a rat subsidiary atrial pacemaker model of sick sinus syndrome. *Journal of Physiology* **596**, 6141-6155.

- Cimino G, Pascariello G, Bernardi N, Calvi E, Arabia G, Salghetti F, Bontempi L, Vizzardi E, Metra M & Curnis A. (2020). Sinus node dysfunction in a young patient with COVID-19. *JACC Case Reports* **2**, 1240-1244.
- Crespo-Leiro MG, Anker SD, Maggioni AP, Coats AJ, Filippatos G, Ruschitzka F, Ferrari R, Piepoli MF, Delgado Jimenez JF, Metra M, Fonseca C, Hradec J, Amir O, Logeart D, Dahlstrom U, Merkely B, Drozd J, Goncalvesova E, Hassanein M, Chioncel O, Lainscak M, Seferovic PM, Tousoulis D, Kavoliuniene A, Fruhwald F, Fazlibegovic E, Temizhan A, Gatzov P, Erglis A, Laroche C, Mebazaa A & Heart Failure Association of the European Society of C. (2016). European Society of Cardiology Heart Failure Long-Term Registry (ESC-HF-LT): 1-year follow-up outcomes and differences across regions. *European Journal of Heart Failure* **18**, 613-625.
- Crouse SF, Meade T, Hansen BE, Green JS & Martin SE. (2009). Electrocardiograms of collegiate football athletes. *Clinical Cardiology* **32**, 37-42.
- Csepe TA, Kalyanasundaram A, Hansen BJ, Zhao J & Fedorov VV. (2015). Fibrosis: a structural modulator of sinoatrial node physiology and dysfunction. *Frontiers in Physiology* **6**, 37.
- D'Souza A, Bucchi A, Johnsen AB, Logantha SJ, Monfredi O, Yanni J, Prehar S, Hart G, Cartwright E, Wisloff U, Dobryznski H, DiFrancesco D, Morris GM & Boyett MR. (2014). Exercise training reduces resting heart rate via downregulation of the funny channel HCN4. *Nature Communications* **5**, 3775.
- D'Souza A, Pearman CM, Wang Y, Nakao S, Logantha S, Cox C, Bennett H, Zhang Y, Johnsen AB, Linscheid N, Poulsen PC, Elliott J, Coulson J, McPhee J, Robertson A, da Costa Martins PA, Kitmitto A, Wisloff U, Cartwright EJ, Monfredi O, Lundby A, Dobrzynski H, Oceandy D, Morris GM & Boyett MR. (2017). Targeting miR-423-5p reverses exercise

training-induced HCN4 channel remodeling and sinus bradycardia. *Circulation Research* **121**, 1058-1068.

D'Souza A, Sharma S & Boyett MR. (2015). CrossTalk opposing view: Bradycardia in the trained athlete is attributable to a downregulation of a pacemaker channel in the sinus node. *Journal of Physiology* **593**, 1749-1751.

D'Souza A, Trussell T, Morris GM, Dobrzynski H & Boyett MR. (2019). Supraventricular arrhythmias in athletes: basic mechanisms and new directions. *Physiology* **34**, 314-326.

D'Souza A, Wang Y, Anderson C, Bucchi A, Baruscotti M, Olieslagers S, Mesirca P, Johnsen AB, Mastitskaya S, Ni H, Zhang Y, Black N, Cox C, Wegner S, Bano-Otalora B, Petit C, Gill E, Logantha SJ, Dobrzynski H, Ashton N, Hart G, Zhang R, Zhang H, Cartwright EJ, Wisloff U, Mangoni ME, Da Costa Martins P, Piggins HD, DiFrancesco D & Boyett MR. (2021). A circadian clock in the sinus node mediates day-night rhythms in Hcn4 and heart rate. *Heart Rhythm* **18**, 801-810.

de Melo SR, de Souza RR & Mandarim-de-Lacerda CA. (2002). Stereologic study of the sinoatrial node of rats - age related changes. *Biogerontology* **3**, 383-390.

DiFrancesco D. (1981). A new interpretation of the pace-maker current in calf Purkinje fibres. *Journal of Physiology* **314**, 359-376.

DiFrancesco D. (1991). The contribution of the 'pacemaker' current (i_f) to generation of spontaneous activity in rabbit sino-atrial node myocytes. *Journal of Physiology* **434**, 23-40.

Dilaveris PE, Farbom P, Batchvarov V, Ghuran A & Malik M. (2001). Circadian behavior of P-wave duration, P-wave area, and PR interval in healthy subjects. *Annals of Noninvasive Electrocardiology* **6**, 92-97.

- Dobrzynski H, Anderson RH, Atkinson A, Borbas Z, D'Souza A, Fraser JF, Inada S, Logantha SJRJ, Monfredi O, Morris GM, Moorman AFM, Nikolaidou T, Schneider H, Szuts V, Temple IP, Yanni J & Boyett MR. (2013). Structure, function and clinical relevance of the cardiac conduction system, including the atrioventricular ring and outflow tract tissues. *Pharmacology & Therapeutics* **139**, 260-288.
- Dobrzynski H, Li J, Tellez J, Greener ID, Nikolski VP, Wright SE, Parson SH, Jones SA, Lancaster MK, Yamamoto M, Honjo H, Takagishi Y, Kodama I, Efimov IR, Billeter R & Boyett MR. (2005). Computer three-dimensional reconstruction of the sinoatrial node. *Circulation* **111**, 846-854.
- Dobrzynski H, Nikolski VP, Sambelashvili AT, Greener ID, Boyett MR & Efimov IR. (2003). Site of origin and molecular substrate of atrioventricular junctional rhythm in the rabbit heart. *Circulation Research* **93**, 1102-1110.
- Du Y, Zhang J, Xi Y, Wu G, Han K, Huang X, Ma A & Wang T. (2016). β 1-adrenergic blocker bisoprolol reverses down-regulated ion channels in sinoatrial node of heart failure rats. *Journal of Physiology and Biochemistry* **72**, 293-302.
- Duhme N, Schweizer PA, Thomas D, Becker R, Schröter J, Barends TR, Schlichting I, Draguhn A, Bruehl C, Katus HA & Koenen M. (2013). Altered HCN4 channel C-linker interaction is associated with familial tachycardia-bradycardia syndrome and atrial fibrillation. *Eur Heart J* **34**, 2768-2775.
- Durgan DJ & Young ME. (2010). The cardiomyocyte circadian clock: emerging roles in health and disease. *Circulation Research* **106**, 647-658.

- El Khoury N, Mathieu S, Marger L, Ross J, El Gebeily G, Ethier N & Fiset C. (2013). Upregulation of the hyperpolarization-activated current increases pacemaker activity of the sinoatrial node and heart rate during pregnancy in mice. *Circulation* **127**, 2009-2020.
- Elvan A, Wylie K & Zipes DP. (1996). Pacing-induced chronic atrial fibrillation impairs sinus node function in dogs. Electrophysiological remodeling. *Circulation* **94**, 2953-2960.
- Faggiano P, d'Aloia A, Gualeni A, Gardini A & Giordano A. (2001). Mechanisms and immediate outcome of in-hospital cardiac arrest in patients with advanced heart failure secondary to ischemic or idiopathic dilated cardiomyopathy. *American Journal of Cardiology* **87**, 655-651.
- Ferdous Z, Qureshi MA, Jayaprakash P, Parekh K, John A, Oz M, Raza H, Dobrzynski H, Adrian TE & Howarth FC. (2016). Different profile of mRNA expression in sinoatrial node from streptozotocin-induced diabetic rat. *PLoS One* **11**, e0153934.
- Finley JP & Nugent ST. (1995). Heart rate variability in infants, children and young adults. *Journal of the Autonomic Nervous System* **51**, 103-108.
- Fontenla A, Villagraz L, de Juan J, Lozano Á, Giacomani S & López-Gil M. (2017). Ivabradine as an alternative to AV node ablation in a patient with permanent atrial fibrillation. *Revista Española de Cardiología* **70**, 1019-1020.
- Fye WB. (1987). The origin of the heart beat: a tale of frogs, jellyfish, and turtles. *Circulation* **76**, 493-500.
- Gaskell WH. (1880). On the tonicity of the heart and blood vessels. *Journal of Physiology* **3**, 48-92

- Gaskell WH. (1883). On the innervation of the heart, with especial reference to the heart of the tortoise. *Journal of Physiology* **4**, 43-230 214.
- Grimm W, Langenfeld H, Maisch B & Kochsiek K. (1990). Symptoms, cardiovascular risk profile and spontaneous ECG in paced patients: a five-year follow-up study. *Pacing and Clinical Electrophysiology* **13**, 2086-2090.
- Hagiwara N, Irisawa H, Kasanuki H & Hosada S. (1992). Background current in sino-atrial node cells of the rabbit heart. *Journal of Physiology* **448**, 53-72.
- Hall ME, George EM & Granger JP. (2011). The heart during pregnancy. *Revista Española de Cardiología* **64**, 1045-1050.
- Hao X, Zhang Y, Zhang X, Nirmalan M, Davies L, Dobrzynski H, Wang X, Grace AA, Zhang H, Boyett MR, Huang CL-H & Lei M. (2011). TGF- β 1 mediated fibrosis and ion channel remodeling are key mechanisms producing sinus node dysfunction associated with SCN5A deficiency and aging. *Circulation: Arrhythmia and Electrophysiology* **4**, 397-406.
- Härtel G & Talvensaari T. (1975). Treatment of sinoatrial syndrome with permanent cardiac pacing in 90 patients. *Acta Medica Scandinavica* **198**, 341-347.
- Hasking GJ, Esler MD, Jennings GL, Burton D, Johns JA & Korner PI. (1986). Norepinephrine spillover to plasma in patients with congestive heart failure: evidence of increased overall and cardiorenal sympathetic nervous activity. *Circulation* **73**, 615-621.
- Hategan L, Csányi B, Ördög B, Kákonyi K, Tringer A, Kiss O, Orosz A, Sággy L, Nagy I, Hegedűs Z, Rudas L, Széll M, Varró A, Forster T & Sepp R. (2017). A novel 'splice site' HCN4 Gene mutation, c.1737+1 G>T, causes familial bradycardia, reduced heart rate response,

impaired chronotropic competence and increased short-term heart rate variability. *International Journal of Cardiology* **241**, 364-372.

Hiraiwa H, Goto Y, Nakamura G, Yasuda Y, Sakai Y, Kasugai D, Jinno S, Tanaka T, Ogawa H, Higashi M, Yamamoto T, Jingushi N, Ozaki M, Numaguchi A, Kondo T, Morimoto R, Okumura T, Matsuda N & Murohara T. (2020). Relative bradycardia as a clinical feature in patients with coronavirus disease 2019 (COVID-19): a report of two cases. *Journal of Cardiology Cases* **22**, 260-264.

Hiss RG & Lamb LE. (1962). Electrocardiographic findings in 122,043 individuals. *Circulation* **25**, 947-961.

Hood S & Northcote RJ. (1999). Cardiac assessment of veteran endurance athletes: a 12 year follow up study. *British Journal of Sports Medicine* **33**, 239-243.

Hoogsteen J, Bennekens JH, Ban de Wall EE, van Hemel NM, Wilde AAM, Crijns HJGM, Gorgels APM, Smeets JLRM, Hauer RNW, Jordaens JLM & Schalij MJ. (2004). Recommendations and cardiological evaluation of athletes with arrhythmias. *Netherlands Heart Journal* **12**, 157-164.

Howarth FC, Jacobson M, Naseer O & Adeghate E. (2005a). Short-term effects of streptozotocin-induced diabetes on the electrocardiogram, physical activity and body temperature in rats. *Experimental Physiology* **90**, 237-245.

Howarth FC, Jacobson M, Shafiullah M & Adeghate E. (2005b). Long-term effects of streptozotocin-induced diabetes on the electrocardiogram, physical activity and body temperature in rats. *Experimental Physiology* **90**, 827-835.

- Hu L, Gong L, Jiang Z, Wang Q, Zou Y & Zhu L. (2020). Clinical analysis of sinus bradycardia in patients with severe COVID-19 pneumonia. *Critical Care* **24**, 257.
- Huang X, Du Y, Yang P, Lin S, Xi Y, Yang Z & Ma A. (2015). Age-dependent alterations of voltage-gated Na⁺ channel isoforms in rat sinoatrial node. *Mechanisms of Ageing and Development* **152**, 80-90.
- Huang X, Yang P, Du Y, Zhang J & Ma A. (2007). Age-related down-regulation of HCN channels in rat sinoatrial node. *Basic Research in Cardiology* **102**, 429-435.
- Huang X, Zhong N, Zhang H, Ma A, Yuan Z & Guo N. (2016). Reduced expression of HCN channels in the sinoatrial node of streptozotocin-induced diabetic rats. *Canadian Journal of Physiology and Pharmacology* **95**, 586-594.
- Idema RN, van den Meiracker AH, Balk AH, Bos E, Schalekamp MA & Man in't Veld AJ. (1994). Decreased circadian blood pressure variation up to three years after heart transplantation. *American Journal of Cardiology* **73**, 1006-1009.
- Ikeuchi K, Saito M, Yamamoto S, Nagai H & Adachi E. (2020). Relative bradycardia in patients with mild-to-moderate coronavirus disease, Japan. *Emerging Infectious Diseases* **26**, 2504-2506.
- Ishii TM, Takano M, Xie LH, Noma A & Ohmori H. (1999). Molecular characterization of the hyperpolarization-activated cation channel in rabbit heart sinoatrial node. *Journal of Biological Chemistry* **274**, 12835-12839.
- Iwataki M, Kim YJ, Sun BJ, Jang JY, Takeuchi M, Fukuda S, Otani K, Yoshitani H, Ohe H, Kohno R, Oginosawa Y, Abe H, Levine RA, Song JK & Otsuji Y. (2015). Different characteristics of

heart failure due to pump failure and bradyarrhythmia. *Journal of Echocardiography* **13**, 27-34.

Johansen CD, Olsen RH, Pedersen LR, Kumarathurai P, Mouridsen MR, Binici Z, Intzilakis T, Køber L & Sajadieh A. (2013). Resting, night-time, and 24 h heart rate as markers of cardiovascular risk in middle-aged and elderly men and women with no apparent heart disease. *European Heart Journal* **34**, 1732-1739.

Jones SA, Boyett MR & Lancaster MK. (2007). Declining into failure: the age-dependent loss of the L-type calcium channel within the sinoatrial node. *Circulation* **115**, 1183-1190.

Jones SA, Lancaster MK & Boyett MR. (2004). Ageing-related changes of connexins and conduction within the sinoatrial node. *Journal of Physiology* **560**, 429-437.

Jose AD & Collison D. (1970). The normal range and determinants of the intrinsic heart rate in man. *Cardiovascular Research* **4**, 160-167.

Jose AD & Taylor RR. (1969). Autonomic blockade by propranolol and atropine to study intrinsic myocardial function in man. *Journal of Clinical Investigation* **48**, 2019-2031.

Kanemoto N & Sasamoto H. (1979). Arrhythmias in primary pulmonary hypertension. *Japanese Heart Journal* **20**, 765-775.

Katona PG, McLean M, Dighton DH & Guz A. (1982). Sympathetic and parasympathetic cardiac control in athletes and nonathletes at rest. *Journal of Applied Physiology* **52**, 1652-1657.

Keith A & Flack MW. (1907). The form and nature of the muscular connections between the primary divisions of the vertebrate heart. *Journal of Anatomy and Physiology* **41**, 172-189.

- Koehler U, Fus E, Grimm W, Pankow W, Schafer H, Stammnitz A & Peter JH. (1998). Heart block in patients with obstructive sleep apnoea: pathogenetic factors and effects of treatment. *European Respiratory Journal* **11**, 434-439.
- Kokubun S, Nishimura M, Noma A & Irisawa H. (1982). Membrane currents in the rabbit atrioventricular node cell. *Pflugers Archiv* **393**, 15-22.
- Kollai M, Bonyhay I, Jokkel G & Szonyi L. (1994). Cardiac vagal hyperactivity in adolescent anorexia nervosa. *European Heart Journal* **15**, 1113-1118.
- Kolloch R, Legler UF, Champion A, Cooper-Dehoff RM, Handberg E, Zhou Q & Pepine CJ. (2008). Impact of resting heart rate on outcomes in hypertensive patients with coronary artery disease: findings from the INternational VErapamil-SR/trandolapril STudy (INVEST). *European Heart Journal* **29**, 1327-1334.
- Kotsis VT, Stabouli SV, Pitiriga V, Lekakis JP, Nanas IN, Toumanidis ST & Zakopoulos NA. (2005). Impact of cardiac transplantation in 24 hours circadian blood pressure and heart rate profile. *Transplantation Proceedings* **37**, 2244-2246.
- Kozasa Y, Nakashima N, Ito M, Ishikawa T, Kimoto H, Ushijima K, Makita N & Takano M. (2018). HCN4 pacemaker channels attenuate the parasympathetic response and stabilize the spontaneous firing of the sinoatrial node. *Journal of Physiology* **596**, 809-825.
- Kuga K, Yamaguchi I & Sugishita Y. (1993). Age-related changes of sinus node function and autonomic regulation in subjects without sinus node disease: assessment by pharmacologic autonomic blockade. *Japanese Circulation Journal* **57**, 760-768.
- Lakatta EG & DiFrancesco D. (2009). What keeps us ticking: a funny current, a calcium clock, or both? *Journal of Molecular and Cellular Cardiology* **47**, 157-170.

- Lakatta EG, Maltsev VA & Vinogradova TM. (2010). A coupled SYSTEM of intracellular Ca^{2+} clocks and surface membrane voltage clocks controls the timekeeping mechanism of the heart's pacemaker. *Circulation Research* **106**, 659-673.
- Laks L, Lehrhaft B, Grunstein RR & Sullivan CE. (1995). Pulmonary hypertension in obstructive sleep apnoea. *European Respiratory Journal* **8**, 537-541.
- Landgraf D, Wang LL, Diemer T & Welsh DK. (2016). NPAS2 compensates for loss of CLOCK in peripheral circadian oscillators. *PLoS Genetics* **12**, e1005882.
- Laroumanie F, Douin-Echinard V, Pozzo J, Lairez O, Tortosa F, Vinel C, Delage C, Calise D, Dutaur M, Parini A & Pizzinat N. (2014). CD4+ T cells promote the transition from hypertrophy to heart failure during chronic pressure overload. *Circulation* **129**, 2111-2124.
- Larson ED, St Clair JR, Sumner WA, Bannister RA & Proenza C. (2013). Depressed pacemaker activity of sinoatrial node myocytes contributes to the age-dependent decline in maximum heart rate. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 18011-18016.
- Lear JT, Lawrence IG & Burden AC. (1996). Prevalence of diabetes in elderly patients requiring permanent cardiac pacemaker insertion. *Acta Diabetol* **33**, 169-170.
- Lemmer B. (2009). Discoveries of rhythms in human biological functions: a historical review. *Chronobiology International* **26**, 1019-1068.
- Li J, Temple IP & Boyett MR. (2014). Theoretical study of the role of the funny current (I_f) and the background inward current (I_b) in atrioventricular nodal conduction. *Computing in Cardiology* **41**, 865-868.

- Lin RZ, Lu Z, Anyukhovskiy EP, Jiang YP, Wang HZ, Gao J, Rosen MR, Ballou LM & Cohen IS. (2019). Regulation of heart rate and the pacemaker current by phosphoinositide 3-kinase signaling. *Journal of General Physiology* **151**, 1051-1058.
- Linscheid N, Logantha S, Poulsen PC, Zhang S, Schrolkamp M, Egerod KL, Thompson JJ, Kitmitto A, Galli G, Humphries MJ, Zhang H, Pers TH, Olsen JV, Boyett M & Lundby A. (2019). Quantitative proteomics and single-nucleus transcriptomics of the sinus node elucidates the foundation of cardiac pacemaking. *Nature Communications* **10**, 2889.
- Liu J, Noble PJ, Xiao G, Abdelrahman M, Dobrzynski H, Boyett MR, Lei M & Noble D. (2008). Role of pacemaking current in cardiac nodes: insights from a comparative study of sinoatrial node and atrioventricular node. *Progress in Biophysics and Molecular Biology* **96**, 294-304.
- Logantha SJRJ, Cai XJ, Yanni J, Jones CB, Stephenson RS, Quigley G, Monfredi OJ, Vohra A, Hutcheon RC, Corno AF, Jarvis JC, Dobrzynski H, Boyett MR & Hart G. (2021). Remodelling of the Purkinje network in congestive heart failure in the rabbit. *Circulation: Heart Failure* (in press).
- Lolicato M, Nardini M, Gazzarrini S, Möller S, Bertinetti D, Herberg FW, Bolognesi M, Martin H, Fasolini M, Bertrand JA, Arrigoni C, Thiel G & Moroni A. (2011). Tetramerization dynamics of C-terminal domain underlies isoform-specific cAMP gating in hyperpolarization-activated cyclic nucleotide-gated channels. *Journal of Biological Chemistry* **286**, 44811-44820.
- Long V & Fiset C. (2020). Contribution of estrogen to the pregnancy-induced increase in cardiac automaticity. *Journal of Molecular and Cellular Cardiology* **147**, 27-34.
- Ludwig A, Zong X, Jeglitsch M, Hofmann F & Biel M. (1998). A family of hyperpolarization-activated mammalian cation channels. *Nature* **393**, 587-591.

- Ludwig A, Zong X, Stieber J, Hullin R, Hofmann F & Biel M. (1999). Two pacemaker channels from human heart with profoundly different activation kinetics. *EMBO J* **18**, 2323-2329.
- Luthi P, Zuber M, Ritter M, Oechslin EN, Jenni R, Seifert B, Baldesberger S & Jost CH. (2008). Echocardiographic findings in former professional cyclists after long-term deconditioning of more than 30 years. *European Journal of Echocardiography* **9**, 261-267.
- Luu M, Stevenson WG, Stevenson LW, Baron K & Walden J. (1989). Diverse mechanisms of unexpected cardiac arrest in advanced heart failure. *Circulation* **80**, 1675-1680.
- Maccaferri G, Mangoni M, Lazzari A & DiFrancesco D. (1993). Properties of the hyperpolarization-activated current in rat hippocampal CA1 pyramidal cells. *Journal of Neurophysiology* **69**, 2129-2136.
- Macri V, Mahida SN, Zhang ML, Sinner MF, Dolmatova EV, Tucker NR, McLellan M, Shea MA, Milan DJ, Lunetta KL, Benjamin EJ & Ellinor PT. (2014). A novel trafficking-defective HCN4 mutation is associated with early-onset atrial fibrillation. *Heart Rhythm* **11**, 1055-1062.
- Makino M, Hayashi H, Takezawa H, Hirai M, Saito H & Ebihara S. (1997). Circadian rhythms of cardiovascular functions are modulated by the baroreflex and the autonomic nervous system in the rat. *Circulation* **96**, 1667-1674.
- Manolis AS, Manolis AA, Manolis TA, Apostolopoulos EJ, Papatheou D & Melita H. (2020). COVID-19 infection and cardiac arrhythmias. *Trends in Cardiovascular Medicine* **30**, 451-460.
- Marger L, Mesirca P, Alig J, Torrente A, Dubel S, Engeland B, Kanani S, Fontanaud P, Striessnig J, Shin HS, Isbrandt D, Ehmke H, Nargeot J & Mangoni ME. (2011). Functional roles of

Ca_v1.3, Ca_v3.1 and HCN channels in automaticity of mouse atrioventricular cells: insights into the atrioventricular pacemaker mechanism. *Channels* **5**, 251-261.

Maron Barry J & Pelliccia A. (2006). The heart of trained athletes: cardiac remodeling and the risks of sports, including sudden death. *Circulation* **114**, 1633-1644.

Martini E, Kunderfranco P, Peano C, Carullo P, Cremonesi M, Schorn T, Carriero R, Termanini A, Colombo FS, Jachetti E, Panico C, Faggian G, Fumero A, Torracca L, Molgora M, Cibella J, Pagiatakis C, Brummelman J, Alvisi G, Mazza EMC, Colombo MP, Lugli E, Condorelli G & Kallikourdis M. (2019). Single-cell sequencing of mouse heart immune infiltrate in pressure overload-driven heart failure reveals extent of immune activation. *Circulation* **140**, 2089-2107.

Merchant FM & Mittal S. (2020). Pacing induced cardiomyopathy. *Journal of Cardiovascular Electrophysiology* **31**, 286-292.

Mesirca P, Alig J, Torrente AG, Muller JC, Marger L, Rollin A, Marquilly C, Vincent A, Dubel S, Bidaud I, Fernandez A, Seniuk A, Engeland B, Singh J, Miquerol L, Ehmke H, Eschenhagen T, Nargeot J, Wickman K, Isbrandt D & Mangoni ME. (2014). Cardiac arrhythmia induced by genetic silencing of 'funny' (f) channels is rescued by GIRK4 inactivation. *Nature Communications* **5**, 4664.

Mesirca P, Bidaud I, Briec F, Evain S, Torrente AG, Le Quang K, Leoni AL, Baudot M, Marger L, Chung You Chong A, Nargeot J, Striessnig J, Wickman K, Charpentier F & Mangoni ME. (2016). G protein-gated I_{KACH} channels as therapeutic targets for treatment of sick sinus syndrome and heart block. *Proceedings of the National Academy of Sciences of the United States of America* **113**, E932-941.

Mesirca P, Nakao S, Dalgas Nissen S, Forte G, Anderson C, Trussell T, Li J, Cox C, Zi M, Logantha S, Yaar S, Cartensen H, Bidaud I, Stuart L, Soattin L, Morris GM, da Costa Martins P, Cartwright EJ, Oceandy D, Mangoni ME, Jespersen T, Buhl R, Dobrzynski H, Boyett MR & D'Souza A. (2021). Why do athletes have AV block? A new role for electrical remodelling of the atrioventricular node in equine and murine models of endurance exercise. *Circulation Research* (in press).

Milanesi R, Baruscotti M, Gneccchi-Ruscione T & DiFrancesco D. (2006). Familial sinus bradycardia associated with a mutation in the cardiac pacemaker channel. *New England Journal of Medicine* **354**, 151-157.

Milano A, Vermeer Alexa MC, Lodder Elisabeth M, Barc J, Verkerk Arie O, Postma Alex V, van der Bilt Ivo AC, Baars Marieke JH, van Haelst Paul L, Caliskan K, Hoedemaekers Yvonne M, Le Scouarnec S, Redon R, Pinto Yigal M, Christiaans I, Wilde Arthur A & Bezzina Connie R. (2014). HCN4 mutations in multiple families with bradycardia and left ventricular noncompaction cardiomyopathy. *Journal of the American College of Cardiology* **64**, 745-756.

Moghtadaei M, Jansen HJ, Mackasey M, Rafferty SA, Bogachev O, Sapp JL, Howlett SE & Rose RA. (2016). The impacts of age and frailty on heart rate and sinoatrial node function. *Journal of Physiology* **594**, 7105-7126.

Mohawk JA, Green CB & Takahashi JS. (2012). Central and peripheral circadian clocks in mammals. *Annual Review of Neuroscience* **35**, 445-462.

Monfredi O & Boyett MR. (2015). Sick sinus syndrome and atrial fibrillation in older persons - A view from the sinoatrial nodal myocyte. *Journal of Molecular and Cellular Cardiology* **83**, 88-100.

- Monfredi O & Lakatta EG. (2019). Complexities in cardiovascular rhythmicity: perspectives on circadian normality, ageing and disease. *Cardiovascular Research* **115**, 1576-1595.
- Monfredi O, Lyashkov AE, Johnsen AB, Inada S, Schneider H, Wang R, Nirmalan M, Wisloff U, Maltsev VA, Lakatta EG, Zhang H & Boyett MR. (2014). Biophysical characterisation of the under-appreciated and important relationship between heart rate variability and heart rate. *Hypertension* **64**, 1334-1343.
- Monfredi O, Maltsev VA & Lakatta EG. (2013). Modern concepts concerning the origin of the heartbeat. *Physiology* **28**, 74-92.
- Morris GM & Boyett MR. (2009). Perspectives - biological pacing, a clinical reality? *Therapeutic Advances in Cardiovascular Disease* **3**, 479-483.
- Morris GM, D'Souza A, Dobrzynski H, Lei M, Choudhury M, Billeter R, Kryukova Y, Robinson RB, Kingston PA & Boyett MR. (2013). Characterization of a right atrial subsidiary pacemaker and acceleration of the pacing rate by HCN over-expression. *Cardiovascular Research* **100**, 160-169.
- Muir-Nisbet A. (2008). The electrophysiology of the atrioventricular node in normal and failing rabbit hearts. *PhD thesis, University of Glasgow*.
- Nagatomo D, Kotooka N, Yoshioka G & Node K. (2020). Strategy for estimating optimal heart rate in refractory heart failure with relative sinus bradycardia: a case report. *Journal of Cardiology Cases* **21**, 153-156.
- Nikolaidou T, Cai X, Stephenson RS, Yanni J, Lowe T, Atkinson AJ, Jones CB, Sardar R, Corno AF, Dobrzynski H, Withers PJ, Jarvis JC, Hart G & Boyett MR. (2015). Congestive heart

failure leads to prolongation of the PR Interval and atrioventricular junction enlargement and ion channel remodelling in the rabbit. *PLoS One* **10**, e0141452.

Nikolaidou T, Ghosh JM & Clark AL. (2016). Outcomes related to first-degree atrioventricular block and therapeutic implications in patients with heart failure. *Journal of the American College of Cardiology: Clinical Electrophysiology* **2**, 181–192.

Noble D. (1960). Cardiac action and pacemaker potentials based on the Hodgkin-Huxley equations. *Nature* **188**, 495-497.

Noble D & Tsien RW. (1968). The kinetics and rectifier properties of the slow potassium current in cardiac Purkinje fibres. *Journal of Physiology* **195**, 185-214.

Noma A, Morad M & Irisawa H. (1983). Does the "pacemaker current" generate the diastolic depolarization in the rabbit SA node cells? *Pflugers Archiv* **397**, 190-194.

Northcote RJ, Canning GP & Ballantyne D. (1989). Electrocardiographic findings in male veteran endurance athletes. *British Heart Journal* **61**, 155-160.

Ntalianis A & Nanas JN. (2006). Immediate relief of congestive heart failure by ventricular pacing in chronic bradycardia. *Cardiology in Review* **14**, e14-15.

Oosting J, Struijker-Boudier HA & Janssen BJ. (1997). Autonomic control of ultradian and circadian rhythms of blood pressure, heart rate, and baroreflex sensitivity in spontaneously hypertensive rats. *Journal of Hypertension* **15**, 401-410.

Opthof T, Coronel R, Rademaker HM, Vermeulen JT, Wilms-Schopman FJ & Janse MJ. (2000). Changes in sinus node function in a rabbit model of heart failure with ventricular arrhythmias and sudden death. *Circulation* **101**, 2975-2980.

- Ostchega Y, Porter KS, Hughes J, Dillon CF & Nwankwo T. (2011). Resting pulse rate reference data for children, adolescents, and adults: United States, 1999–2008. *National Health Statistics Reports* **41**.
- Parati G & Esler M. (2012). The human sympathetic nervous system: its relevance in hypertension and heart failure. *European Heart Journal* **33**, 1058-1066.
- Parodi G, Bellandi B, Valenti R, Memisha G, Giuliani G, Velluzzi S, Migliorini A, Carrabba N & Antoniucci D. (2010). Heart rate as an independent prognostic risk factor in patients with acute myocardial infarction undergoing primary percutaneous coronary intervention. *Atherosclerosis* **211**, 255-259.
- Patke A, Young MW & Axelrod S. (2020). Molecular mechanisms and physiological importance of circadian rhythms. *Nature Reviews Molecular Cell Biology* **21**, 67-84.
- Peigh G, Leya MV, Baman JR, Cantey EP, Knight BP & Flaherty JD. (2020). Novel coronavirus 19 (COVID-19) associated sinus node dysfunction: a case series. *European Heart Journal - Case Reports* **4**, 1-6.
- Penton GB, Miller H & Levine SA. (1956). Some clinical features of complete heart block. *Circulation* **13**, 801-824.
- Peters CH, Sharpe EJ & Proenza C. (2020). Cardiac pacemaker activity and aging. *Annual Review of Physiology* **82**, 21-43.
- Petkova M, Atkinson AJ, Yanni J, Stuart L, Aminu AJ, Ivanova AD, Pustovit KB, Geraghty C, Feather A, Li N, Zhang Y, Oceandy D, Perde F, Molenaar P, D'Souza A, Fedorov VV &

Dobrzynski H. (2020). Identification of key small non-coding microRNAs controlling pacemaker mechanisms in the human sinus node. *J Am Heart Assoc* **9**, e016590.

Portilla MG. (2011). Bradycardia: an important physical finding in anorexia nervosa. *Journal of the Arkansas Medical Society* **107**, 206-208.

Proenza C & Yellen G. (2006). Distinct populations of HCN pacemaker channels produce voltage-dependent and voltage-independent currents. *Journal of General Physiology* **127**, 183-190.

Protas L, DiFrancesco D & Robinson RB. (2001). L-type but not T-type calcium current changes during postnatal development in rabbit sinoatrial node. *American Journal of Physiology* **281**, H1252-H1259.

Protas L, Oren RV, Clancy CE & Robinson RB. Age-dependent changes in Na current magnitude and TTX-sensitivity in the canine sinoatrial node. *Journal of Molecular and Cellular Cardiology* **48**, 172-180.

Rajdev A, Garan H & Biviano A. (2012). Arrhythmias in pulmonary arterial hypertension. *Progress in Cardiovascular Diseases* **55**, 180-186.

Rana S, Prabhu SD & Young ME. (2020). Chronobiological influence over cardiovascular function: the good, the bad, and the ugly. *Circulation Research* **126**, 258-279.

Rautio E, Gadler F, Gudbjörnsdóttir S, Franzén S, Rydén L, Svensson A-M & Mellbin LG. (2020). Patients with type 2 diabetes have an increased demand for pacemaker treatment: a comparison with age- and sex-matched control subjects from the general population. *Diabetes Care*, dc200084.

- Rautio E, Gadler F, Gudbjornsdottir S, Franzen S, Ryden L, Svensson AM & Mellbin L. (2018). Type 2 diabetes increases the need for pacemaker and implantable cardioverter defibrillator treatment - a Swedish registry report. *European Heart Journal* **39**.
- Roche F, Pichot V, Da Costa A, Isaaz K, Costes F, Dall'Acqua T, Duverney D, Lacour JR & Barthelemy JC. (2001). Chronotropic incompetence response to exercise in congestive heart failure, relationship with the cardiac autonomic status. *Clinical Physiology and Functional Imaging* **21**, 335-342.
- Romero-Leon JM, Galvez-Contreras MC & Diez-Garcia LF. (2016). Symptomatic bradycardia and heart failure triggered by ivabradine in a patient receiving antiretroviral therapy. *Revista Española de Cardiología* **69**, 529-530.
- Rosen MR, Brink PR, Cohen IS & Robinson RB. (2007). Biological pacemakers based on I_f. In *Biopacemaking Series in Biomedical Engineering*, ed. Spaan JAE, Coronel R, de Bakker JMT & Zaza A. Springer, Berlin, Heidelberg.
- Rubler S, Reicher-Reiss H & Pulini M. (1975). Diabetes mellitus and impaired atrioventricular conduction. *New York State Journal of Medicine* **75**, 2517-2521.
- Saeed Y, Temple IP, Borbas Z, Atkinson A, Yanni J, Maczewski M, Mackiewicz U, Aly M, Logantha S, Garratt CJ & Dobrzynski H. (2018). Structural and functional remodeling of the atrioventricular node with aging in rats: The role of hyperpolarization-activated cyclic nucleotide-gated and ryanodine 2 channels. *Heart Rhythm* **15**, 752-760.
- Sah R, Mesirca P, Van den Boogert M, Rosen J, Mably J, Mangoni ME & Clapham DE. (2013). Ion channel-kinase TRPM7 is required for maintaining cardiac automaticity. *Proceedings of the National Academy of Sciences of the United States of America* **110**, E3037-3046.

- Sanders P, Kistler PM, Morton JB, Spence SJ & Kalman JM. (2004). Remodeling of sinus node function in patients with congestive heart failure: reduction in sinus node reserve. *Circulation* **110**, 897-903.
- Santoro B & Tibbs GR. (1999). The HCN gene family: molecular basis of the hyperpolarization-activated pacemaker channels. *Annals of the New York Academy of Sciences* **868**, 741-764.
- Scharhag J, Löllgen H & Kindermann W. (2013). Competitive sports and the heart: benefit or risk? *Deutsches Ärzteblatt International* **110**, 14-23; quiz 24; e11-12.
- Scheer FA, Kalsbeek A & Buijs RM. (2003). Cardiovascular control by the suprachiasmatic nucleus: neural and neuroendocrine mechanisms in human and rat. *Biological Chemistry* **384**, 697-709.
- Schoeller R, Andresen D, Buttner P, Oezcelik K, Vey G & Schroder R. (1993). First- or second-degree atrioventricular block as a risk factor in idiopathic dilated cardiomyopathy. *American Journal of Cardiology* **71**, 720-726.
- Schroder EA, Lefta M, Zhang X, Bartos DC, Feng HZ, Zhao Y, Patwardhan A, Jin JP, Esser KA & Delisle BP. (2013). The cardiomyocyte molecular clock, regulation of Scn5a, and arrhythmia susceptibility. *American Journal of Physiology-Cell Physiology* **304**, C954-965.
- Schulze-Bahr E, Neu A, Friederich P, Kaupp UB, Breithardt G, Pongs O & Isbrandt D. (2003). Pacemaker channel dysfunction in a patient with sinus node disease. *Journal of Clinical Investigation* **111**, 1537-1545.
- Semelka M, Gera J & Usman S. (2013). Sick sinus syndrome: a review. *American Family Physician* **87**, 691-696.

- Senga M, Dohi K, Kumagai N, Takamura T, Fujimoto N, Kurita T, Fujii E, Ota S, Tanigawa T, Kitamura T, Onishi K, Yamada N, Nakamura M, Okubo S, Isaka N & Ito M. (2007). A case of bradycardia-induced severe right-sided heart failure with cardiogenic shock rescued by right ventricular pacing. *Therapeutic Research* **28**, 586-589.
- Sharpe EJ, Larson ED & Proenza C. (2017). Cyclic AMP reverses the effects of aging on pacemaker activity and I_f in sinoatrial node myocytes. *Journal of General Physiology* **149**, 237-247.
- Shi S, Hida A, McGuinness OP, Wasserman DH, Yamazaki S & Johnson CH. (2010). Circadian clock gene *Bmal1* is not essential; functional replacement with its paralog, *Bmal2*. *Current Biology* **20**, 316-321.
- Stein R, Medeiros CM, Rosito GA, Zimmerman LI & Ribeiro JP. (2002). Intrinsic sinus and atrioventricular node electrophysiologic adaptations in endurance athletes. *Journal of the American College of Cardiology* **39**, 1033-1038.
- Stephenson RS, Atkinson A, Kottas P, Perde F, Jafarzadeh F, Bateman M, Iaizzo PA, Zhao J, Zhang H, Anderson RH, Jarvis JC & Dobrzynski H. (2017). High resolution 3-dimensional imaging of the human cardiac conduction system from microanatomy to mathematical modeling. *Scientific Reports* **7**, 7188.
- Stephenson RS, Boyett MR, Hart G, Nikolaidou T, Cai X, Corno AF, Alphonso N, Jeffery N & Jarvis JC. (2012). Contrast enhanced micro-computed tomography resolves the 3-dimensional morphology of the cardiac conduction system in mammalian hearts. *PLoS One* **7**, e35299.

- Stevenson WG, Stevenson LW, Middlekauff HR & Saxon LA. (1993). Sudden death prevention in patients with advanced ventricular dysfunction. *Circulation* **88**, 2953-2961.
- Strassheim D, Dempsey EC, Gerasimovskaya E, Stenmark K & Karoor V. (2019). Role of inflammatory cell subtypes in heart failure. *Journal of Immunology Research* **2019**, 2164017.
- Stuart L. (2021). Development of constructs for cardiac conduction system specific gene therapy. *PhD thesis, University of Manchester.*
- Sutherland GA. (1929). The pulse rate and range in health and disease during childhood. *Quarterly Journal of Medicine* **22**, 519-529
- Swoap SJ, Li C, Wess J, Parsons AD, Williams TD & Overton JM. (2008). Vagal tone dominates autonomic control of mouse heart rate at thermoneutrality. *American Journal of Physiology-Heart and Circulatory Physiology* **294**, H1581-1588.
- Talan DA, Bauernfeind RA, Ashley WW, Kanakis C, Jr. & Rosen KM. (1982). Twenty-four hour continuous ECG recordings in long-distance runners. *Chest* **82**, 19-24.
- Tang H, Gao Y, Li Z, Miao Y, Huang Z, Liu X, Xie L, Li H, Wen W, Zheng Y & Su W. (2020). The noncoding and coding transcriptional landscape of the peripheral immune response in patients with COVID-19. *Clinical and Translational Medicine* **10**, e200.
- Tellez JO, Dobrzynski H, Greener ID, Graham GM, Laing E, Honjo H, Hubbard SJ, Boyett MR & Billeter R. (2006). Differential expression of ion channel transcripts in atrial muscle and sinoatrial node in rabbit. *Circulation Research* **99**, 1384-1393.

- Tellez JO, Maczewski M, Yanni J, Sutyagin PV, Mackiewicz U, Atkinson A, Inada S, Beresewicz A, Billeter R, Dobrzynski H & Boyett MR. (2011). Ageing-dependent remodelling of ion channel and Ca²⁺ clock genes underlying sinoatrial node pacemaking. *Experimental Physiology* **96**, 1163-1178.
- Temple IT, Logantha SJRJ, Absi M, Zhang Y, Pervolaraki E, Yanni J, Atkinson A, Petkova M, Quigley GM, Castro S, Drinkhill M, Schneider H, Monfredi O, Cartwright E, Zi M, Yamanushi TT, Mahadevan VS, Gurney AM, White E, Zhang H, Hart G, Boyett MR & Dobrzynski H. (2016). Atrioventricular node dysfunction and ion channel transcriptome in pulmonary hypertension. *Circulation: Arrhythmia and Electrophysiology* **9**, e003432.
- Tong M, Watanabe E, Yamamoto N, Nagahata-Ishiguro M, Maemura K, Takeda N, Nagai R & Ozaki Y. (2013). Circadian expressions of cardiac ion channel genes in mouse might be associated with the central clock in the SCN but not the peripheral clock in the heart. *Biological Rhythm Research* **44**, 519-530.
- Tong MQ, Wang SS, Pang YY, Zhou Y, Cui HB, Ruan LM, Su J & Chen XM. (2016). Circadian expression of connexins in the mouse heart. *Biological Rhythm Research* **47**, 631-639.
- Ueyama T, Krout KE, Nguyen XV, Karpitskiy V, Kollert A, Mettenleiter TC & Loewy AD. (1999). Suprachiasmatic nucleus: a central autonomic clock. *Nature Neuroscience* **2**, 1051-1053.
- Vaccari T, Moroni A, Rocchi M, Gorza L, Bianchi ME, Beltrame M & DiFrancesco D. (1999). The human gene coding for HCN2, a pacemaker channel of the heart. *Biochimica et Biophysica Acta* **1446**, 419-425.
- Vanderdonckt O, Lambert M, Montero MC, Boland B & Brohet C. (2001). The 12-lead electrocardiogram in anorexia nervosa: a report of 2 cases followed by a retrospective study. *Journal of Electrocardiology* **34**, 233-242.

- Vandewalle G, Middleton B, Rajaratnam SM, Stone BM, Thorleifsdottir B, Arendt J & Dijk DJ. (2007). Robust circadian rhythm in heart rate and its variability: influence of exogenous melatonin and photoperiod. *Journal of Sleep Research* **16**, 148-155.
- Verkerk AO, Wilders R, Coronel R, Ravensloot JH & Verheijck EE. (2003). Ionic remodeling of sinoatrial node cells by heart failure. *Circulation* **108**, 760-766.
- Verrier RL, Bonatti R, Silva AF, Batatinha JA, Nearing BD, Liu G, Rajamani S, Zeng D & Belardinelli L. (2014). I_f inhibition in the atrioventricular node by ivabradine causes rate-dependent slowing of conduction and reduces ventricular rate during atrial fibrillation. *Heart Rhythm* **11**, 2288-2296.
- Verrier RL & Josephson ME. (2009). Impact of sleep on arrhythmogenesis. *Circulation Arrhythmia and Electrophysiology* **2**, 450-459.
- Viitasalo MT, Kala R & Eisalo A. (1982). Ambulatory electrocardiographic recording in endurance athletes. *British Heart Journal* **47**, 213-220.
- Wahl-Schott C & Biel M. (2009). HCN channels: structure, cellular regulation and physiological function. *Cellular and Molecular Life Sciences* **66**, 470-494.
- Wang Y, Anderson C, Dobrzynski H, Hart G, D'Souza A & Boyett MR. (2021). RNAseq shows an all-pervasive circadian rhythm in the transcriptome of the pacemaker of the heart, the sinus node. *Scientific Reports* **11**, 3565.
- Warren WS, Champney TH & Cassone VM. (1994). The suprachiasmatic nucleus controls the circadian rhythm of heart rate via the sympathetic nervous system. *Physiology & Behavior* **55**, 1091-1099.

- Wong MC, Kalman JM, Pedagogos E, Toussaint N, Vohra JK, Sparks PB, Sanders P, Kistler PM, Halloran K, Lee G, Joseph SA & Morton JB. (2015a). Bradycardia and asystole is the predominant mechanism of sudden cardiac death in patients with chronic kidney disease. *Journal of the American College of Cardiology* **65**, 1263-1265.
- Wong MC, Kalman JM, Pedagogos E, Toussaint N, Vohra JK, Sparks PB, Sanders P, Kistler PM, Halloran K, Lee G, Joseph SA & Morton JB. (2015b). Temporal distribution of arrhythmic events in chronic kidney disease: Highest incidence in the long interdialytic period. *Heart Rhythm* **12**, 2047-2055.
- Wongcharoen W, Ruttanaphol A, Gunaparn S & Phrommintikul A. (2016). Ivabradine reduced ventricular rate in patients with non-paroxysmal atrial fibrillation. *International Journal of Cardiology* **224**, 252-255.
- Yahalom M, Spitz M, Sandler L, Heno N, Roguin N & Turgeman Y. (2013). The significance of bradycardia in anorexia nervosa. *International Journal of Angiology* **22**, 83-94.
- Yamanushi TT, Yanni J, Dobrzynski H, Kabuto H & Boyett MR. (2010). Changes in ion channel expression in right-sided congestive heart failure. *Journal of Molecular and Cellular Cardiology* **48**, Supplement (S73).
- Yamaya Y, Kubo K, Amada A & Sato K. (1997). Intrinsic atrioventricular conductive function in horses with a second degree atrioventricular block. *Journal of Veterinary Medical Science* **59**, 149-151.
- Yanagihara K & Irisawa H. (1980). Inward current activated during hyperpolarization in the rabbit sinoatrial node cell. *Pflugers Archiv* **385**, 11-19.

- Yanagihara K, Noma A & Irisawa H. (1980). Reconstruction of sino-atrial node pacemaker potential based on the voltage clamp experiments. *Japanese Journal of Physiology* **30**, 841-857.
- Yanni J, D'Souza A, Wang Y, Li N, Hansen BJ, Zakharkin SO, Smith M, Hayward C, Whitson BA, Mohler PJ, Janssen PML, Zeef L, Choudhury M, Zi M, Cai X, Logantha SJRJ, Nakao S, Atkinson A, Petkova M, Doris U, Ariyaratnam J, Cartwright EJ, Griffiths-Jones S, Hart G, Fedorov VV, Oceandy D, Dobrzynski H & Boyett MR. (2020). Silencing miR-370-3p rescues funny current and sinus node function in heart failure. *Scientific Reports* **10**, 11279.
- Yanni J, Tellez JO, Maczewski M, Mackiewicz U, Beresewicz A, Billeter R, Dobrzynski H & Boyett MR. (2011). Changes in ion channel gene expression underlying heart failure-induced sinoatrial node dysfunction. *Circulation: Heart Failure* **4**, 496-508.
- Yanni J, Tellez JO, Sutyagin PV, Boyett MR & Dobrzynski H. (2010). Structural remodelling of the sinoatrial node in obese old rats. *Journal of Molecular and Cellular Cardiology* **48**, 653-662.
- Yavari A, Bellahcene M, Bucchi A, Sirenko S, Pinter K, Herring N, Jung JJ, Tarasov KV, Sharpe EJ, Wolfien M, Czibik G, Steeples V, Ghaffari S, Nguyen C, Stockenhuber A, Clair JRS, Rimmbach C, Okamoto Y, Yang D, Wang M, Ziman BD, Moen JM, Riordon DR, Ramirez C, Paina M, Lee J, Zhang J, Ahmet I, Matt MG, Tarasova YS, Baban D, Sahgal N, Lockstone H, Puliyadi R, de Bono J, Siggs OM, Gomes J, Muskett H, Maguire ML, Beglov Y, Kelly M, Dos Santos PPN, Bright NJ, Woods A, Gehmlich K, Isackson H, Douglas G, Ferguson DJP, Schneider JE, Tinker A, Wolkenhauer O, Channon KM, Cornall RJ, Sternick EB, Paterson DJ, Redwood CS, Carling D, Proenza C, David R, Baruscotti M, DiFrancesco D, Lakatta EG, Watkins H & Ashrafian H. (2017). Mammalian gamma2 AMPK regulates intrinsic heart rate. *Nature Communications* **8**, 1258.

- Yeh YH, Burstein B, Qi XY, Sakabe M, Chartier D, Comtois P, Wang Z, Kuo CT & Nattel S. (2009). Funny current downregulation and sinus node dysfunction associated with atrial tachyarrhythmia: a molecular basis for tachycardia-bradycardia syndrome. *Circulation* **119**, 1576-1585.
- Zaza A & Lombardi F. (2001). Autonomic indexes based on the analysis of heart rate variability: a view from the sinus node. *Cardiovascular Research* **50**, 434-442.
- Zhang H, Boyett MR, Holden AV, Honjo H & Kodama I. (1998). A hypothesis to explain the decline of sinoatrial node function with age. *Journal of Physiology* **511**, 76P-77P.
- Zhang Y, Wang Y, Yanni J, Qureshi MA, Logantha S, Kassab S, Boyett MR, Gardiner NJ, Sun H, Howarth FC & Dobrzynski H. (2019). Electrical conduction system remodeling in streptozotocin-induced diabetes mellitus rat heart. *Frontiers in Physiology* **10**, 826.
- Zhou J, Ding WG, Makiyama T, Miyamoto A, Matsumoto Y, Kimura H, Tarutani Y, Zhao J, Wu J, Zang WJ, Matsuura H & Horie M. (2014a). A novel HCN4 mutation, G1097W, is associated with atrioventricular block. *Circulation Journal* **78**, 938-942.
- Zhou J, Ding WG, Makiyama T, Miyamoto A, Matsumoto Y, Kimura H, Tarutani Y, Zhao J, Wu J, Zang WJ, Matsuura H & Horie M. (2014b). A novel HCN4 mutation, G1097W, is associated with atrioventricular block. *Circulation journal : official journal of the Japanese Circulation Society* **78**, 938-942.
- Zicha S, Fernandez-Velasco M, Lonardo G, L'Heureux N & Nattel S. (2005). Sinus node dysfunction and hyperpolarization-activated (HCN) channel subunit remodeling in a canine heart failure model. *Cardiovascular Research* **66**, 472-481.

Figure legends

Fig. 1. Expression of HCN4 protein in the sinus node. **A**, micro-CT image of a virtual section of the right atrium (RA) of the rabbit heart. The section is cut perpendicular to the crista terminalis (CT) and runs through the sinus node (SAN). **B**, volume rendering based on micro-CT data of the rear wall of the right atrium of the rabbit heart showing the superior and inferior venae cavae (SVC and IVC), sinus node and crista terminalis (PM, pectinate muscles). **C**, segmented 3D surface based on micro-CT data of the sinus node of the rabbit heart showing the sinus node (SAN; yellow) and sinus node artery (SNA; red). **D**, volume rendering based on micro-CT data of the rear wall of the right atrium of the human heart showing the superior and inferior venae cavae (SCV and ICV), sinus node (SN; outlined by a dashed yellow line) and crista terminalis. PcM, pectinate muscles. **E**, section cut perpendicular to the crista terminalis through the intercaval region of the rat heart immunolabelled for Cx43 (red signal) and HCN4 (green signal). RSARB, right sinoatrial ring bundle. A-C from Stephenson *et al.* (Stephenson *et al.*, 2012), D from Stephenson *et al.* (Stephenson *et al.*, 2017) and E from Boyett (Boyett, 2009).

Fig. 2. Resting bradycardia in the athlete and the involvement of HCN4 and I_f . **A**, distribution of resting heart rates in elite athletes and a normal population. Red bars, histogram of resting heart rate of 142 elite cyclists and rowers. Grey bars, histogram of resting heart rate of 3,061 20- to 39-year-old female subjects. From D'Souza *et al.* (D'Souza *et al.*, 2015). **B**, mean hourly heart rate (\pm SEM) of 20 athletes and 20 control subjects over 24 h; for visual purposes, the data are repeated for a second 24 h period. From Northcote *et al.* (Northcote *et al.*, 1989). **C**, density of I_f is reduced in trained mice. Left, representative I_f traces, normalised to cell capacitance, during steps to -55 to -135 mV from a holding potential of -35 mV from single sinus node cells isolated from sedentary and exercise trained mice. Right, mean (\pm SEM) I_f current-voltage relationships from sedentary and exercise trained mice. **D**, antimiR abolishes the exercise training-induced upregulation of miR-423-5p in the sinus node (measured by qPCR; left panel), downregulation of HCN4 protein in the sinus node (measured by western blot; central panel), and decrease in heart rate measured *in vivo* (right panel). Mean \pm SEM data for control (sedentary) mice, exercise

trained mice, and anti-miR treated exercise trained mice shown. In all figures, asterisks indicate significant differences.

Fig. 3. Molecular pathways responsible for the resting bradycardia in the athlete. **A**, schematic diagram of potential events during exercise training. **B** and **C**, effect of exercise training on miR-423-5p and *Hcn4* in the sinus node of wild-type and *Girk4* (also known as Kir3.4 and *Kcnj5*) knockout mice. Black bars, data from control sedentary mice; red bars, data from exercise trained mice. Means \pm SEM shown. **D**, representative HCN4 western blot (upper panel) with corresponding stain-free total protein blot used for quantification (lower panel) in sinus node biopsies isolated from sedentary and trained wild-type or *Girk4*^{-/-} mice. **E**, HCN4 protein expression determined by western blot from data given in D. Black bars, data from control sedentary mice; red bars, data from exercise trained mice. Modified from Bidaud *et al.* (Bidaud *et al.*, 2020b). In B, C and E, means \pm SEM shown.

Fig. 4. Circadian rhythm in the sinus node and the involvement of HCN4 and *I_f*. **A**, schematic diagram of the circadian clock (left) and circadian rhythm in two example clock transcripts (right). On the right, mean \pm SEM transcript abundance shown at six zeitgeber time (ZT) time points over 24 h; the permutation-based P value from JTK Cycle for significance of a day-night rhythm is given; the data have been fitted with a sine wave by a least squares fitting method and the R² value is also given. **B**, families of recordings of *I_f* made from sinus node cells isolated at ZT 6 and ZT 12 (left) and mean (\pm SEM) current-voltage relationships for *I_f* recorded from sinus node cells isolated at ZT 6 and ZT 12 (right). ZT 0 is the start of the 12 h light period and ZT 12 is the start of the 12 h dark period. **C** and **D**, HCN4 protein expression from western blot and density of *I_f* at -120 mV at ZT 6 and ZT 12. **E**, *in vivo* heart rate of wild-type mice measured at ZT 0 (white bars) and ZT 12 (black bars) before and after the administration of ivabradine. In all relevant panels, means \pm SEM shown. Modified from D'Souza *et al.* (D'Souza *et al.*, 2021) and Wang *et al.* (Wang *et al.*, 2021).

Fig. 5. Heart rate during pregnancy and postnatal development and the involvement of HCN4 and I_f . **A**, changes in heart rate during pregnancy in the human. Modified from Hall *et al.* (Hall *et al.*, 2011). **B**, changes in mean (\pm SEM) heart rate whilst awake and during quiet sleep from the neonate to the young adult in the human (n=8-18). Based on data from Finley and Nugent (Finley & Nugent, 1995). **C**, families of recordings of I_f made from sinus node cells isolated from non-pregnant and pregnant mice (left) and mean (\pm SEM) current-voltage relationships for I_f in the two sets of mice (right) (n=26 cells for both non-pregnant and pregnant mice). Modified from El Khoury *et al.* (El Khoury *et al.*, 2013). **D**, mean (\pm SEM) abundance of *Hcn1* and *Hcn4* transcripts in the sinus node, right atrium and left ventricle of neonatal and adult rabbits (n=8 for both neonate and adult). From Abd Allah *et al.* (Abd Allah *et al.*, 2011).

Fig. 6. Age-dependent sinus node dysfunction and the involvement of HCN4 and I_f . **A** and **B**, relationship between the normal heart rate (A) and the intrinsic heart rate measured after complete autonomic blockade (B) and age amongst 56 human subjects. Modified from Kuga *et al.* (Kuga *et al.*, 1993). The dashed lines in B correspond to ± 1 standard deviation. The shaded area corresponds to the 95% confidence limit for the intrinsic heart rate from Jose and Collison (Jose & Collison, 1970). **C**, relationship between sick sinus syndrome and age in 90 female (left hand bars) and male (right hand bars) patients with sick sinus syndrome. Modified from Härtel and Talvensaaari (Härtel & Talvensaaari, 1975) and Benditt *et al.* (Benditt *et al.*, 1995). **D**, mean (\pm SEM) density of I_f at -150 mV from sinus node cells isolated from mice of different ages. **E**, representative I_f families normalised to cell capacitance recorded from sinus node cells from mice of different ages. **F**, expression of a range of transcripts in ~24-month-old mice as a percentage of that in ~2-month-old mice as measured by RNAseq (n=8/8). Left, ion channel transcripts involved in pacemaking; right, major histocompatibility complex Class 2 transcripts.

Fig. 7. Heart failure-dependent nodal dysfunction. **A** and **B**, mean (\pm SEM) normal (A) and intrinsic (B) heart rates in a group of control subjects and patients with non-valvular heart disease (n=17; left) and aortic stenosis (n=17; right) and varying degrees of heart failure (New York Heart

Association classes I-IV). Intrinsic heart rate measured after autonomic blockade with propranolol and atropine. Plotted using data from Jose *et al.* (Jose & Taylor, 1969). **C**, arrhythmia incidence over the course of two years in 297 post-myocardial infarction patients fitted with an implantable loop recorder. Plotted using data from Bloch Thomsen *et al.* (Bloch Thomsen *et al.*, 2010). **D**, association between development of arrhythmias and cardiac and all-cause mortality. Unadjusted hazard ratios calculated using Cox regression analysis. Plotted using data from Bloch Thomsen *et al.* (Bloch Thomsen *et al.*, 2010).

Fig. 8. Molecular pathways responsible for sinus node dysfunction in heart failure. **A**, expression of miR-370-3p (left panel) and *Hcn4* mRNA (centre panel) in the sinus node and the heart rate (measured in conscious animals; right panel) of control mice given vehicle, heart failure mice given vehicle and heart failure mice given anti-miR-370-3p. The heart rate is plotted in the days following transverse aortic constriction (TAC) surgery to induce heart failure. **B**, *Hcn4* mRNA expression, *in vivo* intrinsic heart rate, and corrected sinus node recovery time (SNRTc) in control sham-operated rats, heart failure rats, and heart failure rats treated with bisoprolol. Heart failure was induced by an abdominal arterio-venous shunt (volume overload). **C**, hypothesis of events in heart failure. In A and B, means \pm SEM plotted. A and C modified from Yanni *et al.* (Yanni *et al.*, 2020) and B modified from Du *et al.* (Du *et al.*, 2016).

Fig. 9. Downregulation of HCN expression in the sinus node in pulmonary hypertension. **A**, mean (\pm SEM) expression of *Hcn1* and *Hcn4* mRNA in the right ventricle, right atrium and sinus node of control rats (left bars) and monocrotaline-injected rats with pulmonary hypertension (right bars). **B**, thin sections through the sinus node from a control rat and a monocrotaline-injected rat with pulmonary hypertension immunolabelled for HCN4. From Yamanushi *et al.* (Yamanushi *et al.*, 2010).

Fig. 10. Downregulation of HCN expression and I_f in the sinus node in “AF”. **A**, mean (\pm SEM) *Hcn2* and *Hcn4* mRNA expression in the right atrial free wall and sinus node of control dogs (left bars) and “AF” dogs (subjected to 7-day atrial tachypacing; right bars). **B**, families of I_f

recordings normalised to cell capacitance from sinus node cells isolated from a control dog and an “AF” dog and mean (\pm SEM) current density-voltage relationships from control and “AF” dogs. Modified from Yeh *et al.* (Yeh *et al.*, 2009).

Fig. 11. Circadian rhythm in *Hcn4* in the AV node and downregulation of *Hcn4* in the AV node in pulmonary hypertension. **A**, mean (\pm SEM) expression of *Hcn4* mRNA in the mouse sinus node at four time points over 24 h. The final point is a repeat of the point at ZT 0. The data are fitted with a sine wave. **B**, mean (\pm SEM) expression of *Hcn4* mRNA at the AV junction of control rats (black bars) and monocrotaline-injected rats with pulmonary hypertension (red bars). Expression is shown in atrial muscle, tendon of Todaro, inferior nodal extension, compact node, penetrating bundle and ventricular muscle.

Fig. 12. Summary. **A**, changes in HCN4 expression in health and disease. The size of the HCN4 text is a qualitative indicator of the expression level. From Boyett and D’Souza (Boyett & D’Souza, 2020). **B**, summary of known and putative factors controlling HCN4 transcription and translation covered in this review.

Fig. 1

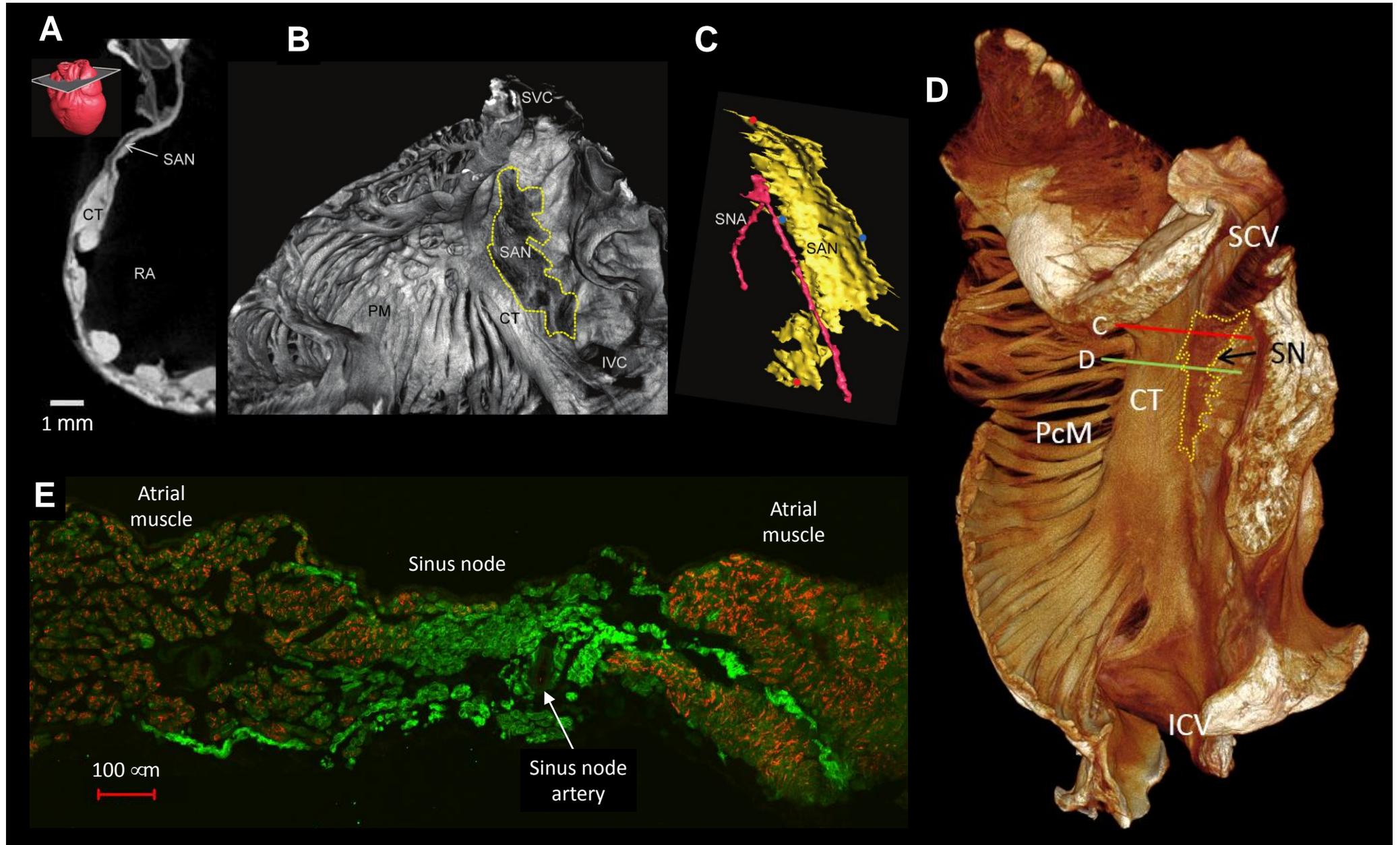
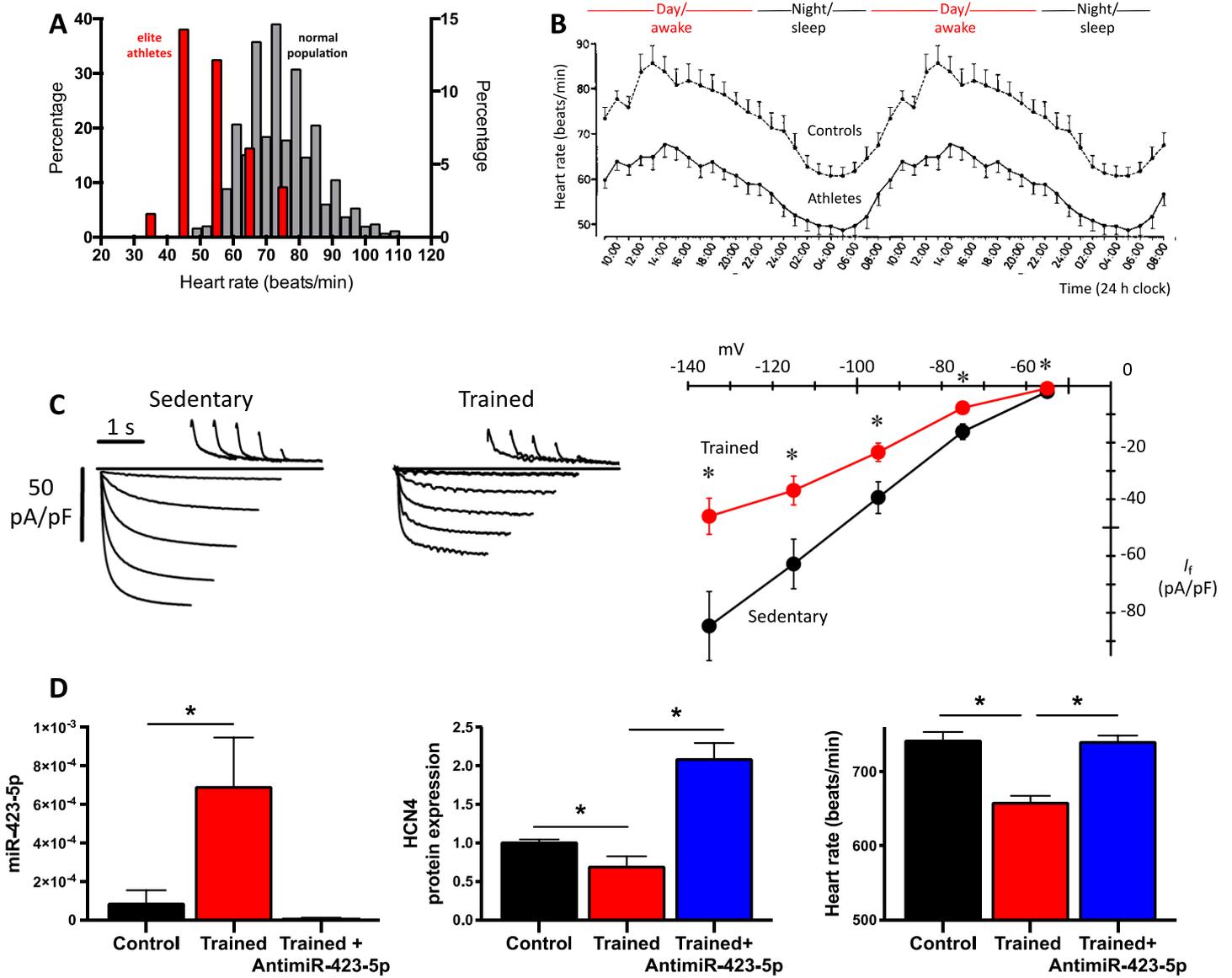


Fig. 2



■ Sedentary (control) ■ Exercise-trained

Fig. 3

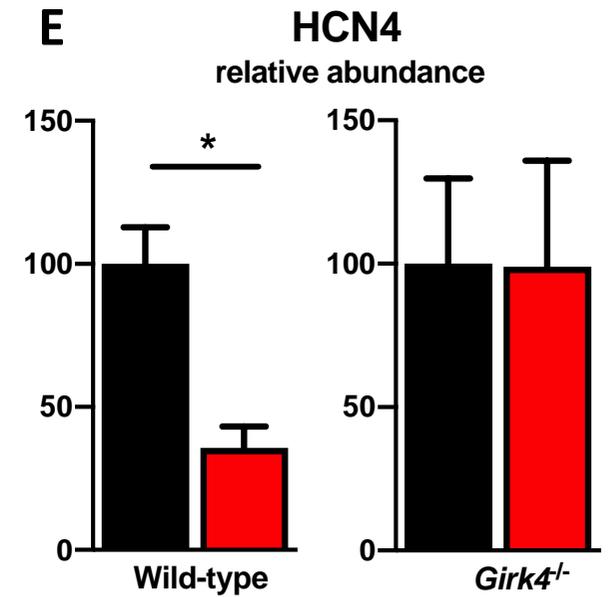
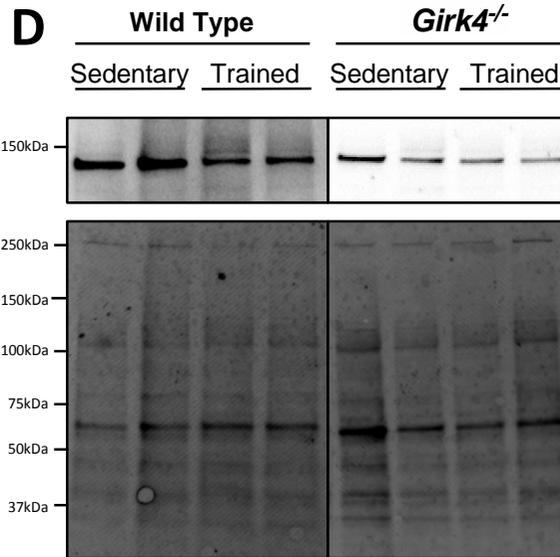
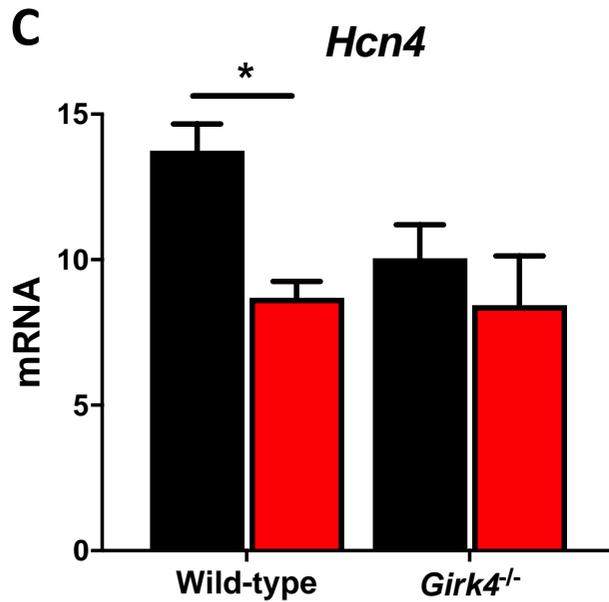
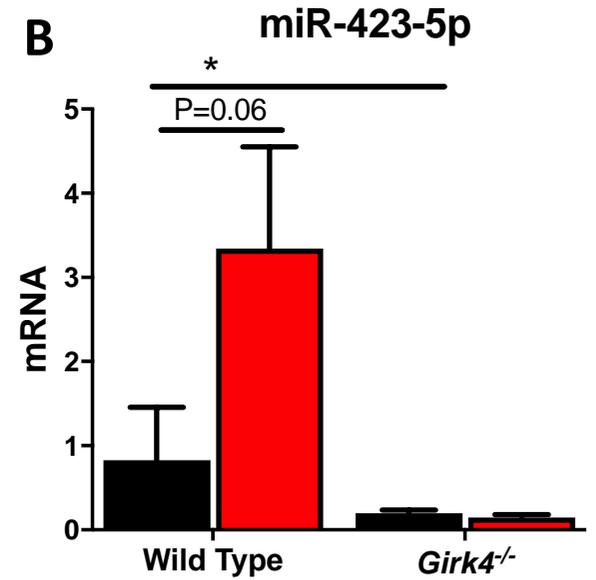
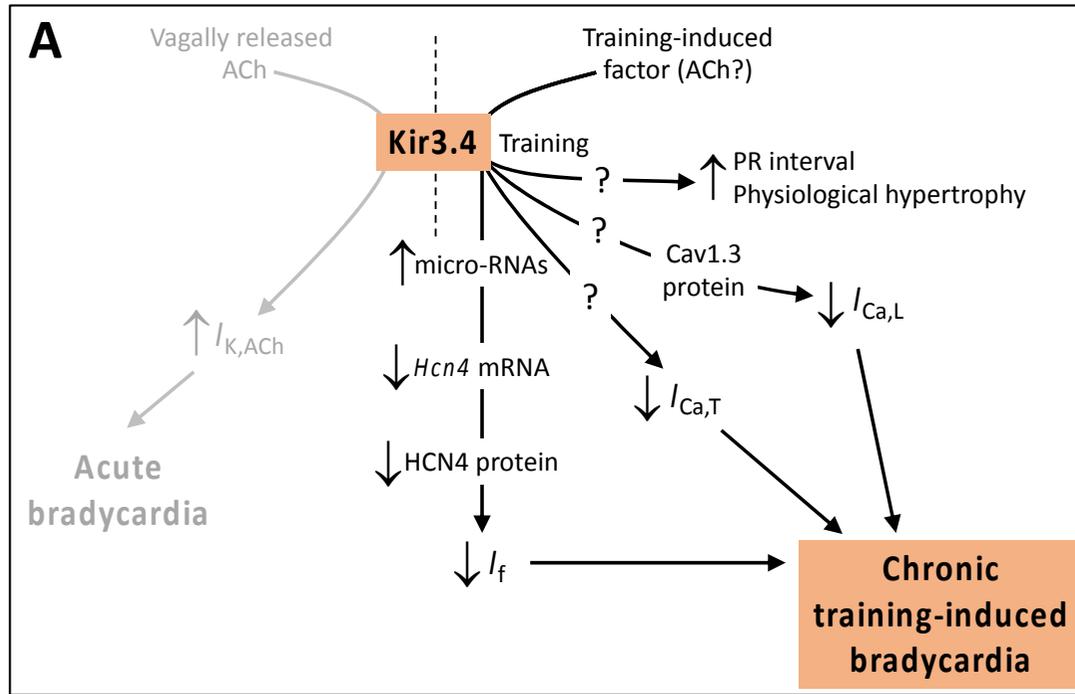


Fig. 4

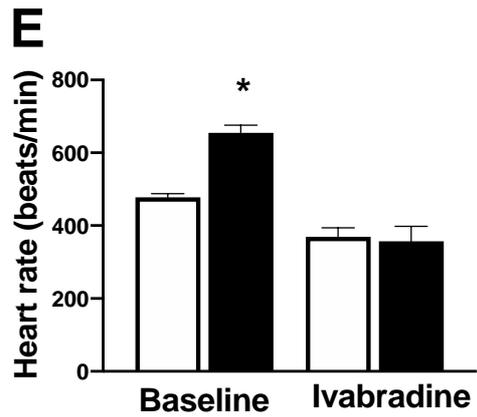
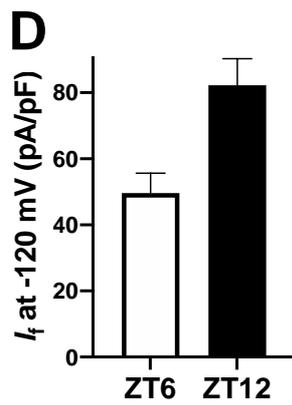
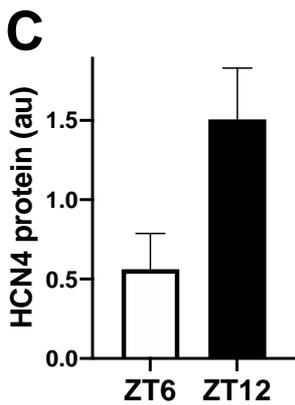
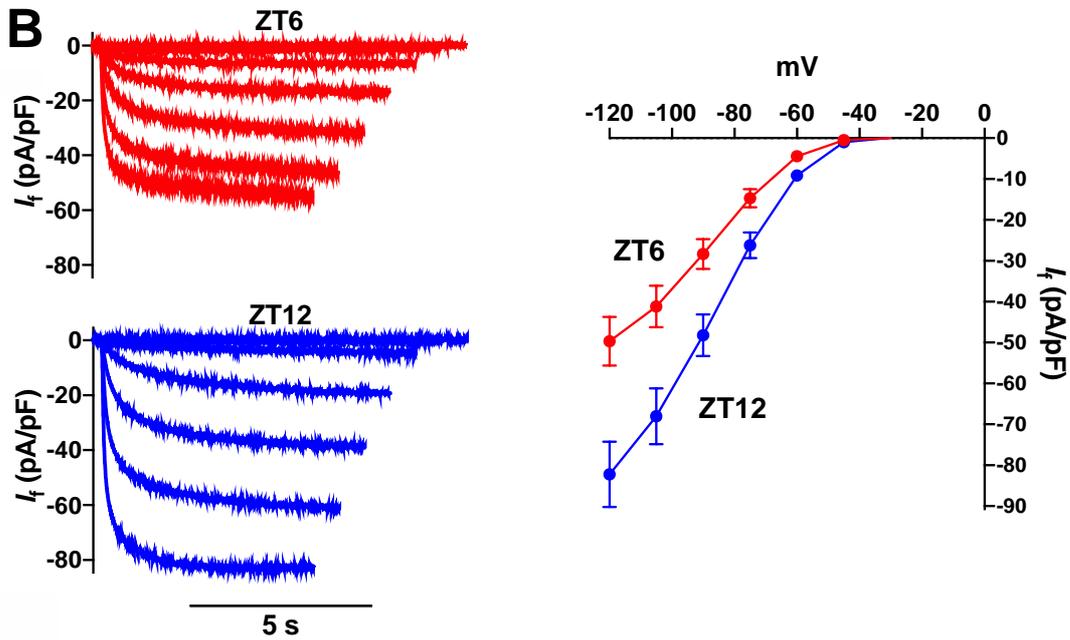
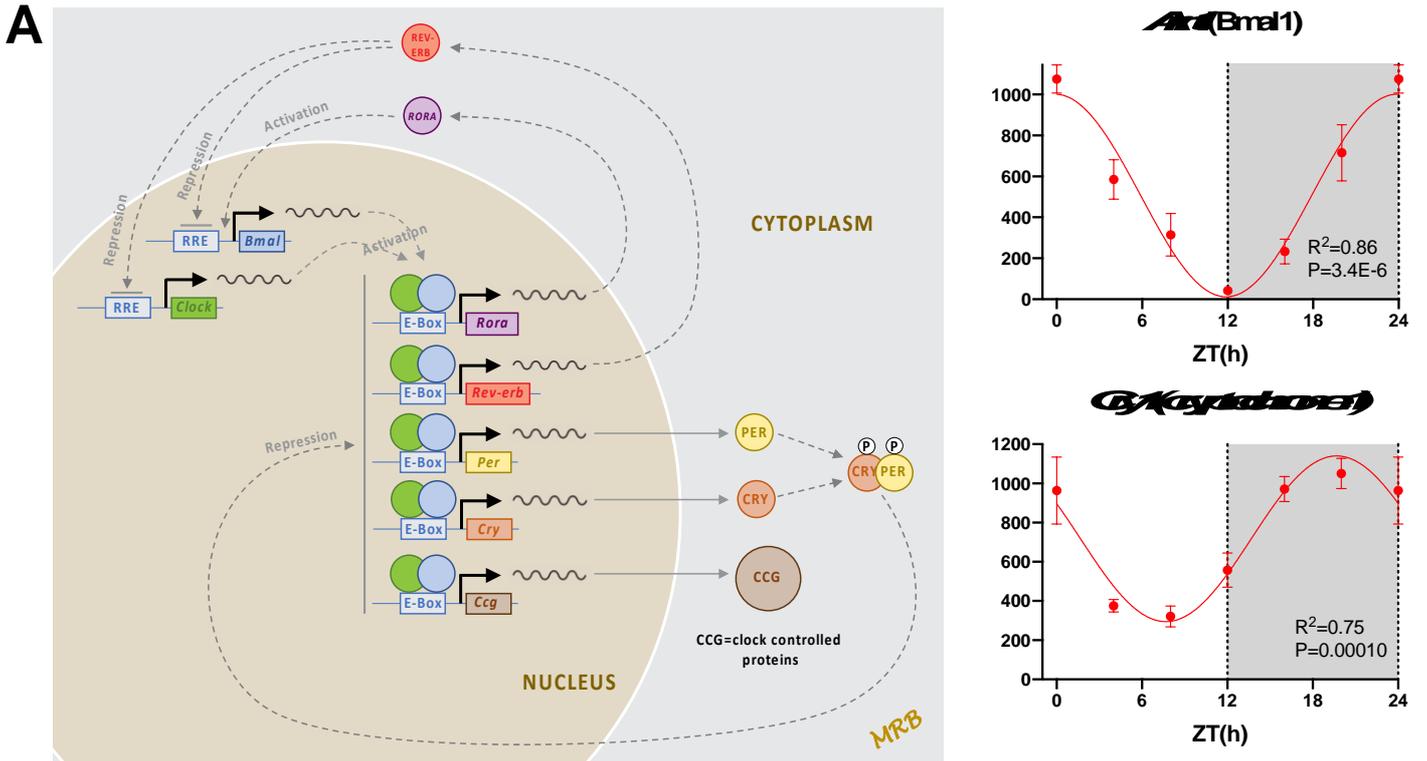


Fig. 5

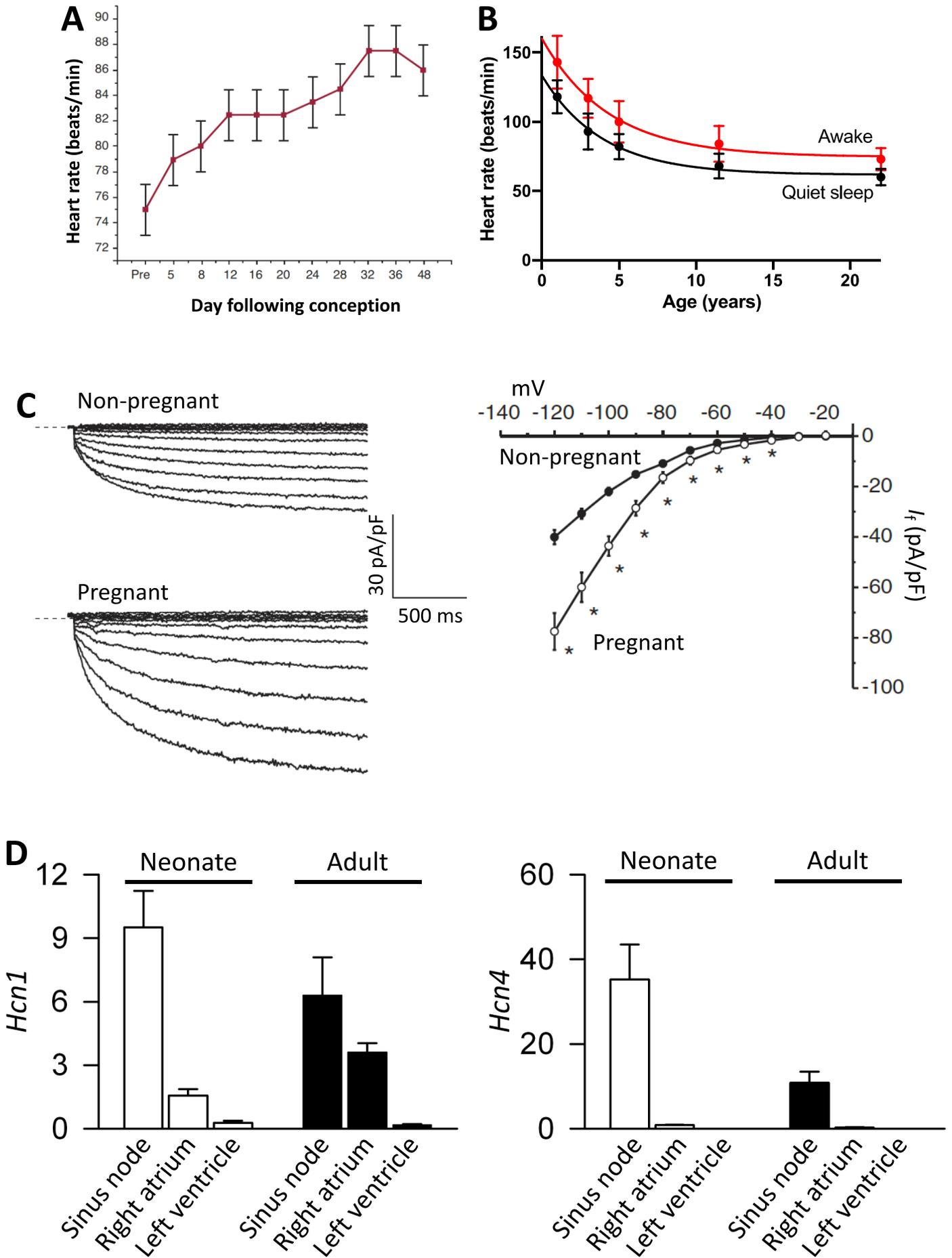


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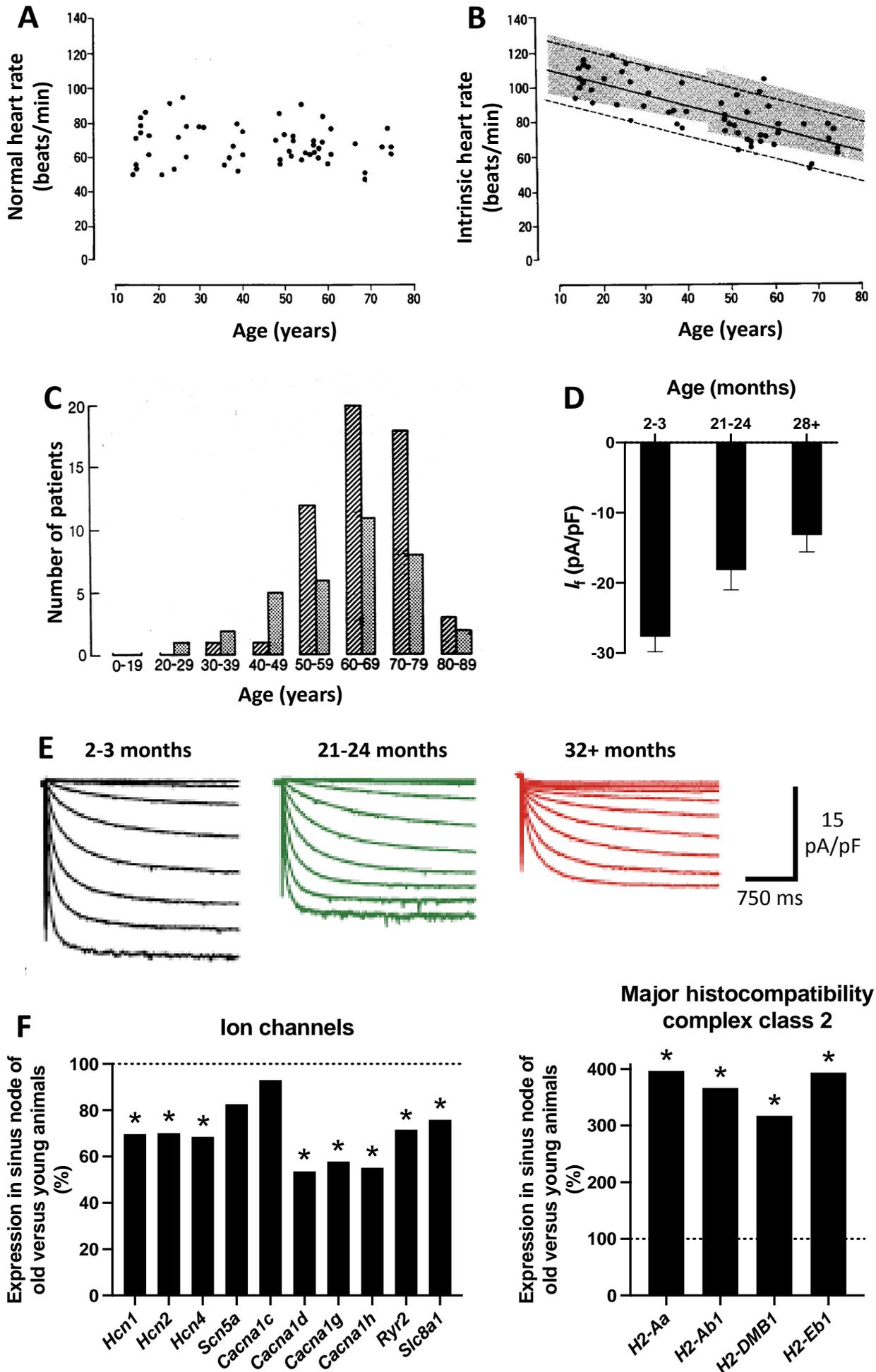


Fig. 7

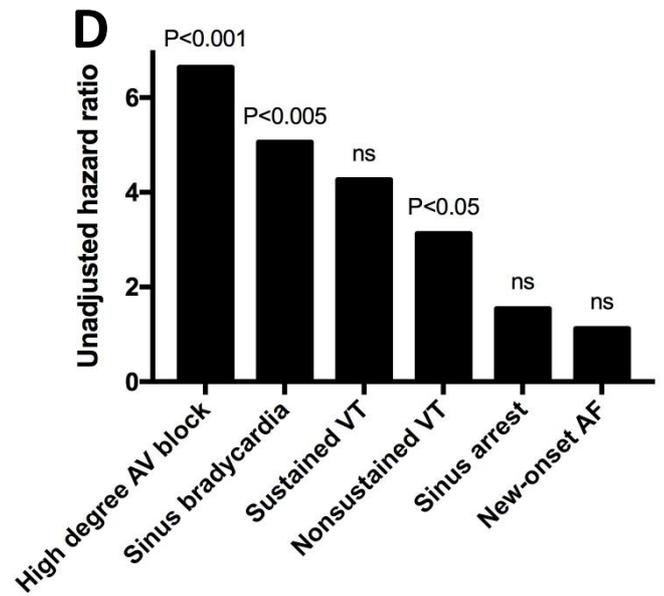
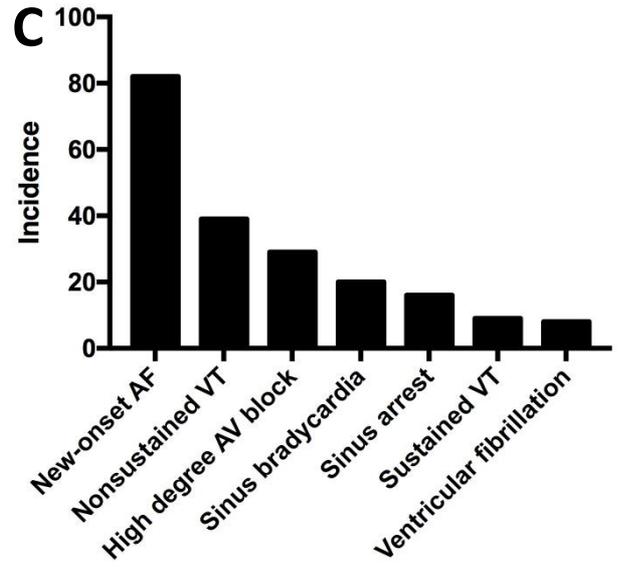
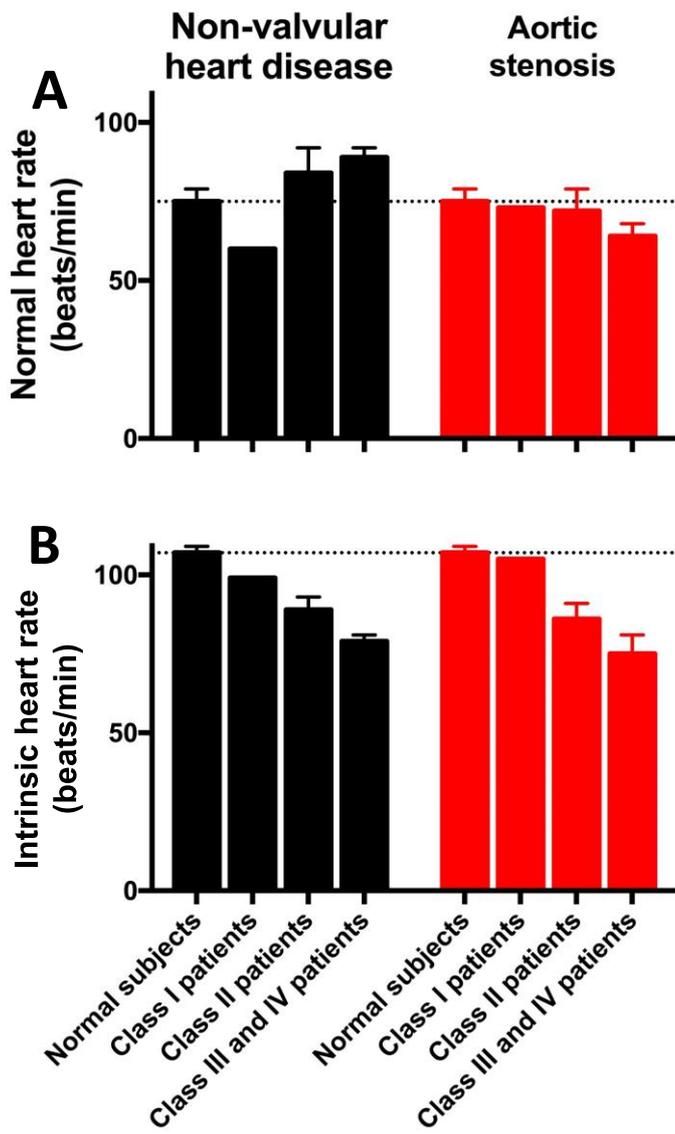


Fig. 8

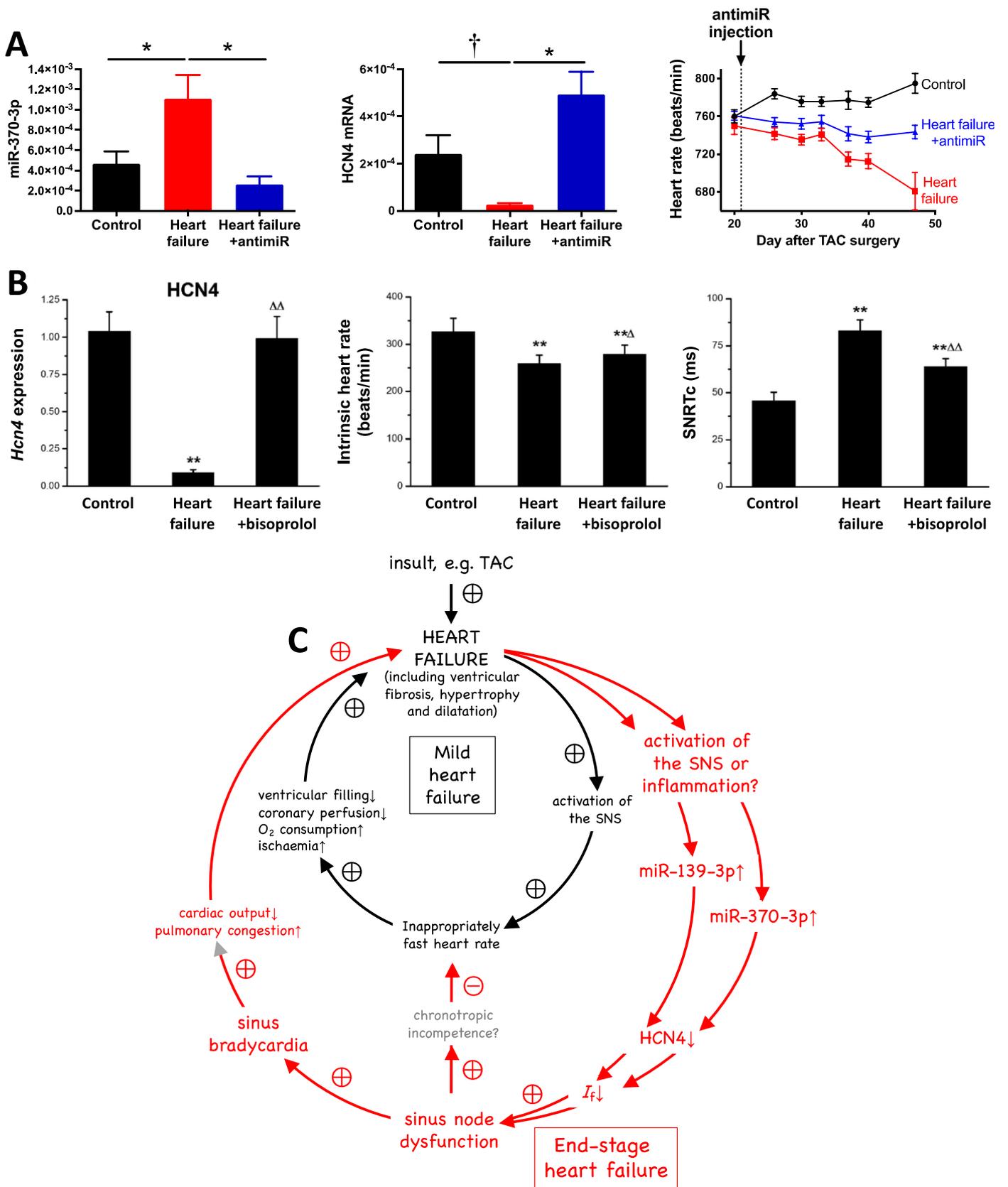


Fig. 9

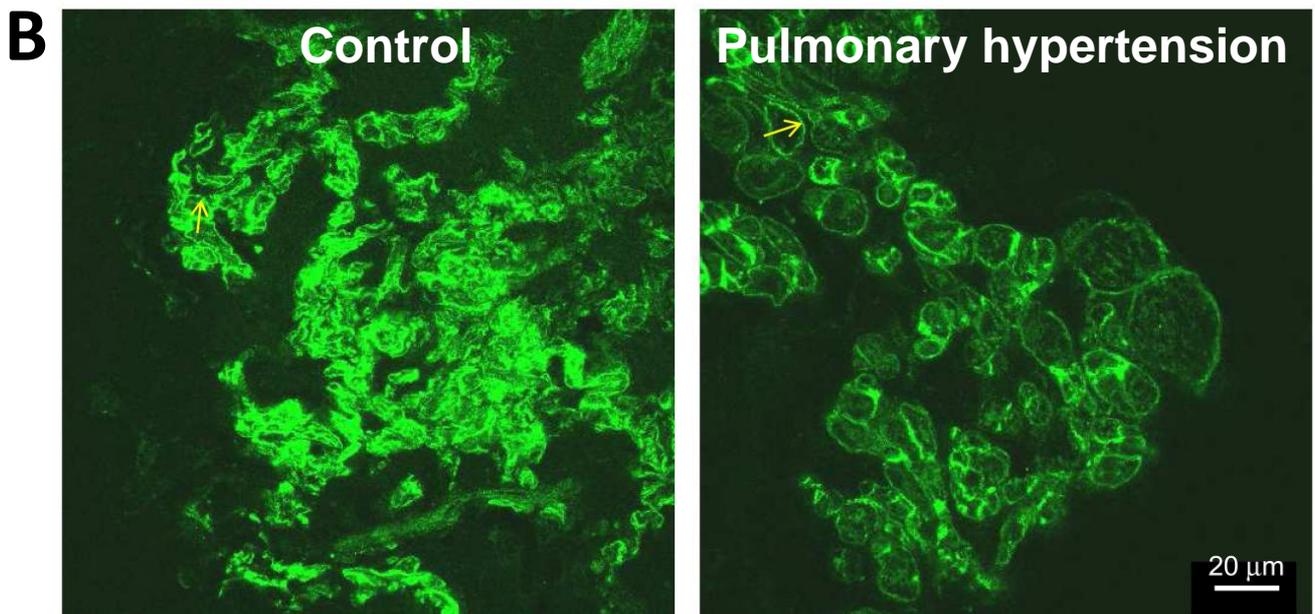
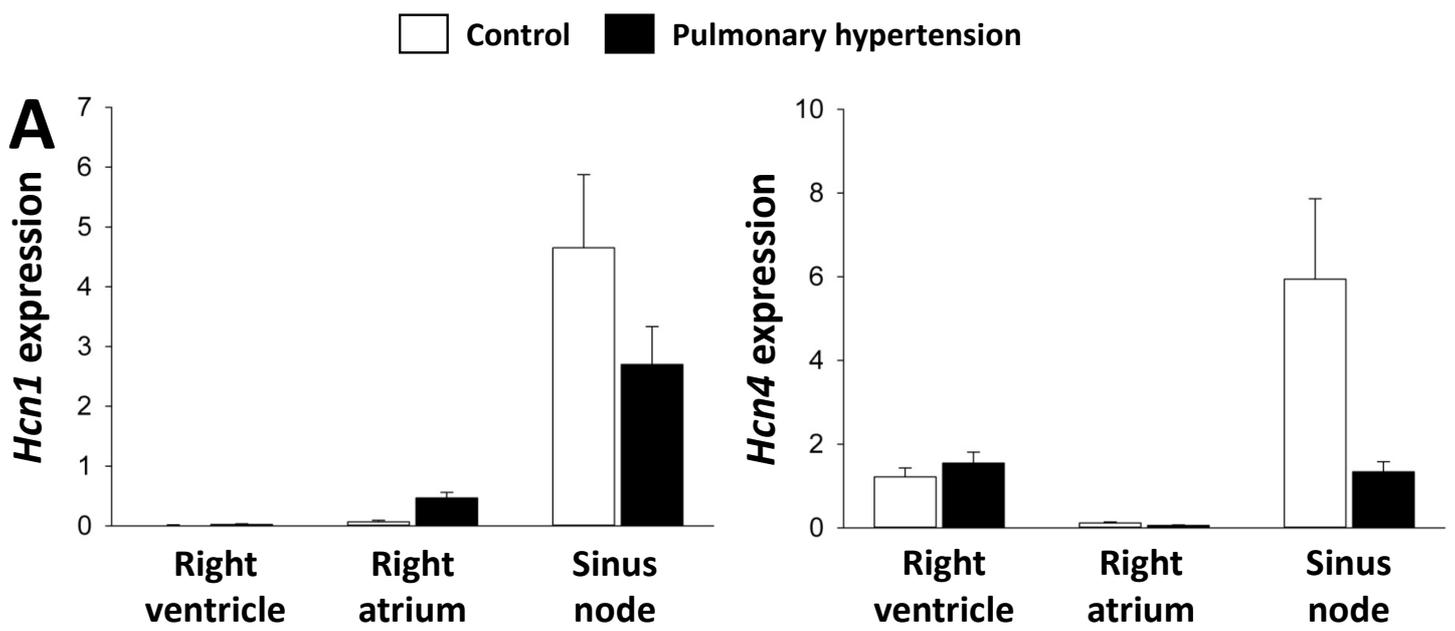


Fig. 10

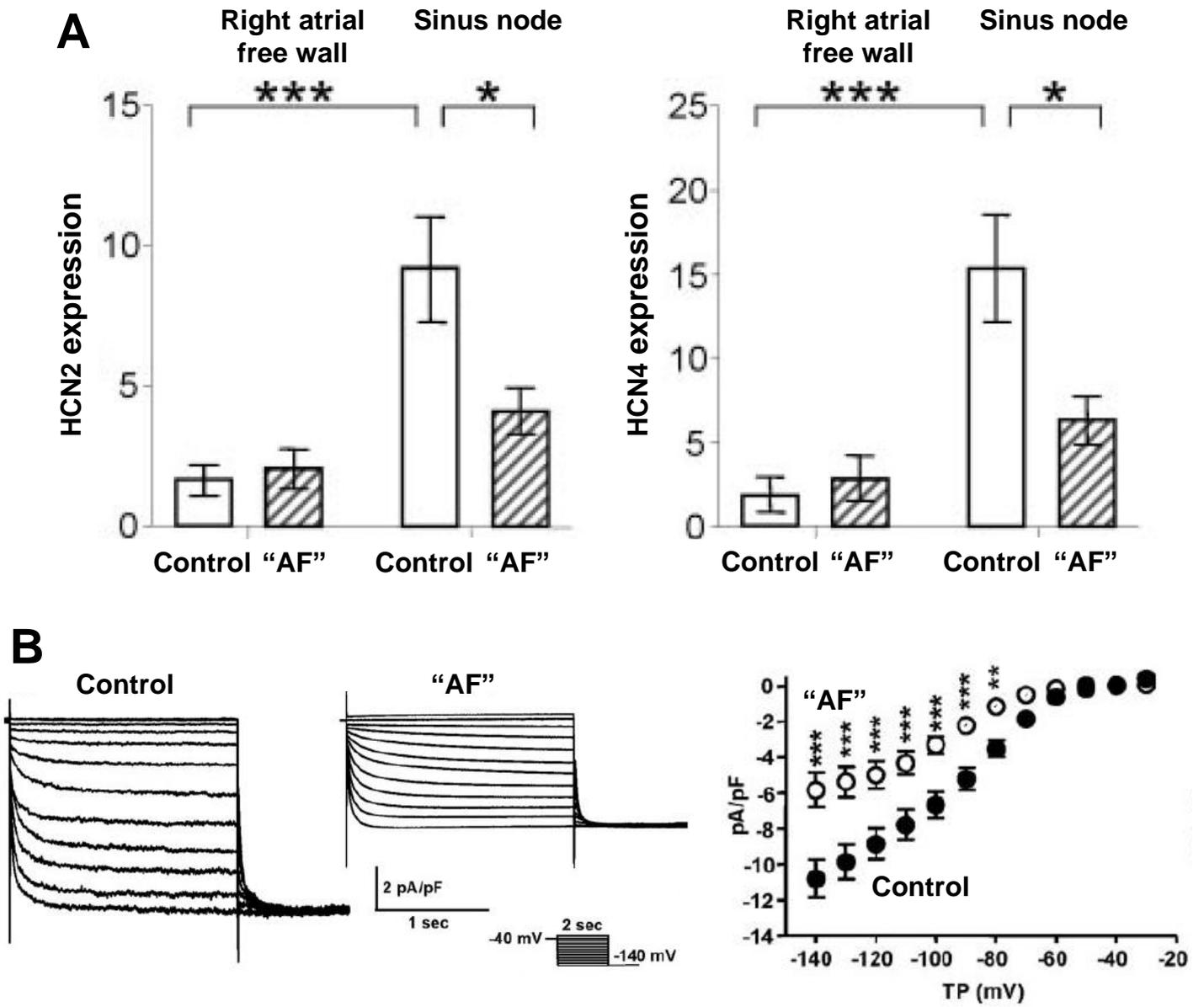


Fig. 11

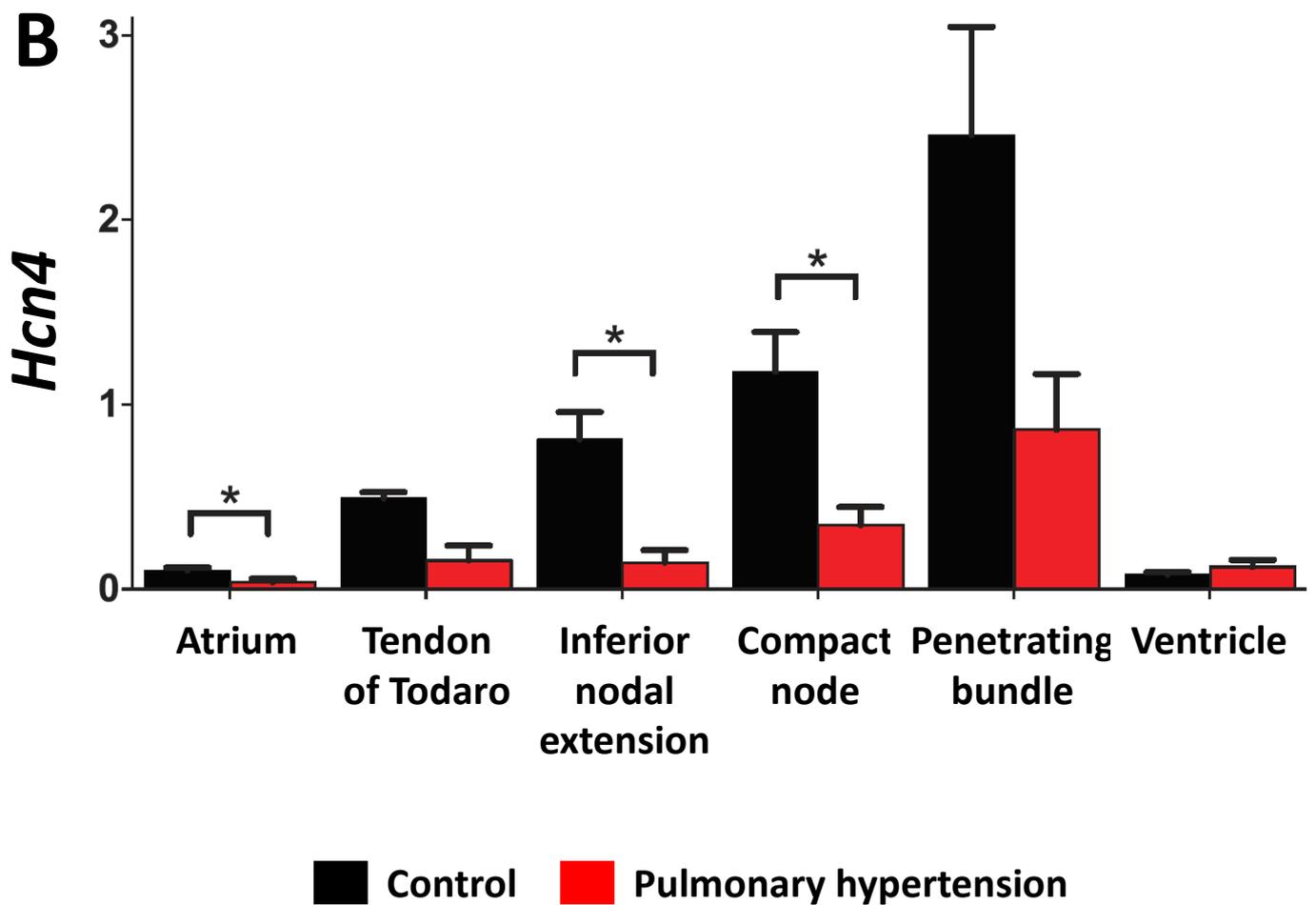
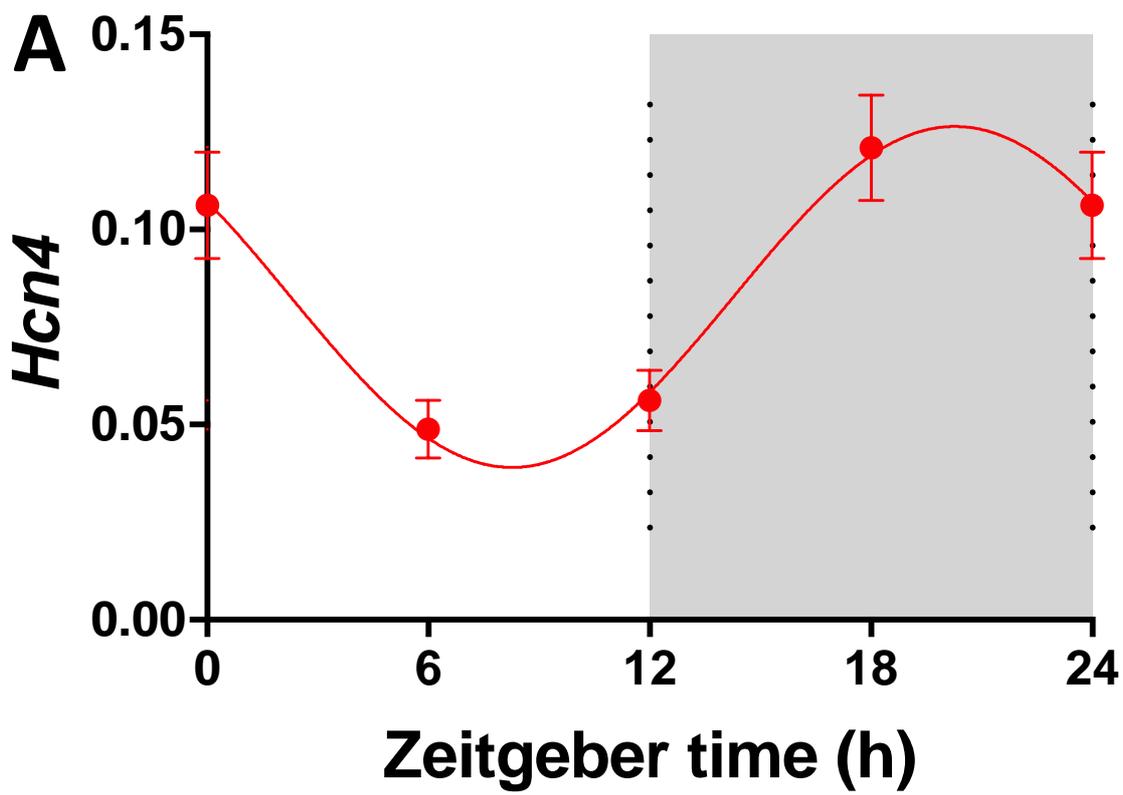


Fig. 12

