

# Mavacamten: A First-in-class Oral Modulator of Cardiac Myosin for the Treatment of Symptomatic Hypertrophic Obstructive Cardiomyopathy

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**H**ypertrophic cardiomyopathy is the most common monogenic cardiovascular disease that is caused by sarcomeric protein gene mutations. A hallmark of the most common form of the disease is outflow obstruction secondary to systolic narrowing of the left ventricular outflow tract from septal hypertrophy, mitral valve abnormalities and, most importantly, hyperdynamic contractility. Recent mechanistic studies have identified excessive myosin adenosine triphosphatase activation and actin–myosin cross-bridging as major underlying causes. These studies have led to the development of mavacamten, a first-in-class myosin adenosine triphosphatase inhibitor and the first specific therapy for hypertrophic obstructive cardiomyopathy. Preclinical and subsequent pivotal clinical studies have demonstrated the efficacy and safety of mavacamten. A remarkable improvement among treated patients in peak oxygen consumption, functional capacity, symptom relief and post-exercise left ventricular outflow tract gradient, along with dramatic reductions in heart failure biomarkers, suggests that this new medication will be transformative for the symptom management of hypertrophic obstructive cardiomyopathy. There is also hope and early evidence that mavacamten may delay or obviate the need for invasive septal reduction therapies. In this article, we review the current evidence for the efficacy and safety of mavacamten and highlight important considerations for its clinical use.

## Keywords

Clinical trial, hypertrophic obstructive cardiomyopathy, mavacamten, myosin inhibitor, review

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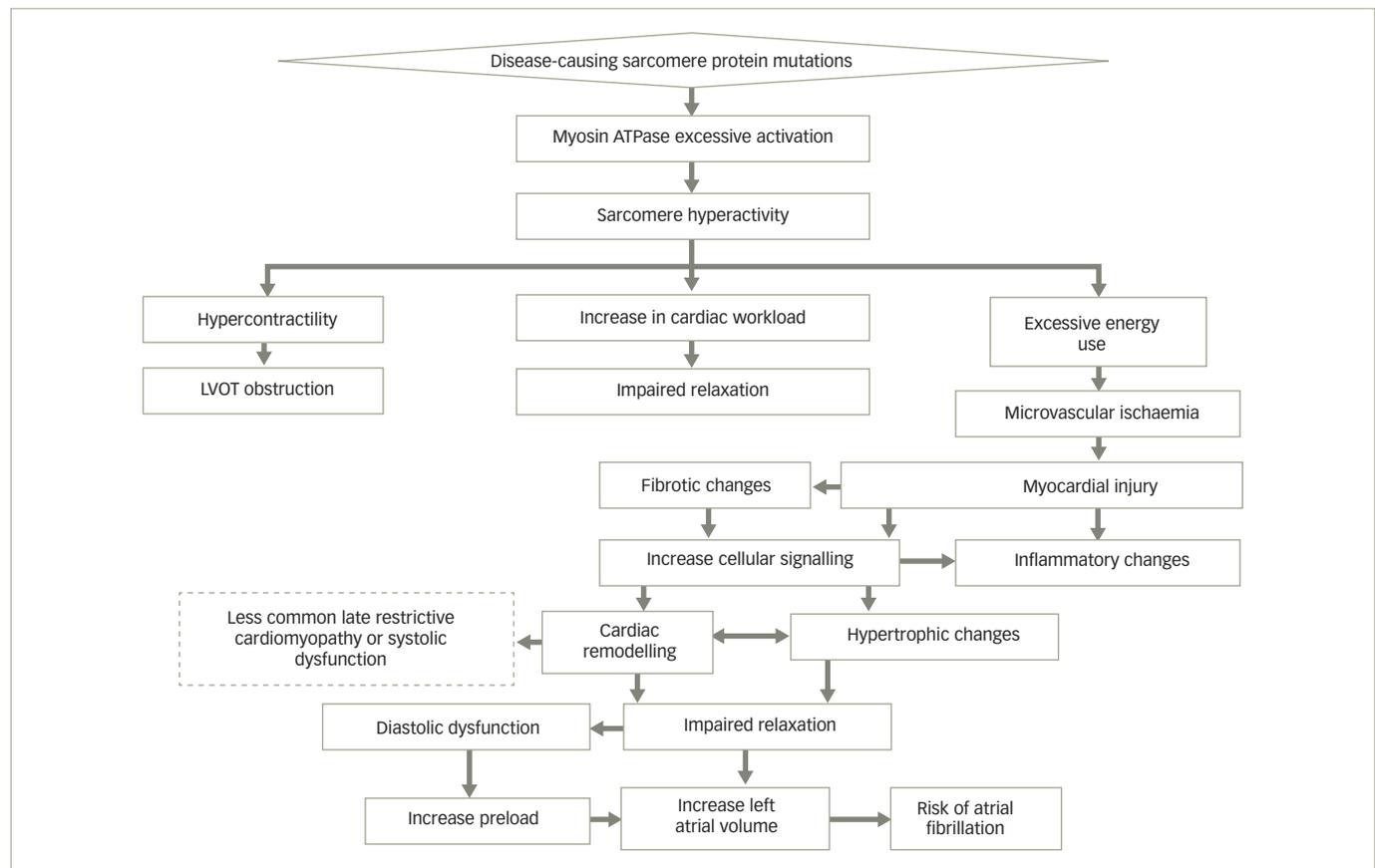
Hypertrophic cardiomyopathy (HCM), along with its more common subgroup, hypertrophic obstructive cardiomyopathy (HOCM), is the most common monogenic cardiovascular disorder, with a prevalence of about 1 in 500,<sup>1</sup> and a dominant inheritance pattern, thus clustering in affected families. Patients with HCM often have significant limitations to their exercise capacity, and while there are several underlying pathomechanisms for common symptoms, such as dyspnoea, angina and fatigue, one major cause and treatment target is left ventricular outflow tract (LVOT) obstruction.<sup>2,3</sup> An increased LVOT gradient (i.e. the quantitative measure of obstruction) occurs due to an interplay between several contributors: (1) left ventricular septal hypertrophy leading to a narrow LVOT, (2) systolic anterior motion of the anterior mitral leaflet from either a Venturi (i.e. suctioning) effect or a posterior-to-anterior systolic flow direction causing a push of the mitral leaflets into the LVOT, (3) abnormal papillary muscle configuration, (4) excessive anterior mitral leaflet tissue and (5) a small left ventricular cavity with hyperdynamic contractility. The latter mechanism has been the primary target for pharmacological therapies to reduce the LVOT gradient.<sup>4</sup> However, until the discovery of myosin adenosine triphosphate (ATP) inhibitors, the effectiveness of available drug therapies was suboptimal in many patients and was often based on small or non-randomized studies.

Myosin ATP inhibitors are a new drug class targeting one underlying cause of the development of hypertrophy, inefficient cellular energetics and LVOT obstruction: excessive actin–myosin cross-bridging.<sup>5–9</sup> The reduction of actin–myosin interactions decreases contractile force, thereby reducing LVOT gradient. However, there is preliminary evidence of mavacamten also having potential beneficial effects on diastolic function<sup>10</sup> and microvascular blood flow and improving in cardiac structure.<sup>11</sup> In this article, we review the preclinical and clinical data that make this novel drug class an attractive new option for the management of patients with symptomatic HOCM

## The hypertrophic cardiomyopathy disease process

The pathophysiology of HCM is not yet fully understood, as it is complex and multifactorial.<sup>12</sup> However, the most accepted pathomechanism is that HCM is a disease process caused by sarcomeric dysfunction secondary to missense mutations of one or several genes coding for contractile proteins, mainly the beta-myosin heavy chain, myosin-binding protein C or troponin.<sup>13,14</sup> These genetic alterations lead to changes in sarcomere physiology, such as hypersensitivity of myofilaments to calcium and an increase in myosin adenosine triphosphatase (ATPase) activity. These changes in sarcomere physiology promote the shifting of more myosin heads from

Figure 1: Pathomechanisms of hypertrophic obstructive cardiomyopathy



ATPase = adenosine triphosphate; LVOT = left ventricular outflow tract.

the physiologically relaxed state to the active state.<sup>6</sup> In a normal cardiomyocyte, 40–50% of the myosin heads are in the relaxed state, resulting in minimal energy consumption.<sup>15–17</sup> In contrast, HCM-afflicted cardiomyocytes only have 15–20% of myosin heads in the relaxed state, which results in excessive activation and unnecessary energy consumption.<sup>15–17</sup> Excess activation of myosin heads not only consumes energy in the form of ATP through the inappropriate activation of myosin ATPase but also predisposes the myosin heads to bind actin more readily, resulting in an increase of actin–myosin cross-bridging throughout the cardiac cycle.<sup>5,18–21</sup> Sarcomere hyperactivity leading to myocardial hypercontractility is an important process in the pathophysiology of HCM because it has been linked to an increase in cellular signalling that leads to hypertrophic changes.<sup>22,23</sup> Ultimately, this results in detrimental cardiac remodelling brought about by fibrotic change, myofibre hypertrophy with disarray secondary to increased activation of pathways involving hypertrophy, inflammation and fibrosis (Figure 1).<sup>18–20</sup> These changes lead to outflow tract obstruction and diastolic dysfunction; they thus lead to an increase in cardiac workload, rendering the heart an ineffective pump, hence leading to the development of symptoms of heart failure (i.e. the inability to maintain normal left atrial pressure).<sup>22</sup>

### Molecular mechanisms of mavacamten

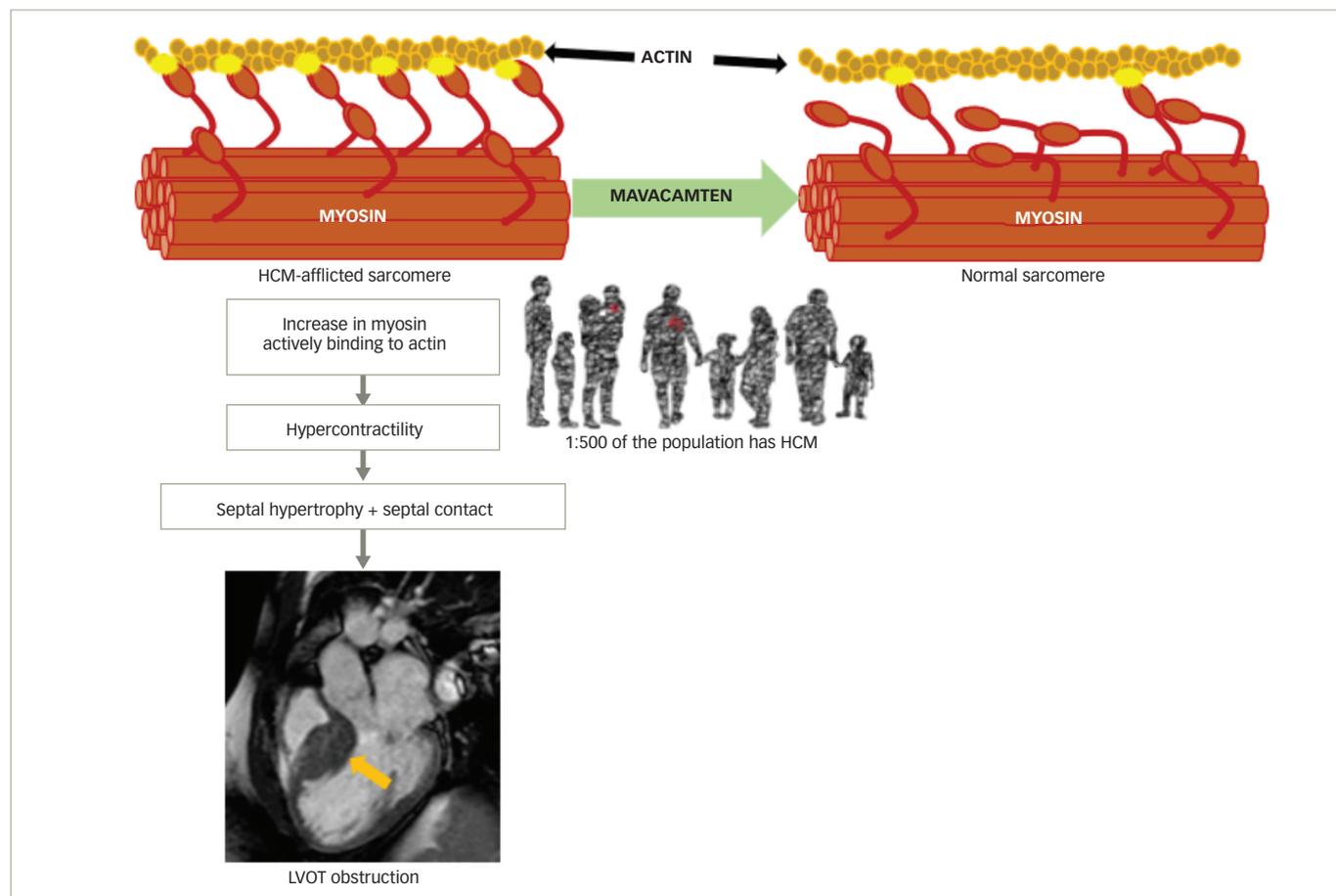
Mavacamten, formerly known as MYK-461, is a first-in-class medication referred to as a cardiac myosin ATPase inhibitor that has recently been approved by the US Food and Drug Administration as a treatment for symptomatic HOCM.<sup>9</sup> Mavacamten is a small molecule that acts selectively and reversibly on the allosteric binding site of the cardiac myosin ATPase

enzyme (Figure 2).<sup>15</sup> Recent studies have shown that the inhibition of cardiac myosin ATPase mitigates the excessive ATP expenditure seen in HCM by preventing the myosin heads from unnecessarily shifting from the relaxed energy-sparing state to the active energy-expending state.<sup>17</sup> As a result, mavacamten reduces actin–myosin cross-bridge formation, thus addressing the underlying pathology of HCM development through the reduction of hypercontractility and improvement in energetics.<sup>5–8</sup> Furthermore, these molecular changes from mavacamten optimize the mechanical environment of the sarcomere by reducing diastolic tension with improved relaxation, increasing ventricular chamber size, reducing myocardial contraction velocity and ultimately decreasing outflow obstruction.<sup>5,17,20,23</sup>

### The primary focus in hypertrophic obstructive cardiomyopathy: The left ventricular outflow tract gradient

HOCM is the most prevalent subgroup of HCM, making up approximately 70% of HCM occurrences; its defining features include asymmetric ventricular septal hypertrophy and systolic anterior motion of the mitral valve.<sup>2</sup> The presence of LVOT obstruction at rest, defined as an LVOT gradient of  $\geq 30$  mm, is associated with a twofold increase in the risk of HCM-related death,<sup>3</sup> suggesting that obstruction in HCM is not only causing symptoms but is also a treatment target for improving patients' longevity. LVOT obstruction is present in about one-third of patients at rest, and another 40% of patients develop LVOT obstruction during exercise or other provocative manoeuvres, which therefore are essential in the assessment of HCM patients.<sup>4</sup> Patients with LVOT obstruction also have a greater risk of developing clinical symptoms, arrhythmias and other HCM-related complications.<sup>1</sup>

Figure 2: How mavacamten works



Mavacamten works by targeting the myosin adenosine triphosphatase in the sarcomere. It leads to the reduction of cardiac cross-bridge formation, thus addressing the underlying pathology of hypertrophic cardiomyopathy development through the reduction of hypercontractility and improvement in energetics. HCM = hypertrophic cardiomyopathy; LVOT = left ventricular outflow tract.

The available pharmacotherapy (i.e. the initial and preferred treatment approach) has been limited; although it is highly effective in some, it has left others with significant residual symptoms that are attributable, at least in part, to residual LVOT obstruction.<sup>24</sup> Before the availability of mavacamten, treatment options were non-dihydropyridine calcium channel blockers, non-vasodilating beta-blockers and disopyramide, which mainly work by modestly decreasing contractility and allowing for prolonged ventricular filling time, thereby increasing left ventricular (including LVOT) size.<sup>25–28</sup> In people who have severe symptoms from persistent obstruction despite maximal-tolerated medical treatment, invasive septal reduction therapy can and should be considered; however, although effective, this therapy has an indisputably small but not negligible risk of complications<sup>29,30</sup> and in some cases does not provide a complete resolution of obstruction and associated symptoms.<sup>31</sup> In addition, neither myectomy nor alcohol septal ablation completely abolishes concomitant myocardial abnormalities typical in HCM, such as abnormal wall tension, diastolic dysfunction and microvascular ischaemia, from poor myocardial energetics.

### Preclinical studies of mavacamten

In a preclinical study, the administration of mavacamten prevented the development of hypertrophy in mice with HCM who had yet to develop myocardial thickening and reversed hypertrophy in mice with HCM with established hypertrophic cardiac changes due to a reduction in the expression of profibrotic and pro-hypertrophic genes.<sup>32</sup> Histopathological studies confirmed that mavacamten prevented the development of myocardial fibrosis and cardiomyocyte disarray. However, some of these

changes remained irreversible, as confirmed by histopathology showing persistent myocardial fibrosis and cardiomyocyte disarray.<sup>32</sup>

Furthermore, the histopathology of untreated hearts of mice with HCM showed patchy fibrosis throughout the myocardium by Masson's trichrome staining, similarly to what can be seen in hearts of humans with HCM. Conversely, mice with HCM treated with mavacamten had minimal fibrosis.<sup>32</sup>

Mavacamten led to a dose-dependent decrease in maximal tension and fractional shortening in an isolated cardiac muscle fibre model.<sup>31</sup> In addition, mavacamten led to regression of left ventricular wall thickness in mice with HCM.<sup>32</sup>

Taken together, these studies in mice with HCM suggest that mavacamten not only has the potential to induce regression of hypertrophy but may also prevent the development of cardiac hypertrophy and fibrosis. These findings indicate that mavacamten may show a similar effect in humans. Such early treatment prevention studies have not been performed in humans to date and, unfortunately, would be difficult to carry out.

### Clinical studies of mavacamten in patients with hypertrophic cardiomyopathy PIONEER-HCM

The initial data on the safety and efficacy of mavacamten were obtained from the PIONEER-HCM study, a phase II, open-label, non-randomized study of patients with symptomatic HOCM (A phase 2 open-label pilot

Table 1: Data collected per clinical study evaluating mavacamten

Study	Data collected							
	LVOT gradient	NYHA classification	LVEF	E/e'	LAVI	CPET (peak VO <sub>2</sub> )	NT-pro BNP levels	Cardiac troponin I
PIONEER-HCM	↓*‡	↔	↓	↔	↔	↑	↓	■
PIONEER-OLE**	↓*‡	↓	↔	↓	↓	■	↓	■
EXPLORER-HCM	↓*‡	↓	↓	↓	↓	↑	↓	↓
VALOR-HCM***	↓*‡	↓	↓	↓	↓	■	↓	↓
MAVA-LTE <sup>§</sup>								
EXPLORER-LTE cohort	↓*‡	↓	↓	↓	↓	■	↓	■

↑ – increase   ↓ – decrease   ↔ – no significant change   ■ – Not reported

\*Resting LVOT gradient; †post-Valsalva LVOT gradient; ‡post-exercise LVOT gradient; §preliminary report; \*\*significant reduction in IVS thickness by 1.5 mm; \*\*\*significant reduction in guideline-directed indication for SRT.

CPET = cardiopulmonary exercise testing; E/e' = ratio between early mitral inflow velocity and early diastolic mitral annular velocity; HCM = hypertrophic cardiomyopathy; IVS = interventricular septum; LAVI = left atrial volume index; LTE = long-term extension; LVEF = left ventricular ejection fraction; LVOT = left ventricular outflow tract; NT-pro BNP = N-terminal pro B-type brain natriuretic peptide; NYHA = New York Heart Association; OLE = open-label extension; SRT = septal reduction therapy.

study evaluating MYK-461 in subjects with symptomatic hypertrophic cardiomyopathy and left ventricular outflow tract obstruction [PIONEER-HCM]; ClinicalTrials.gov identifier: NCT02842242) (Table 1).<sup>33</sup> Key inclusion criteria were age 18–70 years, a clinical diagnosis of HCM, a screening of left ventricular ejection fraction (LVEF) of  $\geq 55\%$  by echocardiography, usual definitions of HCM by maximum left ventricular wall thickness and LVOT obstruction of  $\geq 30$  mmHg at rest or  $\geq 50$  mmHg post-exercise. What all mavacamten studies have in common are New York Heart Association (NYHA) class II or III symptoms. Patients who had exertional syncope in the past 6 months, sustained ventricular tachycardia, a history of LVEF of  $< 45\%$ , persistent atrial fibrillation, atrial fibrillation with a heart rate of  $> 100$  bpm within a year of screening or obstructive coronary artery disease were excluded from the study.<sup>33</sup>

Of 25 participants initially enrolled, 21 completed the study and were assigned either to cohort A (n=11) or cohort B (n=10). Patients in cohort A were started on 10 mg/day if their weight was  $\leq 60$  kg or on 15 mg if their weight was  $> 60$  kg. Cessation of calcium channel blockers, beta-blockers and disopyramide 14 days prior to the first dose of mavacamten was required in participants of cohort A. Drug titrations were based on changes in LVEF during weekly follow-ups to a dose of up to 20 mg/day. Patients assigned to cohort B were started on lower doses, starting at 2 mg/day with a continuation of beta-blockers at a stable dose. Drug adjustment for cohort B was based on the patient's LVOT gradient at the end of the week 4: a 5 mg/day increase was initiated if the gradient had decreased by  $< 50\%$  from baseline. At week 12, all patients in cohort B received the 5 mg/day dose increase.<sup>33</sup>

Patients from cohort A who received a mean mavacamten dose of 15 mg/day demonstrated overall beneficial clinical effects at 12 weeks, with a more profound effect seen among patients on a higher dose. At 12 weeks, the mean post-exercise LVOT gradient decreased from 103 mmHg at baseline to 19 mmHg in cohort A and from 86 mmHg at baseline to 64 mmHg in cohort B. Valsalva LVOT gradient decreased by an average of 85 mmHg (95% confidence interval [CI]: 56–114 mmHg) in cohort A and 47 mmHg (95% CI: 12–82 mmHg) in cohort B. LVEF decreased by 15% (95% CI 6–23%) in cohort A and 6% (95% CI: 1–10%) in cohort B. These data confirm that the effects of mavacamten on

both LVOT gradient and LVEF reduction are directly proportional to drug dosage.<sup>33</sup>

Mavacamten use was also associated with improvement in patients' functional status, as demonstrated by an average of 0.9 (cohort A) and 1.0 (cohort B) reduction in NYHA class. The Kansas City Cardiomyopathy Questionnaire (KCCQ) also demonstrated improvements, from an average score of 65.0 to 14.4 in cohort A and from 61.0 to 16.0 in cohort B.<sup>33</sup>

In summary, the PIONEER-HCM study showed promising improvements in LVOT gradient and clinical symptoms among enrolled patients with HOCM and formed the basis for subsequent phase III trials.<sup>33</sup>

### PIONEER-OLE

This PIONEER-OLE study (Extension study of mavacamten [MYK-461] in adults with symptomatic obstructive hypertrophic cardiomyopathy previously enrolled in PIONEER; ClinicalTrials.gov identifier: NCT03496168) was designed to examine the long-term safety and clinical symptoms in patients who completed the previous PIONEER-HCM study (Table 1).<sup>34</sup> After medication washout, patients were started on a mavacamten dose of 5 mg/day. At 6 weeks, doses could be increased to 10 or 15 mg. Patient assessments were conducted at 4, 6, 8, and 12 weeks initially and at 12-week intervals thereafter. During follow-up visits, LVEF, LVOT gradient, NYHA class, N-terminal pro B-type brain natriuretic peptide (NT-pro BNP), drug concentrations and adverse effects were assessed.

At 48 weeks, mavacamten use was again associated with improvements in LVOT gradient of 14.0 mmHg and 22.4 mmHg at rest and post-Valsalva, respectively. Improvements in diastolic function were also captured objectively through a 9.8 mL/m<sup>2</sup> reduction in the left atrial volume index and a 3.4-point reduction in lateral E/e' (ratio between early mitral inflow velocity and early diastolic mitral annular velocity). Interestingly, there was a statistically significant reduction of 1.5 mm in interventricular septal thickness, representing the first-in-human evidence for hypertrophy regression in patients with HCM treated with mavacamten. The ejection fraction remained normal, with mean values of 67.6% and no reductions to  $< 50\%$  throughout the study. A mean reduction of 472 pg/mL in NT-pro BNP levels was also observed. Three patients were considered NYHA

class I, and three patients were considered NYHA class II. The KCCQ was also reported to have improved.<sup>34</sup>

Regarding drug toxicity, mavacamten was generally well tolerated, with all adverse events described as mild to moderate and self-resolving. No serious or cardiac events were noted in patients taking mavacamten.<sup>34</sup> Although the results of this extension study were promising, major limitations were the small sample size (n=12 at the end of the study) and the non-randomized design.<sup>34</sup>

### EXPLORER-HCM

EXPLORER-HCM (Clinical study to evaluate mavacamten [MYK-461] in adults with symptomatic obstructive hypertrophic cardiomyopathy; ClinicalTrials.gov identifier: NCT03470545) was the pivotal phase III, randomized, double-blind, placebo-controlled, multicentre trial of mavacamten in symptomatic HOCM conducted in 13 countries (Table 1).<sup>9</sup> Study participants were diagnosed with HOCM according to the usual criteria, with an LVOT gradient of  $\geq 50$  mmHg, an LVEF of  $\geq 55\%$ , NYHA class II or III, and age  $\geq 18$  years at screening. Key exclusion criteria were a history of syncope and sustained ventricular tachycardia with exercise within 6 months prior to screening. While background therapy with a beta-blocker or calcium channel blocker was allowed, patients could not be on both. Disopyramide was also washed out prior to enrolment. Of the 251 enrolled patients, 123 were randomized to the mavacamten arm and 128 to the placebo arm. Overall, 97.2% of participants completed the study. Results showed that 36.6% of patients on mavacamten achieved the positive clinical response compared with placebo, which demonstrated an increase in peak volume of oxygen consumption ( $VO_2$ ) of  $\geq 1.5$  mL/kg/min plus  $\geq 1$  NYHA class improvement, or peak  $VO_2$  increase by  $\geq 3.0$  mL/kg/min with no worsening of NYHA class at 30 weeks. Peak  $VO_2$  improved by 1.4 mL/kg/min from baseline to week 30 among patients who received mavacamten but did not change in the placebo group. The KCCQ administered at 30 weeks of treatment revealed a higher score among patients receiving mavacamten. The Hypertrophic Cardiomyopathy Symptoms Questionnaire Shortness-of-Breath administered at 30 weeks of treatment showed a reduced score in patients given mavacamten, indicating that mavacamten relieved frequency and severity of shortness of breath. In addition, profound reductions in NT-pro BNP by 80% were observed in patients treated with mavacamten.

Overall, this study demonstrated that treatment with mavacamten improved functional capacity, symptom status, LVOT gradient and clinically important reductions in biomarkers. In addition, a magnetic resonance imaging substudy reported the following findings, demonstrating that mavacamten was associated with structural improvements: a 17.4 g/m<sup>2</sup> reduction in left ventricular mass index and a 10.3 mL/m<sup>2</sup> reduction in left atrial volume index.<sup>11</sup>

In terms of safety and tolerability, patients who were given mavacamten experienced similar adverse events to those experienced in the placebo group; however, there were more reports of dizziness and syncope, which were unlikely to be arrhythmic in nature. One participant in the placebo arm died from sudden death during the study. Overall, seven patients in the mavacamten arm and two patients in the placebo arm developed reductions of LVEF below 50%. In all seven patients, LVEF recovered with cessation of mavacamten; however, this observation led to current requirements for a stringent risk mitigation programme set forth by the US Food and Drug Administration to closely monitor patients for the development of systolic dysfunction and also to avoid prescription of concomitant medications that can affect the metabolism of mavacamten

or the metabolism of the concomitant medication (e.g. cytochrome P450 substrates). Six patients, three from each group, underwent temporary discontinuation because they satisfied the predefined criteria for changes in QT interval. There were no temporary discontinuations due to mavacamten plasma concentrations  $>1,000$  ng/mL.<sup>8</sup>

### VALOR-HCM

The VALOR-HCM study was a multicentre, randomized, double-blind, placebo-controlled, phase III study designed to evaluate the safety and efficacy of adding mavacamten to an established medical regimen on reducing the number of people with symptomatic HOCM needing guideline-directed septal reduction therapy after 16 weeks of treatment (A study to evaluate mavacamten in adults with symptomatic obstructive HCM who are eligible for septal reduction therapy; ClinicalTrials.gov identifier: NCT04349072) (Table 1).<sup>35</sup>

Key inclusion criteria were people with HOCM defined by the usual criteria and an LVOT gradient of  $\geq 50$  mmHg at rest or post-exercise who were referred for septal reduction therapy within the last 12 months because of severe exertional symptoms (NYHA classification of III to IV or NYHA classification II if with syncopal episodes) despite maximal medical therapy, which may include disopyramide and/or a combination of beta-blockers and calcium channel blockers. For patients on beta-blockers, calcium channel blockers or disopyramide, doses had to be stable for 14 days.

Out of the 112 participants, 56 patients were randomly assigned to the mavacamten arm and 56 patients to the placebo arm. A starting dose of 5 mg/day of mavacamten was given to each participant in the mavacamten group. These patients were given blinded dose adjustments based on the LVEF and LVOT gradient at rest and with Valsalva provocation.

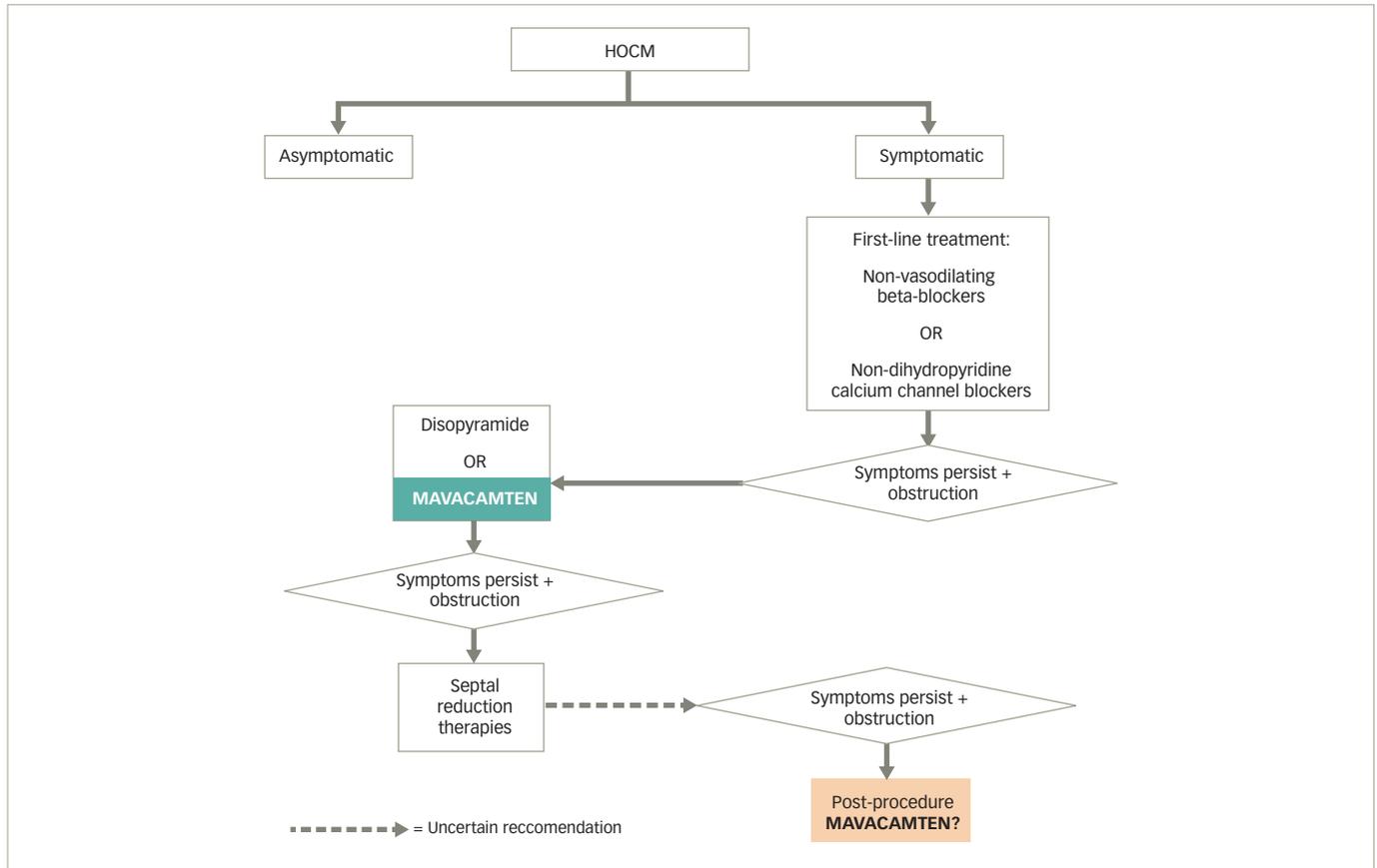
At 16 weeks, patients were reassessed for eligibility for guideline-directed septal reduction therapy. Only 17.9% of patients who were receiving mavacamten remained eligible for septal reduction therapy compared with 76.8% in the placebo group. The improvement in NYHA class was superior in the mavacamten group compared with the placebo group. Resting LVOT gradients at 16 weeks averaged 14 mmHg in the mavacamten group versus 46 mmHg in the placebo group. The Valsalva LVOT gradient was also notably lower in the mavacamten group than in the placebo group, at 28 mmHg and 78 mmHg, respectively. Patients taking mavacamten scored higher on KCCQ-23, averaging 80 versus 67 in the placebo group, indicating symptom improvement in the former group.

Regarding adverse events, there was no detected non-sustained ventricular tachycardia in the mavacamten group compared with 9.1% in the placebo group. Mild adverse events were higher in patients taking mavacamten in the placebo arm. No patients experienced any serious adverse events; however, temporary drug cessation was necessary for two patients due to LVEF below 50%; no LVEF below 30%, which requires permanent drug cessation, was reported.<sup>35</sup>

### Longer-term effectiveness and safety data: MAVALTE

MAVALTE is an on-going, dose-blinded extension study (A long-term safety extension study of mavacamten in adults who have completed MAVERICK-HCM or EXPLORER-HCM; ClinicalTrials.gov identifier: NCT03723655) that was conducted on patients who completed either MAVERICK-HCM, a proof-of-concept study in non-obstructive HCM (A phase 2 study of mavacamten in adults with symptomatic non-obstructive hypertrophic cardiomyopathy [nHCM]; ClinicalTrials.gov

Figure 3: Proposed treatment algorithm of symptomatic hypertrophic obstructive cardiomyopathy including mavacamten



HOCM = hypertrophic obstructive cardiomyopathy.

identifier: NCT03442764) or EXPLORER-HCM (ClinicalTrials.gov identifier: NCT03470545).<sup>36</sup> It was designed to assess long-term data in patients with HCM taking mavacamten, including the frequency and severity of treatment-emergent adverse and serious adverse events over 5 years and to demonstrate long-term durability of the initially observed benefits of mavacamten in HCM (Table 1).<sup>36</sup>

Eligible patients must have completed the parent study, with a persistent LVEF of >50% by transthoracic echocardiography assessed by the echo core lab, with laboratory parameters in the normal range for safety.

All patients, principal investigators and site coordinators who perform study assessment are blinded to the mavacamten dose but aware of active treatment. Nine patient assessments are planned in the first year, five in the second year, four in the third year and, finally, two in the fourth and fifth years. Patients undergo transthoracic echocardiography, electrocardiogram, physical examination, blood work, pharmacokinetic studies, accelerometer measurements and implantable cardiac defibrillator checks, if applicable. At the end of each visit, appropriate drug adjustments are recommended by the site investigators for optimal mavacamten dosing (i.e. the lowest effective dose). To date, only interim results from MAVA-LTE have been published; they will likely determine the clinical use of mavacamten in future practice.<sup>36,37</sup>

### Where does mavacamten fit into current hypertrophic cardiomyopathy treatment algorithms?

The guiding principle in treating HCM has traditionally been directed towards ameliorating symptoms. Guidelines on the stepwise approach to pharmacological and invasive treatment options are available.<sup>28,38-40</sup>

Table 2: CYP2C19 inhibitors

Weak	Moderate*	Strong*	Class not well defined
Allicin	Eslicarbazepine	Amitriptyline	Cannabidiol
Armodafinil	Esomeprazole	Clomipramine	Cenobamate
Carbamazepine	Fluoxetine	Fluconazole	Lansoprazole
Cimetidine	Moclobemide	Fluvoxamine	Oxcarbazepine
Desipramine	Omeprazole	Imipramine	Telmisartan
Etravirine	Voriconazole	Ticlopidine	Vilazodone
Ethinylestradiol			
Felbamate			
Fenofibrate			
Ketoconazole			
Nortriptyline			
Oral contraceptives†			
Topiramate			

Concomitant use of mavacamten with CYP2C19 inhibitors can inhibit mavacamten metabolism, and it may increase the risk of adverse drug reactions and may require dose adjustments.

\*Concomitant use of mavacamten with moderate or strong CYP2C19 inhibitors increase blood drug levels and may increase the risk of heart failure due to systolic dysfunction and are therefore contraindicated. † Mavacamten may reduce the effectiveness of combined hormonal contraception drugs. The patients should be advised to use the appropriate contraception methods.

Current pharmacological guidelines employ the use of negative chronotropic drugs as initial treatment (non-vasodilating beta-blockers and non-dihydropyridine calcium channel blockers) to decrease heart rate, which in turn prolongs ventricular filling time.<sup>38-40</sup> This causes larger left ventricular end-diastolic volume and LVOT with a reduction of obstruction.

Table 3: CYP2C19 inducers

Weak	Moderate*	Strong*	Class not well defined
Ritonavir	Apalutamide Enzalutamide Efavirenz Phenytoin	Rifampin	Tocilizumab Letermovir St John's Wort TNF inhibitors: Adalimumab Certolizumab Etanercept Golimumab Infliximab

\*Concomitant use of mavacamten with moderate or strong CYP2C19 inducers may decrease drug efficacy.  
TNF = tumour necrosis factor.

Table 4: CYP3A4 inducers

Weak	Moderate*	Strong*	Class not well defined
Aprepitant Armodafinil Clobazam Delafloxacin Echinacea Lesinurad Pioglitazone Pitolisant Prednisone Rufinamide Topiramate Oral contraceptives† Topiramate	Bosentan Efavirenz Etravirine Modafinil Nafacillin Voriconazole	Carbamazepine Enzalutamide Phenobarbital Phenytoin Rifampin St John's Wort	Cenobamate Dabrafenib Dexamethasone Esllicarbazepine Felbamate Fosamprenavir Griseofulvin Nevirapine Oxcarbazepine Primidone Rifabutin Rifapentine Tocilizumab TNF inhibitors: Adalimumab Certolizumab Etanercept Golimumab Infliximab

\*Concomitant use of mavacamten with moderate to strong CYP3A4 inducers may reduce mavacamten exposure and decrease its effectiveness, and are therefore contraindicated. †Mavacamten may reduce the effectiveness of combined hormonal contraception drugs. The patients should be advised to use the appropriate contraception methods.  
TNF = tumour necrosis factor.

In addition, the negative inotropic effects of the beta-blockers, the calcium channel blockers and disopyramide reduce contractile forces and LVOT obstruction. Whether beta-blockers and calcium channel blockers worsen or improve diastolic function is incompletely understood. Currently, the data supporting the effect of these pharmacological therapies on the natural history of HCM are incomplete.<sup>39-42</sup> There are currently no guideline-recommended algorithms on the optimal use of mavacamten in clinical practice; nonetheless, given some continued access and cost issues and the requirement for frequent and regular clinical and echocardiographic monitoring with mavacamten use, beta-blockers and calcium channel blockers are likely to continue as the first-line treatment option for most patients with HOCM, at least until longer-term data are available (Figure 3). However, such longer-term safety follow-up studies may lessen the clinical monitoring requirements in the future and encourage broader-scale implementation. Additional follow-up studies will also inform the question of whether mavacamten alters long-term clinical

Table 5: CYP3A4 Inhibitors

Weak	Moderate*	Strong†	Class not well defined
Alprazolam Amiodarone Amiodipine Atorvastatin Bicalutamide Cilostazol Cimetidine Dihydroergotamine Ergotamine Fluoxetine Ginkgo Glecaprevir Goldenseal Grazoprevir Imipramine Isradipine Isoniazid Ivacaftor Lapatinib Nilotinib Oral contraceptives Pibrentasvir Ranitidine	Aprepitant Atazanavir Ciprofloxacin Clindamycin Darunavir Diltiazem Dronedarone Erythromycin Fluconazole Fosamprenavir Grapefruit juice Imatinib Letermovir Verapamil	Boceprevir Clarithromycin Cobicistat Conivaptan Danazol Fluvoxamine Grapefruit juice Indinavir Itraconazole Ketoconazole Lopinavir Ritonavir Nefazodone Posaconazole Quinupristin Saquinavir Telaprevir Telithromycin Voriconazole	Azithromycin Bromocriptine Cenobamate Chloramphenicol Delavirdine Desipramine Danazol Felodipine Ibexafungerp Iloperidone Lefamulin Linagliptin Nicardipine Quinidine Simeprevir Spironolactone Zafirlukast Golimumab Infliximab

\*Concomitant use of mavacamten with moderate CYP3A4 inhibitors can inhibit mavacamten metabolism and it may increase risk of adverse drug reactions and are therefore contraindicated. †Concomitant use of mavacamten with strong CYP3A4 inhibitors increase blood drug level and may increase the risk of heart failure due to systolic dysfunction and are therefore contraindicated.

outcomes and reverses or halts the development of hypertrophic and fibrotic changes in the affected myocardium. If on-going studies confirm this hypothesis, mavacamten may become the preferred first-line treatment option for symptomatic HOCM in the near future.

### Limitations of using mavacamten

Although mavacamten is a highly effective medication for symptomatic HOCM, there are some difficulties with its use in clinical practice. A limitation to its use in clinical practice is that it should not be used in patients with LVEF <55%, which disqualifies many patients with longer-standing cardiomyopathy. In addition, its use is contraindicated in pregnant patients and patients taking drugs known to interact with the CYP2C19 and CYP3A4 enzymes by either inhibiting or inducing them (Tables 2–5). Regular echocardiographic assessments to evaluate ejection fraction are crucial; however, this adds to the overall cost to the healthcare system and, in some cases, to the patient. Regular medication reconciliations are also key in optimizing the effectiveness and safety of mavacamten.

### Conclusions

Until now, the treatment of HOCM had been limited to a few pharmacological agents that have not been studied with optimal scientific rigour and leave with treatment-refractory symptoms a significant proportion of patients who thus require invasive septal reduction therapies to relieve symptoms secondary to LVOT obstruction. Although these techniques are highly effective and, in general, safe when performed in high-volume centres, they do have some residual risk for procedural complications. With the availability of mavacamten, a novel myosin inhibitor targeting the underlying cause of many HCM-related

symptoms, the medical treatment of HOCM has become more effective but not trivial in clinical practice. Given the intricacies of mavacamten with the potential for causing reversible systolic heart failure, significant drug–drug interactions and close monitoring requirements, its place

in current treatment algorithms has yet to be defined. However, there is great hope and early data suggesting that mavacamten will alter the disease trajectory and thus may soon be the preferred first-line treatment option for patients with HOCM. □

- Maron BJ, Ommen SR, Semsarian C, et al. Hypertrophic cardiomyopathy: Present and future, with translation into contemporary cardiovascular medicine. *J Am Coll Cardiol*. 2014;64:83–99.
- Lang RM, Goldstein SA, Kronzon I, et al. (eds). *Ase's Comprehensive Echocardiography*. Philadelphia: Elsevier, 2022.
- Elliott PM, Gimeno JR, Torné MT, et al. Left ventricular outflow tract obstruction and sudden death risk in patients with hypertrophic cardiomyopathy. *Eur Heart J*. 2006;27:1933–41.
- Maron BJ, Maron MS, Wigle ED, Braunwald E. The 50-year history, controversy, and clinical implications of left ventricular outflow tract obstruction in hypertrophic cardiomyopathy: From idiopathic hypertrophic subaortic stenosis to hypertrophic cardiomyopathy. *J Am Coll Cardiol*. 2009;54:191–200.
- Kawas RF, Anderson RL, Ingle SRB, et al. A small-molecule modulator of cardiac myosin acts on multiple stages of the myosin chemomechanical cycle. *J Biol Chem*. 2017;292:16571–7.
- van der Velden J, Tocchetti CG, Varricchi G, et al. Metabolic changes in hypertrophic cardiomyopathies: Scientific update from the Working Group of Myocardial Function of the European Society of Cardiology. *Cardiovasc Res*. 2018;114:1273–80.
- Lim GB. First-in-class cardiac myosin inhibitor reduces symptoms of HCM. *Nat Rev Cardiol*. 2020;17:677.
- Olivetto I, Oreziak A, Barriales-Villa R, et al. Mavacamten for treatment of symptomatic obstructive hypertrophic cardiomyopathy (EXPLORER-HCM): A randomised, double-blind, placebo-controlled, phase 3 trial. *Lancet*. 2020;396:759–69.
- Bristol-Myers Squibb. CAMZYOS™ (mavacamten). Prescribing Information. 2022. Available at: [https://packageinserts.bms.com/pi/pi\\_camzyos.pdf](https://packageinserts.bms.com/pi/pi_camzyos.pdf) (accessed 20 September 2022).
- Sewanani LR, Shen S, Campbell SG. Mavacamten preserves length-dependent contractility and improves diastolic function in human engineered heart tissue. *Am J Physiol Heart Circ Physiol*. 2021;320:H1112–23.
- Saberí S, Cardim N, Yamani M, et al. Mavacamten favorably impacts cardiac structure in obstructive hypertrophic cardiomyopathy: EXPLORER-HCM cardiac magnetic resonance substudy analysis. *Circulation*. 2021;143:606–8.
- Sequeira V, Bertero E, Maack C. Energetic drain driving hypertrophic cardiomyopathy. *FEBS Lett*. 2019;593:1616–26.
- Wolf CM. Hypertrophic cardiomyopathy: Genetics and clinical perspectives. *Cardiovasc Diagn Ther*. 2019;9(Suppl. 2):S388–415.
- Nishi H, Kimura A, Harada H, et al. A myosin missense mutation, not a null allele, causes familial hypertrophic cardiomyopathy. *Circulation* 1995;91:2911–5.
- Alamo L, Ware JS, Pinto A, et al. Effects of myosin variants on interacting-heads motif explain distinct hypertrophic and dilated cardiomyopathy phenotypes. *Elife*. 2017;6:e24634.
- Trivedi DV, Adhikari AS, Sarkar SS, et al. Hypertrophic cardiomyopathy and the myosin mesa: Viewing an old disease in a new light. *Biophys Rev*. 2018;10:27–48.
- Anderson RL, Trivedi DV, Sarkar SS, et al. Deciphering the super relaxed state of human  $\beta$ -cardiac myosin and the mode of action of mavacamten from myosin molecules to muscle fibers. *Proc Natl Acad Sci U S A*. 2018;115:e8143–52.
- Spudich JA. Three perspectives on the molecular basis of hypercontractility caused by hypertrophic cardiomyopathy mutations. *Pflugers Arch*. 2019;471:701–17.
- Maron BJ. Clinical course and management of hypertrophic cardiomyopathy. *N Engl J Med*. 2018;379:655–68.
- Bonne G, Carrier L, Richard P, et al. Familial hypertrophic cardiomyopathy: From mutations to functional defects. *Circ Res*. 1998;83:580–93.
- Daniels MJ, Fusi L, Semsarian C, Naidu SS. Myosin modulation in hypertrophic cardiomyopathy and systolic heart failure: Getting inside the engine. *Circulation*. 2021;144:759–62.
- Wijker PJM, Sequeira V, Kuster DWD, et al. Hypertrophic cardiomyopathy: A vicious cycle triggered by sarcomere mutations and secondary disease hits. *Antioxid Redox Signal*. 2019;31:318–58.
- Edelberg J, Sehnt A, Mealiffe M, et al. The impact of mavacamten on the pathophysiology of hypertrophic cardiomyopathy: A narrative review. *Am J Cardiovasc Drugs*. 2022; doi: 10.1007/s40256-022-00532-x.
- Dybro A, Rasmussen T, Nielsen R, et al. Randomized trial of metoprolol in patients with obstructive hypertrophic cardiomyopathy. *J Am Coll Cardiol*. 2021;78:2505–17.
- Sherrid MV, Shetty A, Winson G, et al. Treatment of obstructive hypertrophic cardiomyopathy symptoms and gradient resistant to first-line therapy with  $\beta$ -blockade or verapamil. *Circ Heart Fail*. 2013;6:694–702.
- Ommen SR. AHA/ACC guideline for the diagnosis and treatment of patients with hypertrophic cardiomyopathy. *Circulation*. 2020;142:e558–631.
- Spoladore R, Maron MS, D'Amato R, et al. Pharmacological treatment options for hypertrophic cardiomyopathy: High time for evidence. *Eur Heart J*. 2012;33:1724–33.
- Spirito P, Seidman CE, McKenna WJ, Maron BJ. The management of hypertrophic cardiomyopathy. *N Engl J Med*. 1997;336:775–85.
- Liebrechts M, Vriesendorp PA, Mahmoodi BK, et al. A systematic review and meta-analysis of long-term outcomes after septal reduction therapy in patients with hypertrophic cardiomyopathy. *JACC Heart Fail*. 2015;3:896–905.
- El-Sabawi B, Nishimura RA, Barsness GW, et al. Temporal occurrence of arrhythmic complications after alcohol septal ablation. *Circ Cardiovasc Interv*. 2020;13:e008540.
- Leonardi RA, Kransdorf EP, Simel DL, Wang A. Meta-analyses of septal reduction therapies for obstructive hypertrophic cardiomyopathy. *Circ Cardiovasc Interv*. 2010;3:97–104.
- Green EM, Wakimoto H, Anderson RL, et al. A small-molecule inhibitor of sarcomere contractility suppresses hypertrophic cardiomyopathy in mice. *Science*. 2016;35:617–21.
- Heitner SB, Jacoby D, Lester SJ, et al. Mavacamten treatment for obstructive hypertrophic cardiomyopathy: A clinical trial. *Ann Intern Med*. 2019;170:741–8.
- MyoKardia, Inc. MyoKardia announces 48-week data from Pioneer-Ole Study of mavacamten. 11 November 2019. Available at: [www.globenewswire.com/en/news-release/2019/11/11/1944654/37418/en/MyoKardia-Announces-48-week-Data-from-PIONEER-OLE-Study-of-Mavacamten.html](http://www.globenewswire.com/en/news-release/2019/11/11/1944654/37418/en/MyoKardia-Announces-48-week-Data-from-PIONEER-OLE-Study-of-Mavacamten.html) (accessed 17 August 2022).
- Desai MY, Wolski K, Owens A, et al. Study design and rationale of VALOR-HCM: Evaluation of mavacamten in adults with symptomatic obstructive hypertrophic cardiomyopathy who are eligible for septal reduction therapy. *Am Heart J*. 2021;239:80–9.
- ClinicalTrials.gov. A Long-term Safety Extension Study of Mavacamten in Adults Who Have Completed Maverick-HCM or Explorer-HCM. ClinicalTrials.gov Identifier: NCT03723655. Available at: [www.clinicaltrials.gov/ct2/show/NCT03723655](http://www.clinicaltrials.gov/ct2/show/NCT03723655) (accessed 13 June 2022).
- Rader F. Updated cumulative results of treatment with mavacamten from the explorer-LTE cohort of the mava-LTE study in patients with obstructive hypertrophic cardiomyopathy. 2022. Available at: [www.tctmd.com/slide/updated-cumulative-results-treatment-mavacamten-explorer-lte-cohort-mava-lte-study-patients](http://www.tctmd.com/slide/updated-cumulative-results-treatment-mavacamten-explorer-lte-cohort-mava-lte-study-patients) (accessed 15 September 2022).
- Houston BA, Stevens GR. Hypertrophic cardiomyopathy: A review. *Clin Med Insights Cardiol*. 2015;8(Suppl. 1):53–65.
- Kaltenbach M, Hopf R, Kober G, et al. Treatment of hypertrophic obstructive cardiomyopathy with verapamil. *Br Heart J*. 1979;42:35–42.
- Choudhury L, Elliott P, Rimoldi O, et al. Transmural myocardial blood flow distribution in hypertrophic cardiomyopathy and effect of treatment. *Basic Res Cardiol*. 1999;94:49–59.
- Kimmelstiel C, Zisa DC, Kuttub JS, et al. Guideline-based referral for septal reduction therapy in obstructive hypertrophic cardiomyopathy is associated with excellent clinical outcomes. *Circ Cardiovasc Interv*. 2019;12:e007673.
- Andries G, Yandrapalli S, Naidu S. Novel pharmacotherapy in hypertrophic cardiomyopathy. *Cardiol Rev*. 2018;26:239–44.