Regarding the included study, Impulse Dynamics is providing this information for educational purposes only. Some or all the studied uses of the Optimizer described in the article have not been approved or cleared by the FDA.

INDICATIONS

The safety and performance of the OPTIMIZER Smart System is based on clinical investigations conducted with the prior generation devices, the OPTIMIZER IVs and III Systems, given the similarities between the Systems with regard to function, intended use, design characteristics, and the CCM™ signals. Summaries of these studies are available on Impulse Dynamics' website. (http://www.impulse-dynamics.com/int/for-physicians/clinical-data/)

The OPTIMIZER Smart System, which delivers CCM™ therapy, is indicated to improve 6-minute hall walk distance, quality of life and functional status of NYHA Class III heart failure patients who remain symptomatic despite guideline directed medical therapy, who are in normal sinus rhythm, are not indicated for CRT, and have an LVEF ranging from 25% to 45%.

The OPTIMIZER Smart system delivers non-excitatory CCM™ signals to the heart and has no pacemaker or ICD functions.

CONTRAINDICATIONS AND PRECAUTIONS

Use of the OPTIMIZER Smart system is ***contraindicated*** *in:*

1. Patients with permanent or long-standing persistent atrial fibrillation or flutter
2. Patients with a mechanical tricuspid valve
3. Patients in whom vascular access for implantation of the leads cannot be obtained

WARNINGS

Potential Complications of Device Implantation

Just like any surgical procedure, implantation of an OPTIMIZER Smart IPG is associated with a certain risk. Complications of IPG implantation reported in the literature include but are not limited to: arrhythmias induced by the IPG, including life-threatening arrhythmias (e.g., ventricular fibrillation), infection, skin necrosis, device migration, hematoma formation, seroma and histotoxic reactions (also see: Potential Adverse Effects in the Appendix).

Programming high sensitivities (i.e., sensitivity settings less than 2 mV) may increase the system's susceptibility to electromagnetic interference, which could either inhibit or trigger signal delivery.

Acute and chronic complications reported in the literature include, but are not limited to: lead fracture, lead displacement, atrial or ventricular perforation, and rare cases of pericardial tamponade. Perforation of the ventricular wall can induce direct stimulation of the phrenic nerve or the diaphragm. An impedance change demonstrated on a check-up can be indicative of lead fracture, lead displacement, or perforation (also see: Potential Adverse Effects in the Appendix).

In very rare cases (<1%), transvenous lead placement can also lead to venous thrombosis and subsequent SVC syndrome.

Loss of sensing shortly after implant can be the result of lead displacement. In addition, loss of CCM™ signal delivery could be due to a lead fracture.

Atrial and Ventricular Arrhythmias Potentially Caused by Lead Implantation

As noted above, the use of transvenous leads may lead to arrhythmias, some of which may be life-threatening such as ventricular fibrillation and ventricular tachycardia. The use of screw-in leads such as those used for CCM™ signal delivery also have the potential of causing conduction disturbances such as bundle branch block. These can be minimized by performing the implant with the use of fluoroscopic guidance, ensuring that the leads are in appropriate position prior to fixation and by limiting the number of lead manipulations. Please read and follow all directions of the original Physician Manual for the leads that you intend to use to minimize adverse events connected to lead implantation.

Ventricular Arrhythmias Potentially Caused by CCM™ Signals

CCM™ signals are of greater strength than that of typical pacing pulses and are thus capable of eliciting activation of cardiac tissue when delivered outside of the absolute refractory period. CCM™ signals delivered outside of the ventricular absolute refractory period thus have the potential of causing signal-induced arrhythmias (some of which may be life-threatening, such as ventricular fibrillation and tachycardia). For this reason, it is imperative that CCM™ signal delivery parameters be chosen carefully. Most importantly, the various settings related to conditions that inhibit CCM™ signal delivery (e.g. Long AV Delay, Short AV Delay, LS Alert Window, refractory periods, and IEGM sensitivities) must be selected to allow delivery of CCM™ signals only on normally conducted (e.g. non-arrhythmic) beats, but inhibit them on beats of suspected ectopic or premature origin.

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In addition, CCM™ signals may cause changes in the electrical conduction of tissue. For this reason, the delivery of CCM™ signals to the ventricular septum has the potential of causing bundle branch block that could lead to bradycardia. Through similar mechanisms, CCM™-induced changes in the electrical conduction of the myocardium have the potential of inducing tissue refractoriness that may facilitate the induction of reentrant tachyrrhythmias. It is recommended that the patient's rhythm be monitored carefully for changes in rhythm when CCM™ signals are delivered during lead implantation, as well as during first activation of the OPTIMIZER Smart IPG and subsequent follow-up visits. Changes in ventricular rhythm caused by the delivery of CCM™ signals may require relocating the leads, as well as reprogramming the CCM™ delay and amplitude to settings that do not cause changes in the patient's ventricular rhythm.

Atrial Arrhythmias Potentially Caused by CCM™ Signals

Atrial and supraventricular arrhythmias could theoretically be initiated when CCM™-induced ventricular activity is conducted retrograde to the atria, resulting in premature atrial depolarization. The OPTIMIZER Smart IPG may sense the ventricular activation resulting from the retrograde-induced atrial event and deliver CCM™ as programmed. In addition, strong CCM™ signals delivered through leads implanted in basal position close to the atria have the potential of directly stimulating the atria. If CCM™ delivery causes atrial activation through either of these mechanisms, and the atrial signal is then conducted to the ventricles, the cycle may develop into a condition similar to pacemaker-mediated tachycardia (PMT).

The main variables that may have an impact on CCM™ events leading to atrial activation are the location of lead placement on the right ventricular septum, CCM™ amplitude, and CCM™ delay. To prevent the occurrence of atrial arrhythmias due to CCM™ signal delivery, it is recommended that basal lead implant locations be avoided. The potential for direct atrial activation by CCM™ signals can be tested during the implant by delivering the strongest possible CCM™ signal 20 to 30 ms longer than the LS-CCM delay with which the IPG will be ultimately programmed, as long as this delay places the CCM™ signal, including its 40 ms balancing phase, completely within the ventricular absolute refractory period, and monitoring for atrial activations. In such a case, the delay should be programmed to a longer value and lack of atrial activation confirmed. Besides proper lead location and CCM™ parameter programming, the "Atrial Tachycardia Rate" must be programmed to a sufficiently low value as a protective measure against atrial arrhythmias that could be induced by CCM™ signal delivery.

APPENDIX

Potential Adverse Effects

Examples of adverse effects that may occur as the result of the surgical procedure are listed below in the order of their clinical severity:

1. Death
2. Arrhythmias (brady- or tachyarrhythmias including fibrillation)
3. Stroke or TIA ("transient ischemic attack")
4. Respiratory/ventilatory failure
5. RA/RV perforation
6. Hemorrhage
7. Infection
8. Pleura or pericardial effusion
9. Pneumothorax

Examples of additional adverse effects potentially occurring secondary to CCM™ signal delivery are listed in the table below in the order of their clinical severity:

1. Abnormal cardiac function
2. Atrial and Ventricular Tachyarrhythmias
3. Atrial and Ventricular Bradyarrhythmias
4. Worsening heart failure
5. Myocardial tissue damage
6. Chest pain

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ESC European Society of Cardiology

European Journal of Heart Failure (2018)
doi:10.1002/ejhf.1349

REVIEW

Cardiac contractility modulation: mechanisms of action in heart failure with reduced ejection fraction and beyond

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Received 1 May 2018; revised 4 August 2018; accepted 20 August 2018

Heart failure (HF) is responsible for substantial morbidity and mortality and is increasing in prevalence. Although there has been remarkable progress in the treatment of HF with reduced ejection fraction (HFrEF), morbidity and mortality are still substantial. Cardiac contractility modulation (CCM) signals, consisting of biphasic high-voltage bipolar signals delivered to the right ventricular septum during the absolute refractory period, have been shown to improve symptoms, exercise tolerance and quality of life and reduce the rate of HF hospitalizations in patients with ejection fractions (EF) between 25% and 45%. CCM therapy is currently approved in the European Union, China, India, Australia and Brazil for use in symptomatic HFrEF patients with normal or slightly prolonged QRS duration. CCM is particularly beneficial in patients with baseline EF between 35% and 45%, which includes half the range of HF patients with mid-range EFs (HFmrEF). At the cellular level, CCM has been shown in HFrEF patients to improve calcium handling, to reverse the foetal myocyte gene programme associated with HF, and to facilitate reverse remodelling. This review highlights the preclinical and clinical literature related to CCM in HFrEF and HFmrEF and outlines the potential of CCM for HF with preserved EF, concluding that CCM may fill an important unmet need in the therapeutic approach to HF across the range of EFs.

Keywords Cardiac contractility modulation • Heart failure • Pathophysiology • Treatment • Preserved ejection fraction

Introduction

Heart failure (HF) is the cardiovascular epidemic of the 21st century.[1] Worldwide the prevalence of HF is estimated to exceed 25 million[2] and its prevalence is rising. The HF epidemic can be explained by the paradox of clinical success, including more effective treatment of acute coronary syndromes, leading to a decrease in mortality following acute myocardial infarction. Unfortunately, this is accompanied by a greater incidence in cardiac dysfunction among survivors. An aging population also contributes to the development of HF,[3] while the growing problems of obesity and diabetes are co-morbidities that contribute to HF with preserved ejection fraction (HFpEF).[4]

Chronic HF patients stratified by categories of left ventricular ejection fraction (EF) represent different phenotypes in terms of demographics, clinical presentation, aetiology, mechanical and electrical remodelling, and pharmacotherapies. HF patients are currently classified as HF with reduced EF (HFrEF; EF $< 40\%$), HF with mid-range EF (HFmrEF; EF 40–49%) and HFpEF (EF $\geq 50\%$).[5] Despite major improvements in pharmacological and device therapies for HFrEF treatment during the last several decades, the 5-year survival rate has remained unchanged at 50%.[6–8] Particularly prob-

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Table 1 Data from registries or subgroup analyses showing that treatments able to improve clinical outcome in heart failure with reduced ejection fraction seem to be beneficial in heart failure with mid-range ejection fraction, but not in heart failure with preserved ejection fraction too

	HFrEF	HFmrEF	HFpEF
ACEI	+	NA	–
ARB	+	(+)	–
BB	+	(+)	–
Ivabradine	+	NA	–
MRA	+	(+)	–
Digitalis	+	NA	–
ARNI	+	NA	NA
Diuretics	+c	+c	+c
Defibrillator	+	+*	+*
CRT	+	+c	NA
CCM	+c	+c	Case reports

ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; ARNI, angiotensin receptor-neprilysin inhibitor; BB, beta-blocker; CRT, cardiac resynchronization therapy; CCM, cardiac contractility modulation; HFmrEF, heart failure with mid-range ejection fraction; HFpEF, heart failure with preserved ejection fraction; HFrEF, heart failure with reduced ejection fraction; MRA, mineralocorticoid receptor blocker; NA, not available/not analysed.
+: positive results for mortality and/or morbidity in prospective randomized controlled trials.
(+): positive results from registries, subgroup analysis or retrospective analyses. No data from randomized controlled trials available.
–: negatively investigated for mortality and/or morbidity in prospective randomized controlled trials.
+*: secondary prevention.
+c: recommended to relieve symptoms and/or signs of congestion.

lematic is that virtually all therapeutic innovations for HF have focused on HFrEF.[9] Results of registry studies imply similar benefits of beta-blockers and renin–angiotensin–aldosterone system inhibitors in HFmrEF and HFrEF, but such therapies have been unsuccessful in improving long-term outcomes in HFmrEF and HFpEF patients,[6] highlighting a critical gap in therapeutic options (*Table 1*).[5,10] The differential impact of therapies on HFrEF, HFmrEF and HFpEF suggests fundamental differences in the underlying pathophysiology and an incomplete understanding of the mechanisms involved.[11,12]

Specifically related to HFrEF, beta-blockers, angiotensin-converting enzyme inhibitors or angiotensin receptor blockers, and aldosterone antagonists have served as the mainstays of guideline-directed medical treatment for nearly two decades. Each of these agents provide a mortality benefit in most patients with HFrEF.[13] Since their introduction to treat HF in the '90s, the funny channel inhibitor, ivabradine, has been approved in 2010,[14] and recently the combination of an angiotensin receptor blocker with a neprilysin inhibitor was launched.[15] With respect to medical devices, implantable cardioverter defibrillator (ICD), atrio-biventricular cardiac resynchronization therapy (CRT) and ventricular assist devices have been introduced to treat HF over the last decades. ICDs are indicated to prolong survival in HF subjects with an EF < 35% despite optimal medical therapy (OMT),[16] but do not improve functional capacity or symptoms. The majority of HF patients are not candidates for CRT or a ventricular assist device since they lack a prolonged QRS or have insufficiently severe symptoms, respectively. Thus, despite all the progress, there remains the need for new, effective therapies across the entire EF spectrum.

Cardiac contractility modulation overview

Cardiac contractility modulation (CCM) signals are biphasic relatively high-voltage signals (7.5 V/22 ms duration) delivered to the right ventricular septum during the absolute refractory period.[17,18] Clinically, CCM is currently suggested for consideration by the European Society of Cardiology guidelines in patients with symptomatic HF on OMT and with normal or mildly prolonged QRS duration and reduced EF.[19] Detailed descriptions of the device and the implantation procedure (essentially identical to implantation of a standard implanted pulse generator and pacing leads) have been provided previously.[20,21] CCM has been shown to improve quality of life [Minnesota Living with Heart Failure Questionnaire (MLHFQ)], left ventricular EF,[22,23] indexes of diastolic function,[23] New York Heart Association (NYHA) classification, 6 min walk test,[24] and peak oxygen consumption during cardiopulmonary stress testing[25,26] in patients with symptomatic HF on OMT (including ICD when indicated), with QRS duration < 130 ms and EF < 45%. These findings have recently been confirmed in the randomized FIX-HF-5C study, which also showed a reduction in the 6-month composite rate of cardiac mortality and HF hospitalizations.[27] Furthermore, this latter study also confirmed findings that patients with EF between 35% and 45% derive clinical benefits greater than those experienced by patients with EF < 35%. Most recently, all of these findings were also confirmed in a real-world registry study (the CCM-REG study, Personal communication of Prof. Gerd Hasenfuss.) that showed CCM decreased overall 3-year mortality in patients with EF between 35% and 45% significantly below that predicted by both the Seattle Heart Failure Model[28] and the Meta-Analysis Global Group in Chronic Heart Failure (MAGGIC) score.[29] These and other studies[26,30] have all shown that CCM is safe and non-arrhythmogenic.

The main purpose of this review is to provide a summary of current knowledge of the mechanistic effects of CCM in the setting of HFrEF and explain how many of those mechanisms might also serve to improve cardiovascular function and clinical outcomes for HF patients with higher EFs.

Cardiac contractility modulation mechanisms of action

Cardiac contractility modulation signals increase contractile strength of isolated rabbit papillary muscle strips[31] and trabeculae obtained from human hearts explanted from patients. With optimal parameter settings, contractile strength increased in these settings by an average of ~30%.[32] In early clinical

Table 2 Summary of the impact of cardiac contractility modulation in patients with heart failure with reduced ejection fraction

	CCM effect in HFrEF
Intracellular Ca^{2+} metabolism ↑	↑
Improvement in diastolic Ca^{2+} levels (SERCA2a; phosphorylation of phospholamban)	
Phosphorylation of myofilaments (troponin I, myosin light chain 2, myosin binding protein)	↑
Titin phosphorylation	↑
Titin distensibility	↑
Small heat shock protein (e.g. αB-crystallin)	↑
Oxidative stress	↓
Cardiac fibrosis	↓
Sympathetic nerve activity	↓
Neutral metabolic activity	+
Improvement in LV systolic reserve	+
Improvement in LV diastolic filling (E/E´)	+
Improvement in QoL	+

HFrEF, heart failure with reduced ejection fraction; LV, left ventricular; QoL, quality of life; SERCA2, sarcoplasmic reticulum Ca^{2+}-ATPase 2a.

studies, CCM signals were shown to increase left ventricular dP/dt_{max} more modestly by 5–10%.[26,30] In one study of dogs with intracoronary microembolization-induced HF, active CCM monotherapy for 3 months induced an increase in left ventricular EF (27 ± 1% vs. 33 ± 1%, $P < 0.0001$) compared with a decrease in sham-operated control animals (27 ± 1% vs. 23 ± 1%, $P < 0.001$).[33] This increase was accompanied by reduced left ventricular volumes and improved myocardial structure. Importantly, the effects of CCM on function are not associated with increases in myocardial oxygen consumption as measured in patients with severe chronic HF under resting or stress conditions and independent of HF aetiology.[34,35]

Concurrent with the mechanical effects of CCM, CCM exerts multiple effects at cellular and molecular levels (*Table 2*). As will be detailed below, CCM improves calcium (Ca^{2+}) handling in cardiomyocytes, initiates molecular reverse remodelling of the foetal gene programme observed in HF back towards that of a normal adult[33,36] and a host of other pathways involved in myocyte and interstitial fibrosis. Furthermore, these effects are not only observed locally at the site of signal delivery but, over months, benefits extend remotely through global adaptive cardiac reverse remodelling.[23,37]

Intracellular calcium metabolism

Disorders of intracellular Ca^{2+} homeostasis associated with HF have been shown to contribute to both systolic and diastolic dysfunction[38] by interfering with the ryanodine receptor (RyR2),[39] the sarcoplasmic reticulum Ca^{2+}-ATPase 2a (SERCA2a) pathway and the sodium–potassium pump.[40] In the intracoronary microembolization-induced HF study noted above,[33] CCM also led to rapid normalization of phospholamban phosphorylation, which increased the ability of the sarcoplasmic reticulum to sequester calcium.[33] In another study in dogs with HF, chronic therapy with CCM normalized the downregulated left ventricular expression of the Ca^{2+} binding protein S100A1.[41] S100A1 interacts in a Ca^{2+}-dependent manner with the RyR2, the SERCA2a–phospholamban complex, cardiac titin, and mitochondrial F_1-ATPase. Its protein expression is reduced in cardiomyocytes from patients with end-stage HFrEF.[42] Its relevance in contractile function follows from experimental findings showing that downregulation of S100A1 protein contributes to contractile dysfunction of the diseased heart in mice,[43] whereas S100A1 gene transfer restores contractile function of failing myocardium in rat models of HF.[44]

Butter *et al.*[36] analysed endomyocardial biopsies at baseline and 3 and 6 months after CCM implantation from 11 HFrEF patients with an EF < 35% and NYHA functional class II/III despite OMT. CCM therapy was delivered in random order to be switched off and on for 3 months. The findings showed that 3 months of CCM therapy resulted in increased expression of SERCA2a, phospholamban, and RyR2, suggesting that CCM therapy in HFrEF patients normalized the expression of the key sarcoplasmic reticulum Ca^{2+} cycling and stretch response genes. In summary, CCM is able to induce beneficial molecular remodelling of intracellular Ca^{2+} regulatory proteins in HFrEF.

Myofilaments

Cardiac force generation results from protein interactions between the thin filaments [α-actin, α-tropomyosin and the troponin complex, comprised of troponin I (TnI), troponin T and troponin C] and the thick filaments [the myosin complex, comprised of a pair of myosin heavy chains (MHC) and two pairs each of myosin light chain 1 and 2 (MLC1, MLC2), and associated proteins such as myosin binding protein C].[45] TnI and MLC2 are important myofibrillar proteins involved in the regulation of myofilament Ca^{2+} sensitivity and cardiac inotropy. The sensitivity of the cardiac myofilaments to Ca^{2+} is primarily regulated by the phosphorylation state of TnI and MLC2.[46] Butter *et al.*[36] demonstrated that 3 months of CCM therapy reverses the downregulated expression of the α isoform of MHC in HFrEF patients. In HFrEF patients, CCM has shown an increase in the phosphorylation state of TnI and of myosin-binding protein C in the left and right ventricle, which occurred as soon as 30 min after signal delivery and which remained after 3 months of therapy (*Figure 1*).

The large cytoskeletal protein titin acts as a bidirectional spring and is involved in early diastolic recoil and late diastolic distensibility of cardiomyocytes.[46] Its characteristics are modified through isoform shifts and through phosphorylation by several kinases including protein kinase A (PKA),[47] G (PKG),[48] and C (PKC).[49] PKA and PKG promote titin compliance, but PKC reduces compliance.[11] In a dog model of HF, CCM therapy reversed the downregulated expression of titin.[37] Large-scale analyses are not yet available from human HF myocardium. However, these findings were also confirmed in two HFrEF patients (*Figure 1*).

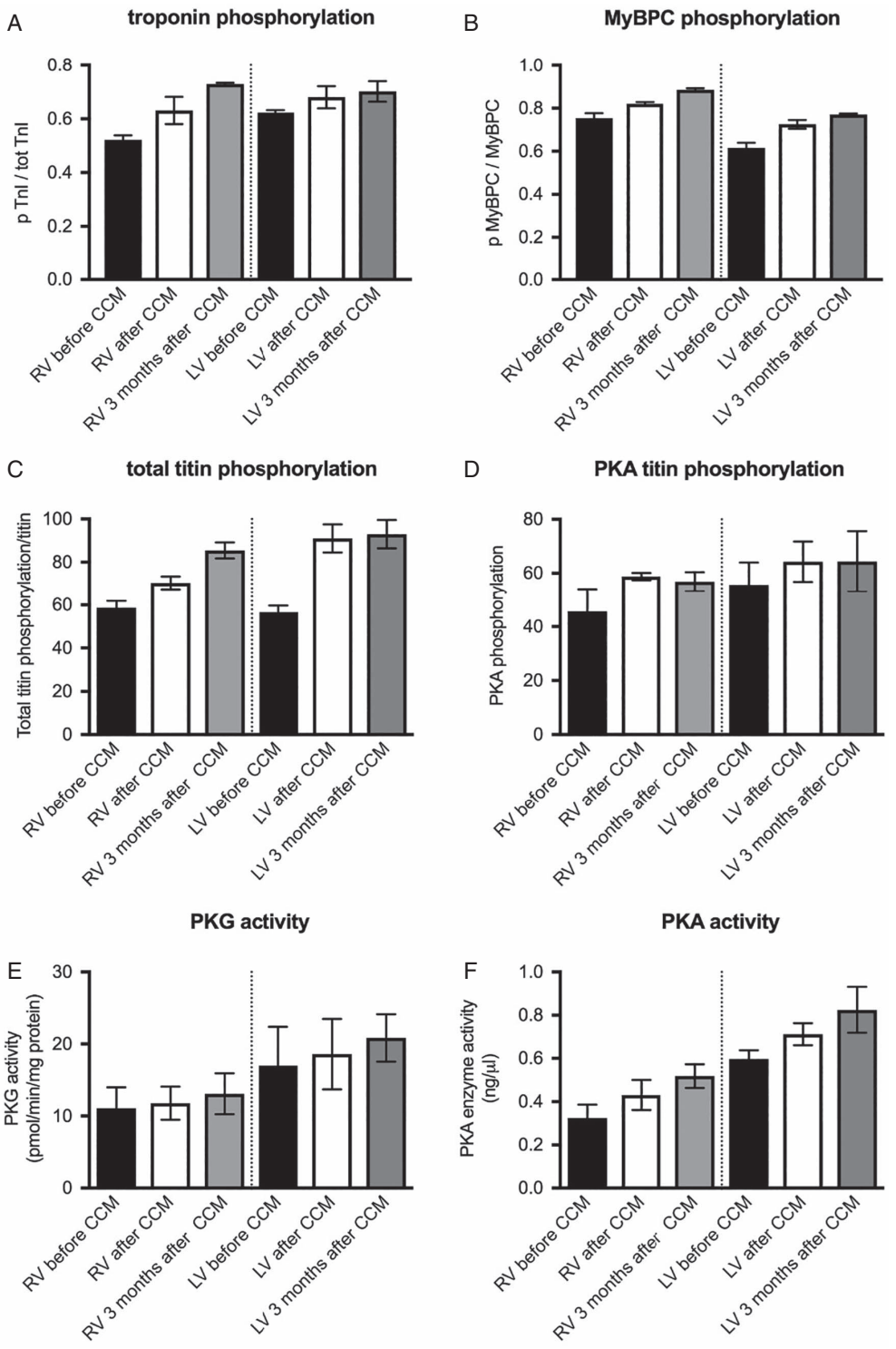
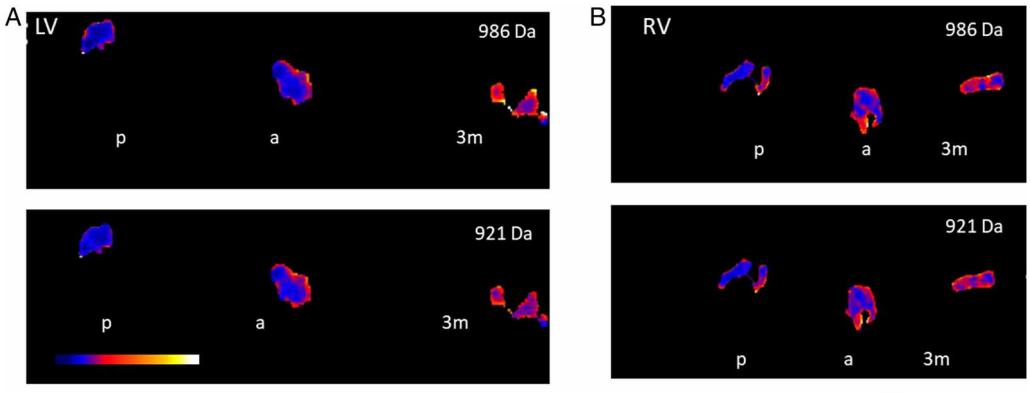


Figure 1 Impact of cardiac contractility modulation (CCM) on phosphorylation of troponin I (*A*), myosin-binding protein C (MyBPC) (*B*), titin (*C*), and protein kinase G (PKG) and A (PKA) activity (*D*–*F*) in patients with heart failure with reduced ejection fraction (HFrEF). (*A*–*D*) Mean ± standard error of the mean of the ratio of phosphorylated to total MyBPC, of phosphorylated to total troponin I (TnI), of phosphorylated to total titin, and of PKA-induced phosphorylation of titin to total titin, respectively, in endomyocardial biopsies from the right ventricle (RV) or left ventricle (LV) before (black bars), 30 min after (white bars), and 3 months after initiating CCM (grey bars) of two HFrEF patients, as indicated. (*E*, *F*) Mean ± standard error of the mean of PKG activity (pmol/min/mg protein) and PKA activity (ng/µL), respectively, in the RV and LV at the same time points after initiating CCM in two HFrEF patients.



C

Centroid [m/z]	± [Da]	ROC [AUC] LV after vs prior	ROC [AUC] LV 3 months vs after	ROC [AUC] LV 3 months vs prior
986.494	0.152	0.608	0.617	0.698
921.504	0.152	0.655	0.533	0.683

Centroid [m/z]	± [Da]	ROC [AUC] RV after vs prior	ROC [AUC] RV 3 months vs after	ROC [AUC] RV 3 months vs prior
986.494	0.152	0.618	0.522	0.626
921.504	0.152	0.628	0.535	0.658

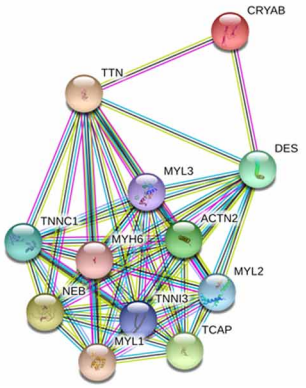


Figure 2 Imaging mass spectrometry of endomyocardial biopsies. Ion density distributions of m/z-values 986 Da and 921 Da (α-crystallin B chain) are significantly increased after 3 months (3m) in comparison to prior (p) cardiac contractility modulation intervention. (*A*) Left ventricle (LV) and (*B*) right ventricle (RV) endomyocardial biopsies ($P < 0.001$). (*C*) Receiver operating characteristic (ROC) values show the discrimination capability of m/z 956 Da/921 Da between shortly after/prior, 3 months/shortly after and 3 months/prior cardiac contractility modulation intervention in the LV (upper table) and RV (lower table) [area under the curve (AUC) > 0.6] of two heart failure with reduced ejection fraction patients. (*D*) String database analysis[56] demonstrating the interaction between α-crystallin B chain (CryAB) and titin. (a) stands for shortly after cardiac contractility modulation intervention.

Another recently identified protective mechanism for I-band titin domains involves the small heat shock proteins (sHSPs) HSP27 (HSPB1) and αB-crystallin (HSPB5). These are abundantly expressed in cardiac myocytes and are further induced by stress such as cardiac ischaemic injury or end-stage HF. Their overexpression protects cells from oxidative stress, energy depletion, and other unfavourable conditions.[50] HSP27 and αB-crystallin are translocated under acidic stress preferentially to the sarcomeres; in particular to the I-band region. Binding of HSP27/αB-crystallin to unfolded titin domains prevents titin aggregation under stress, thereby maintaining normal myocyte stiffness. Contractility of myocytes is also strongly affected by intracellular acidosis, which increases the passive stiffness of the heart. These findings suggest that aggregation of unfolded titin-immunoglobulin domains under mechanical and acidic stress stiffens cardiomyocytes, but that sHSPs translocate to these domains to prevent this aggregation and protect against stiffening, thus preserving diastolic function.[50]

Consistent with these findings, it has been shown that mouse hearts deficient in αB-crystallin and HSPB2 display normal systolic function but exhibit increased passive stiffness and diastolic dysfunction when exposed to stress,[51] suggesting a potential beneficial role of sHSPs on titin-based passive stiffness in patients with HFpEF. This hypothesis has now been supported by Franssen *et al.*[52] who recently demonstrated that αB-crystallin reverses the pronounced diastolic stiffness of failing human cardiomyocytes probably through relief of titin aggregation. Interestingly, sHSPs are upregulated by exposure to magnetic fields as shown in cardiomyocytes for HSP70[53] and HSP27, 70, and 90 in endothelial cells.[54] Imaging mass spectrometry[55] findings from a HFrEF patient who underwent CCM therapy illustrate an upregulation of αB-crystallin 3 months post-CCM (*Figure* 2).[56] These insights lead to the hypothesis that heat shock activation by CCM may mimic the benefit observed during preconditioning.

Extracellular matrix: fibrosis

In dogs with chronic HF, chronic CCM monotherapy increases left ventricular EF and stroke volume, which is paralleled by a reduction in volume fraction of replacement fibrosis and interstitial fibrosis.[33] Further evaluation of the impact of 3 months of CCM therapy on cardiac remodelling in dogs with HF showed upregulation and normalization of the matrix metalloproteinases 1, 2, and 9.[37] In a

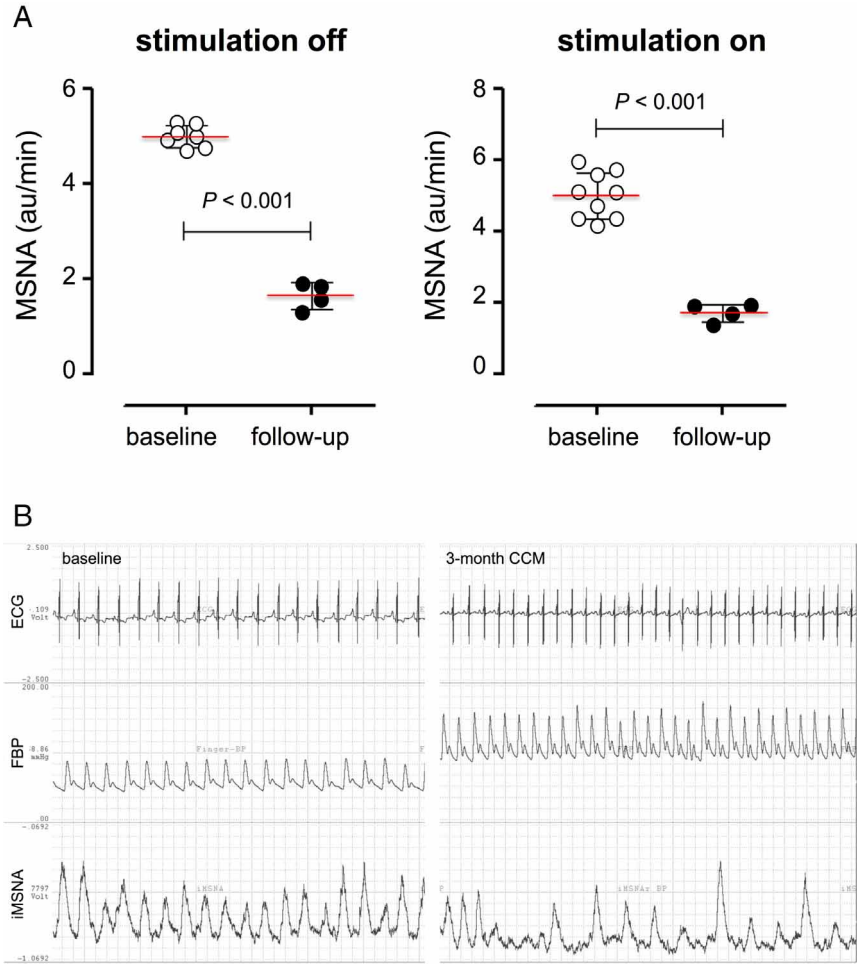


Figure 3 Impact of cardiac contractility modulation (CCM) on muscle sympathetic nerve activity (MSNA). (*A*) Bar graphs depict MSNA (au/min) at baseline and 3 months after (follow-up), off stimulation (left panel), or on stimulation (right panel). MSNA did not acutely change during short on/off stimulations, either at baseline (white circles left panel vs. white circles right panel) nor 3 months later (black circles left panel vs. black circles right panel). After 3 months of treatment, MSNA basal levels (black circles) were significantly reduced compared to baseline (white circles), suggesting that CCM induces a remodelling process, which includes at least indirectly also the sympathetic nerve activity. (*B*) Representative sympathetic nerve recording of a heart failure with reduced ejection fraction patient with CCM stimulation one day after implantation (left) and after 3 months of intermittent therapy. Note the remarkable reduction in sympathetic burst incidence with chronic CCM stimulation (at baseline; 100%; after 3-month CCM stimulation: ~50%). ECG, electrocardiogram; FBP, phospholamban.

chronic rabbit model of HF, CCM lasting 6 h per day for 4 weeks attenuated myocardial fibrosis and collagen deposition potentially by inhibiting transforming growth factor-β1/Smad3 signalling.[57]

Autonomic nervous system

Since CCM initially increases septal contractility, this has been shown to activate vagal afferent fibres.[58] Accordingly, a reduction of excess sympathetic activation associated with HF is expected with a resulting improvement in autonomic balance. Similarly, CRT improves cardiac haemodynamics in part by a reduction of excessive sympathetic activity. Normalization of sympathetic activity is also characteristic of clinical responders to atrio-biventricular pacing. Our own findings in a patient with HFrEF illustrate that CCM also decreased muscle sympathetic nerve activity (MSNA) after several months of treatment (*Figure 3*). There was, however, no immediate effect of CCM stimulation on MSNA burst incidence (bursts/min and bursts/100 heart beats), which is in line with the CRT results.[59]

Cardiac contractility modulation in patients with higher ejection fractions: clinical effects and mechanistic implications

As noted above, while the focus of prior studies of CCM therapy has been on patients with HFrEF, significant amounts of data are

available on the effects of CCM in patients with NYHA class III and IV symptoms with EFs between 35% and 45%. This includes half of the range of EFs of the HF population now designated as HFmrEF (defined as patients with EFs from 40% to 49%). It was initially observed in a small subset of 40 patients from the FIX-HF-5 study that CCM improved exercise tolerance (indexed by both peak oxygen consumption and 6 min walking test), and quality of life (indexed by both MLHFQ and NYHA classification) more in patients with EFs between 35% and 45% than in patients with EF < 35%.[21] This finding was reconfirmed prospectively in the recently completed FIX-HF-5C study which showed, in this same subgroup, a 1.76 ml O_2/min/kg increase of peak oxygen consumption, a 15 point improvement in MLHFQ and 59.3 m improvement in 6 min walk test with 71% of patients exhibiting at least one NYHA class improvement.[27] In all parameters, these effects were larger than in the group with EF < 35%. These clinical findings motivated us to undertake a preliminary investigation into possible mechanisms by which CCM could impact cardiovascular properties in HFmrEF and HFpEF that will be summarized below.

Interestingly, the mechanisms of action of CCM impact certain processes that are also mechanistically implicated in the pathophysiology of HFpEF.[60] Therefore, consistent with results discussed above concerning even greater clinical effects in patients with EF between 35% and 45%,[21,27,61] CCM has potential to provide a new therapeutic approach for HF patients with higher EFs.

Recent data increasingly recognize the roles of non-cardiac systemic processes such as vascular tone, renal dysfunction, metabolic disorders, pro-inflammatory, pro-fibrotic, immunological alterations[11] and right heart dysfunction[62] in the development of clinical HFpEF and HFmrEF. Such abnormalities, which are often linked with co-morbidities commonly present in these populations (e.g. obesity, diabetes, renal dysfunction, hypertension), promote myocyte hypertrophy, increase resting myocyte tension, impaire calcium metabolism and increase interstitial fibrosis via many of the same mechanisms detailed above for HFrEF.

Accordingly, it is possible that mechanisms by which CCM improves myocyte function in HFrEF may also play a beneficial role in HFmrEF and HFpEF. Studies into this possibility have just begun with the publication summarizing the cellular and molecular effects of CCM in one HFpEF patient and one HFmrEF patient in whom functional class and exercise tolerance where improved. In these cases, CCM was shown to downregulate the expression of the foetal gene product myosin 7 and to increase phosphorylation of MLC2 and TnI in the left and right ventricle both early (30 min) and late (3 months) following the initiation of CCM therapy.[60] This change was associated with an increase in contractile reserve induced by stress echocardiography. Furthermore, following both 30 min and 3 months of CCM therapy, PKA and PKG activity and the degree of phosphorylated titin in the right and left ventricles were higher when compared to values obtained prior to initiating CCM, which can contribute to improved relaxation.[60] Similarly, the effects of CCM therapy on markers of cardiac fibrosis in the right ventricle of the patient with severe HFpEF showed that the expression of collagen I, collagen III and of the myofibroblast marker α-smooth muscle actin were reduced by 29%, 22%, and 22%, respectively, after 3 months of CCM therapy.[60] Consistent reductions in collagen I, collagen III and α-smooth muscle actin expression 3 months following CCM were also observed in both ventricles of the HFmrEF patient.[60] Blinded evaluation of the region-dependent proteome signature via imaging mass spectrometry[55] further revealed a reduction in the expression of collagen 2a (VI) chain in the right and left ventricles 3 months after initiating CCM in the HFmrEF patient, suggesting an impact of CCM on cardiac collagen regulation.

Summary

Cardiac contractility modulation improves a variety of myocardial and systemic cardiovascular properties that are involved in the pathophysiology of HFrEF (*Table 2*). The evidence from animal models and patients with HFrEF demonstrates that CCM therapy has the potential to have beneficial effects in HF via processes involved in Ca^{2+} handling, the cytoskeleton, the extracellular matrix, and potentially the autonomous nervous system. Clinical studies show trends for greater improvements in exercise tolerance, quality of life and functional status in patients with EF 35–45% vs. those with lower EFs, a finding that was reproduced in separate studies. It is noteworthy that this EF range spans half that used to define the HFmrEF population. Whether the mechanisms observed in HFrEF also apply to patients with HFpEF needs to be investigated. Therefore, a prospective, multicentre, single arm, open-label 24-week exploratory study evaluating CCM therapy in patients who are symptomatic despite OMT is planned: Cardiac Contractility Modulation (CCM™) Therapy in Subjects with Heart Failure with preserved Ejection Fraction, in brief CCM-HFpEF (EUDAMED; number CIV1612017844).

Conflict of interest: C.T. and B.K. received lecturing fees from Impulse Dynamics. D.G. and D.B. are consultants for Impulse Dynamics. The other authors have no conflicts to declare.

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