**Differences in the Clinical Course of Sarcomeric and Non-Sarcomeric Hypertrophic Cardiomyopathy**

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**Running Title:** Sarcomeric and non-sarcomeric HCM

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**Word count**

Abstract: 414 words (Limit: 350 words)

Manuscript: 3855 words (Limit: 5000 words)

**ABSTRACT:**

***Background***: Rare variants in sarcomere genes are a common cause of hypertrophic cardiomyopathy (HCM). However, a monogenic cause is not identified in most patients. Studies indicate clinical differences based on the presence of sarcomere variants, but comprehensive comparisons, including to what degree that genetics modulate clinical outcomes, have not been performed.

***Methods***: We conducted a longitudinal cohort study including patients with HCM from 12 international, high-volume cardiomyopathy clinics in the Sarcomeric Human Cardiomyopathy Registry. Inclusion required genetic testing that identified pathogenic or likely pathogenic variants (LP/P) in the 8 classic sarcomere genes (sarcomeric HCM) or genetically-elusive (non-sarcomeric) HCM. The temporal association and sequence of cardiovascular events were assessed in time-varying Cox proportional hazards models.

***Results***: We analyzed 5,454 patients (38% female, 89% probands, 50% sarcomeric HCM). Patients with sarcomeric HCM were younger at diagnosis (median age 36.7 versus 49.6 years), had a lower burden of obesity, hypertension, and left ventricular (LV) obstruction, but a higher burden of atrial fibrillation, LV systolic dysfunction and ventricular arrhythmias.

Time-to-event analysis revealed a high co-occurrence of hypertension, LV obstruction and obesity, with a stronger association between these features in patients with non-sarcomeric HCM. In addition, LV obstruction associated with atrial fibrillation (HR 1.74 [CI 1.50-2.03]), but not advanced heart failure, ventricular arrhythmias or death. Atrial fibrillation was found to be an important disease modifier leading to both LV systolic dysfunction (HR 2.76 [CI 2.25-3.3]), stroke (HR 2.27 [CI 1.66-3.12]), ventricular arrhythmias (HR 3.13 [CI 2.34-4.20]), cardiac transplantation (HR 7.6 [CI 5.1-11]), and death (HR 1.95 [CI 1.63-2.33]). Interaction analysis identifying a significantly larger disease-modifying effect of atrial fibrillation in sarcomeric HCM patients for all outcomes excluding stroke.

Finally, we investigated mortality and observed that patients with sarcomeric HCM died younger (mean age 63 versus 70 years), with an age-standardized incidence ratio of 1.27 (CI 1.13-1.43) for all-cause mortality and were twice as likely to die from sudden cardiac death, heart failure or stroke.

***Conclusions***: We provide a comprehensive description of the cardiac phenotypes and clinical outcomes in sarcomeric and non-sarcomeric HCM. We found sarcomeric HCM to associate with more severe heart failure and arrhythmias, and an HCM-related mortality-rate twice that of non-sarcomeric HCM. Crucially, we observed that genetic status significantly augmented the disease-modifying impact of cardiovascular comorbidities on downstream HCM outcomes, (mostly) with larger additive effects observed in patients with sarcomeric HCM. These findings offer valuable insights into the clinical course of these two major subtypes of HCM and have potential implications regarding future risk stratification and management.

***Keywords:*** hypertrophic cardiomyopathy, Cardiovascular outcomes, heart failure, genetics

**CLINICAL PERSPECTIVE**

**What is new?**

* The clinical trajectory and temporal sequence of cardiovascular events tend to diverge between patients with sarcomeric versus non-sarcomeric hypertrophic cardiomyopathy (HCM).
* Hypertension, obesity and obstructive physiology, show a high rate of co-occurrence, and is more common in non-sarcomeric HCM, but is not associated with an excess risk of advanced heart failure or sudden cardiac death.
* Atrial fibrillation showed strong temporal associations with advanced heart failure, ventricular arrhythmias, stroke and death in all patients, but with a significantly bigger additive effect in patients with sarcomeric HCM.
* The risk of HCM-related mortality was twice as high in patients with sarcomeric HCM compared to with patients with non-sarcomeric HCM
* **What are the clinical implications?**
* Patients with sarcomeric HCM are at higher risk for disease-related adverse outcomes, including death, thus more intensive surveillance for cardiac arrhythmias and LV dysfunction may be appropriate.
* Integrating genetic testing results may improve clinical risk stratification algorithms and predictive models for cardiovascular outcomes.

**Abbreviations**

BMI = Body-mass index

HCM = Hypertrophic cardiomyopathy

ICD = implantable cardioverter defibrillator

LV = Left ventricle

NYHA = New York Heart Association

P/LP = Pathogenic or likely pathogenic

SHaRe = Sarcomeric Human Cardiomyopathy Registry

VT = ventricular tachycardia

**INTRODUCTION**

Hypertrophic cardiomyopathy (HCM) is a complex cardiovascular disorder characterized by unexplained left ventricular hypertrophy (LVH). Although HCM can arise from different etiologies, a considerable proportion of disease is attributable to variants in genes encoding sarcomere proteins, such as *MYH7*, *MYBPC3*, *TNNT2*, and others.1,2 Previous studies have investigated the impact of specific genetic mutations and sarcomere variants overall, on HCM phenotypes and outcomes.3,4 However, patients with sarcomeric HCM have not previously been comprehensively compared to those with non-sarcomeric HCM where a genetic etiology remains elusive despite genetic testing. Understanding the differences in disease progression, the influence of risk factors, and outcomes between these two groups is crucial for optimizing the care of individual patients and for informing personalized treatment strategies. In light of these gaps in the literature, our study aims to contrast the prognosis and outcomes of patients with sarcomeric and non-sarcomeric HCM, with a particular focus on the characterizing clinical trajectories and the temporal sequence of events in these key subgroups. By analyzing a large cohort of genotyped HCM patients, we seek to uncover patterns that may provide valuable insights into disease progression, risk stratification, and providing more personalized clinical management of HCM.

**METHODS:**

***Study Design:***

This was a multicenter observational study using data from the Sarcomeric Human Cardiomyopathy Registry (SHaRe).SHaRe is a longitudinal database of patients with HCM who receive care at 12 international, high-volume, expert HCM centers.

Collected data include cardiovascular events prior to initial visit at a SHaRe site, demographics, clinical characteristics, echocardiographic measurements, genetic testing results, cardiovascular comorbidities, and longitudinal, prospective assessment of clinical features and outcomes as previously described.3 Institutional review board and ethics approval was obtained in accordance with local policies at each SHaRe site.

***Population:***

This study included patients who had undergone clinical evaluation and genetic testing for sarcomere gene variants at a SHaRe site. Patients were stratified into two groups based on the presence or absence of pathogenic or likely pathogenic (P/LP) variants in 8 core sarcomere genes (*MYBPC3, MYH7, TNNT2, TNNI3, TPM1, MYL2, MYL3*, and *ACTC*).12 Patients carrying variants of uncertain significance (or with no genetic testing) were excluded. Genetic variants were classified based on criteria of the American College of Medical Genetics and Genomics and Association for Molecular Pathology.5,6 Patients carrying LP/P sarcomere variants were defined to have sarcomeric HCM, while patients negative for sarcomere variants were defined to have non-sarcomeric HCM.

***Clinical Features:***

Features of interest were selected based on their clinical relevance and potential impact on patients' morbidity and mortality. They were categorized into the following groups:

1. Cardiovascular comorbidities: Hypertension and obesity (BMI > 30).
2. Cardiac remodeling and function: left ventricular (LV) ejection fraction, LV outflow gradient and maximal LV wall thickness.
3. Heart failure: New York Heart Association (NYHA) functional class III-IV, LV systolic dysfunction (LV ejection fraction (EF) <50%), cardiac transplantation or LV assist device (LVAD) implantation.
4. Arrhythmias: Unexplained syncope, atrial fibrillation, non-sustained ventricular tachycardia (VT), cardiac arrest, and a composite ventricular arrhythmia (VA) outcome which included sudden cardiac death, aborted sudden cardiac death, sustained ventricular tachycardia and appropriate implantable cardioverter-defibrillator [ICD] therapy.
5. Stroke.
6. Mortality: All-cause and HCM-related mortality (sudden cardiac death [SCD], heart failure and stroke).

These phenotypic features were compared between sarcomeric and non-sarcomeric HCM to determine differences in clinical course and overall prognosis. Additionally, the occurrence, timing, and sequence of these features were analyzed to better understand the natural history of HCM and the potential influence of genetic etiology on disease progression and management.

***Statistical Analyses*:**

SHaRedata through June 2022 were analyzed. Continuous variables were presented as mean ± SD if normally distributed or as median (interquartile range, IQR) if deviating substantially from the normal distribution as evaluated by quantile-quantile plots. Categorical variables are presented as counts and percentages. Between group comparisons were evaluated statistically using Welch’s t-test, Wilcoxon rank sum test, Fisher’s exact test or Chi-square tests as appropriate.

Logistic regression was used to calculate odds ratios (OR) and 95% confidence intervals (CI) for comparing the clinical characteristics of patients with sarcomeric and non-sarcomeric HCM. For the analysis of cardiac function and remodeling, we report results from both simple linear regression and multivariable linear regression to adjust for age, sex, and body surface area. Linear mixed-effects regression was performed when investigating results from cardiopulmonary exercise testing.

We computed the relative risk of cardiovascular comorbidities and adverse events in patients with non-sarcomeric and sarcomeric HCM. The incidence of cardiovascular outcomes during follow-up was compared using the Kaplan-Meier method or the cumulative incidence function using log-rank tests to determine statistical significance. In addition, age-specific incidence rates were reported according to age quintiles (<30, 31-45, 46-55, 56-65 and >65 years of age). Age-standardized incidence rates were calculated, and Cox proportional hazards models were used to estimate hazard ratios (HR) and 95% CI, adjusting for potential confounders. Age-specific and age-standardized rates were compared by computing a standardized incidence ratio and the reference age was set to be the age-distribution of the combined cohort at the time of study inclusion.

We assessed the clinical course of HCM over time by examining the relative timing of developing LV obstruction, atrial fibrillation, NYHA class III-IV symptoms, LV systolic dysfunction, the composite VA outcome, stroke, cardiac transplantation, LVAD implantation, and death. We used Cox proportional hazards modeling with age as the time-scale with delayed entry (i.e., left-truncated at the time of the first SHaRe visit). Time-varying covariates (exposures) included obesity, hypertension, LV obstruction, atrial fibrillation, onset of NYHA class III-IV symptoms, LV systolic dysfunction, and the composite ventricular arrhythmia outcome. We adjusted for sex and age at diagnosis with HCM and applied Bonferroni correction for multiple testing.

We also investigated potential interactions between these exposures and genetic status (non-sarcomeric versus sarcomeric HCM) for all outcomes. In cases with a significant interaction we have reported the combined effect of the exposure and genetic status on developing the outcome of interest.

A p-value of <0.05 was considered significant. Statistical analyses were conducted using R version 4.1.1 (R Foundation for statistical computing, Vienna, Austria), and the packages *tidyverse*, *broom*, *ggtext*, *scico*, *survival*, *survMiner*, *epiR*, *epitools*, *gt*, *gtsummary*, *patchwork* and *janitor*. Due to patient privacy concerns, the data that support the findings of this study are not publicly available. The code for statistical analysis and creating figures can be found online7.

**RESULTS:**

This study focused on 5,454 patients (38% female, 89% probands) diagnosed with HCM in whom genetic testing had been performed and either identified a LP/P genetic sarcomere variant (sarcomeric HCM, n= 2715) or was negative (non-sarcomeric HCM, n= 2739). Median age at time of HCM diagnosis was 46.1 years (IQR: 30.4 to 58.3) and age at initial visit to a SHaRe site was 50 years (IQR: 35 to 62). At initial SHaRe visit, hypertension was prevalent or had been diagnosed in 29%, atrial fibrillation in 13%, stroke in 2.8%; 10% had a history of syncope and 2.1% had resuscitated cardiac arrest.

**Clinical characteristics of Sarcomeric versus Non-sarcomeric HCM**

Clinical characteristics stratified by genetic subgroup are presented in **Table 1**. Patients with sarcomeric HCM were ~13 years younger at diagnosis (median age 36.7 versus 49.6 years, p<0.001) and had higher European Society of Cardiology (ESC) 5-year SCD risk scores (median 2.5% versus 1.9%, p <0.001). Patients with non-sarcomeric HCM were less likely to be female (OR 0.71 [CI, 0.64-0.80]), white (OR 0.71 [CI, 0.64-0.80]), or have a family history of sudden cardiac death (OR 0.36 [CI, 0.30-0.42]), but more likely to report significant symptoms at baseline (New York Heart Association [NYHA] functional class III-IV).

**Figure 1** depicts the relative risk of cardiovascular co-morbidities and adverse events in patients with non-sarcomeric versus sarcomeric HCM. Overall, patients with non-sarcomeric HCM were more likely to have classic cardiovascular co-morbidities (RR for hypertension 1.83 [CI 1.72-1.97]; RR for obesity 1.46 [CI 1.34-1.60]) and obstructive physiology (gradient >30 mmHg; RR 1.51 [CI 1.42-1.60]). Patients with sarcomeric HCM were more likely to experience cardiac arrhythmias (RR for atrial fibrillation 1.12 [CI 1.02-1.22] and RR for composite VA 1.92 [CI 1.60-2.31]) and left ventricular systolic dysfunction (RR 1.72 [CI 1.45-2.04]).

**Cardiac Structure and Function in Sarcomeric versus Non-sarcomeric HCM**

Measures of cardiac function and remodeling were relatively similar between the two groups. However, patients with non-sarcomeric HCM had slightly higher LV ejection fraction (+1.6 %-points [CI: 1.0 to 2.1], p <0.001; **Table 1** and higher LV gradients (+19.7 mmHg [CI: 17.4 to 22.0], p <0.001). Patients with sarcomeric HCM had greater maximal LV wall thickness, both in absolute terms (+1.3 mm [CI: 0.9 to 1.6], p <0.001) and when converted to BSA-adjusted z-scores (+1.5 z [CI: 1.1 to 1.9], p <0.001).

We investigated the peak oxygen uptake from 2895 cardiopulmonary exercise tests, performed in 1537 patients (50% with sarcomeric HCM) and found that carrying a sarcomere variant was associated with a lower peak oxygen uptake (unadjusted -0.6 ml O2/kg/min [CI: -1.3 to 0.1], p = 0.083 ; adjusted for age, sex, BMI, presence of atrial fibrillation and effort [highest achieved respiratory exchange ratio] -1.9 ml O2/kg/min [CI: -2.7 to -1.1], p <0.001). For further information on clinical characteristics, see **Table 1**.

**Incident events during longitudinal follow up**

We evaluated the incidence of LV obstruction, atrial fibrillation, the composite ventricular arrhythmia outcome and LV systolic dysfunction in patients without these outcomes at baseline. In this analysis, we found patients with non-sarcomeric HCM had higher cumulative and age-specific incidences of LV obstruction (**Supplements**). Overall, having non-sarcomeric HCM was associated with an aHR of 1.59 (CI: 1.32-1.92) for obstructive physiology (adjusted for age at HCM diagnosis, sex, obesity, presence of hypertension and being the family proband).

In contrast, sarcomeric HCM was associated with a higher incidence of both atrial fibrillation, ventricular arrhythmias and LV systolic dysfunction (Supplements). For atrial fibrillation the biggest relative differences in age-specific incidence was observed earlier in life, and sarcomeric HCM was associated with an aHR of 1.41 (CI: 1.18 to 1.67, p=0.0001) for developing atrial fibrillation (adjusted for age, obesity and hypertension). For the composite ventricular arrhythmia and the LV systolic dysfunction outcomes, the biggest relative difference in the age-specific incidences of the outcomes were observed late in life with an overall age-standardized incidence ratio of 1.35 (CI: 1.15 to 1.59, p <0.001) for ventricular arrhythmias and 1.33 (CI: 1.17 to 1.50, p <0.001) for LV systolic dysfunction in sarcomeric HCM.

To evaluate the longitudinal course of HCM from time of birth, we evaluated the timing of onset of 6 adverse outcomes associated with HCM: atrial fibrillation, New York Heart Association [NYHA] class III/IV symptoms, LV systolic dysfunction (LVEF<50%), composite ventricular arrhythmias, cardiac transplantation, and death. Results from this analysis are summarized in **Figure 2**, which shows the distribution of events according to age. Consistent with a younger age at diagnosis of HCM, the age-distribution of investigated outcomes skewed earlier in life for patients with sarcomeric HCM. In addition, we observed a sharper peak in the distribution of age at occurrence of these outcomes in patients with non-sarcomeric HCM, mostly centered around the time of diagnosis of HCM. This contrasts with a wider distribution of incident events in sarcomeric HCM; spread over most of adulthood (**Figure 2**).

**Temporal patterns of cardiovascular events and genetic modifiers**

Our next objective was to evaluate the co-occurrence and temporal pattern of cardiovascular features, and if these effects were modified by genetic status. To do this, we performed Cox proportional hazards modelling, including time-varying effects of six key exposures on eight cardiovascular outcomes (adjusted for sex and corrected for multiple testing) and tested for interaction with genetic status.

In this analysis, we found significant temporal associations between 20 exposure-outcome pairs (**Figure 3)**. Obesity was associated with a higher rate of obstructive physiology (HR 1.78 [CI 1.56-2.02]), atrial fibrillation (HR 1.54 [CI 1.32-1.80]) and NYHA class III-IV symptoms (HR 1.92 [CI 1.62-2.27]). Hypertension showed an association with incident LV obstruction (HR 1.40 [CI 1.22-1.61]), while obstruction was associated with incident atrial fibrillation (HR 1.74 [CI 1.50-2.03]) and NYHA class III-IV symptoms (2.13 [CI 1.80-2.51]). Atrial fibrillation was found to have a consistent association with incident heart failure outcomes (HR 2.03 for NYHA III-IV symptoms, HR 2.76 for LVSD, and 7.6 for cardiac transplantation), ventricular arrhythmias (HR 3.13 [CI: 2.34-4.2]), stroke (HR 2.27 [CI: 1.66-3.12]) and death (HR 1.95 [CI: 1.63-2.33]). LV systolic dysfunction associated with incident NYHA class III-IV symptoms (HR 2.13 [CI 1.65-2.80]), ventricular arrhythmias (HR 3.82 [CI 2.73-5.3]), cardiac transplantation (HR 37 [CI: 25-56]) and death (HR 3.80 [CI 3.09-4.7],). Finally, ventricular arrhythmias were associated with incident atrial fibrillation (HR 1.81 [CI 1.39-2.36]), LV systolic dysfunction (HR 3.84 [CI 3.00-4.9]), cardiac transplantation (HR 7.4 [CI 4.9-11]) and death (HR 5.6 [CI 4.6-6.9]).

In interaction analysis, we found that genetic status modified the effect of 12 of the 20 exposure outcome pairs. In 10 of these pairs a larger additive effect was observed in sarcomeric HCM.

**Figure 4** illustrates the combined effect of the exposures and genetic status on various HCM outcomes. The most significant finding was the interaction between genetic status and the disease-modifying effect of atrial fibrillation. A significantly larger additive effect of atrial fibrillation was observed in sarcomeric HCM on the development of NYHA class III-IV symptoms, LV systolic dysfunction, ventricular arrhythmia and death. The largest interaction effects were found for developing LV systolic dysfunction (effect ratio 2.04 [CI 1.47-2.84]) and ventricular arrhythmias (effect ratio 1.79 [CI 1.14-2.81]).

In contrast, for patients with non-sarcomeric HCM, we found a larger additive effect of both obesity (effect ratio 2.11 [CI 1.69-2.62]) and hypertension (effect ratio 2.65 [CI 2.14-3.30]) on developing LV obstruction was found in non-sarcomeric HCM. In sarcomeric HCM, a larger effect of obesity (effect ratio 1.36 [CI 1.05-1.75)] and LV obstruction (effect ratio 1.63 [CI 1.31-2.02]) for developing atrial fibrillation was observed.

Lastly, we noted an effect modification of LV systolic dysfunction on the risk of developing NYHA class III-IV symptoms (effect ratio 3.05 [CI 1.62-5.74]) and death (effect ratio 1.85 [CI 1.24-2.75]) and on ventricular arrhythmias leading to LV systolic dysfunction (effect ratio 1.72 [CI 1.00-2.95]) or death (effect ratio 1.51 [CI 1.05-2.18]). These interactions showed larger additive effects in patients with sarcomeric HCM.

**Mortality in sarcomeric and non-sarcomeric HCM**

Finally, we investigated the timing and causes of death in patients with sarcomeric and non-sarcomeric HCM. At the end of follow-up, 541 (9.9%) patients had died, with similar all-cause mortality in patients with sarcomeric and non-sarcomeric HCM (10% and 9.5% respectively). The mean age at time of death was lower (63 versus 70 years, p <0.0001), and the standardized incidence ratio for all-cause mortality (SIR 1.27 [CI: 1.13 to 1.43]) and cardiovascular death (SIR 1.90 [CI: 1.61 to 2.23) was higher among patients with sarcomeric HCM . Additionally, patients with sarcomeric HCM had a higher likelihood of dying from sudden cardiac death (21 versus 11% of deaths) and heart failure (27 versus 9.2% of deaths). Overall, having sarcomeric HCM was associated with an odds ratio of 2.70 (CI: 1.94 to 3.82, p<0.0001) of dying of either heart failure or sudden cardiac death. A summary of the causes of death in our cohort can be seen in **Table 2**. Next, we sought to investigate the cumulative incidence of HCM-related death (heart failure, stroke or SCD), from time of inclusion in SHaRe and the age-specific incidence of HCM-related death in patients with sarcomeric and non-sarcomeric HCM. Results from this analysis can be seen in **Figure 4**, which shows a higher cumulative incidence of HCM-related death during follow-up (corresponding to a hazard ratio of 1.69 [CI: 1.22 to 2.35, p =0.002] in Cox modelling), and a significantly higher age-specific incidence in patients older than 45 years of age, with an overall standardized incidence ratio of 2.3 (CI: 1.9 to 2.7) for HCM-related death in patients with sarcomeric HCM.

**DISCUSSION:**

In this study we provide a comprehensive description of the cardiac phenotypes and clinical outcomes in sarcomeric and non-sarcomeric HCM. Notably, sarcomeric HCM was characterized by a more severe phenotype, with patients diagnosed at a younger age, exhibiting greater LVH, and having a higher burden of cardiac arrhythmias and severe heart failure. Furthermore, the HCM-related mortality-rate was twice that of non-sarcomeric HCM.

Our findings also highlight strong temporal associations between various cardiovascular exposures and HCM outcomes. Crucially, the genetic status of HCM patients significantly augmented the impact of cardiovascular features on HCM outcomes, (mostly) with larger additive effects observed in patients with sarcomeric HCM. These findings offer valuable insights into the clinical course of these two major subtypes of HCM and have potential implications regarding future risk stratification and management.

**Cardiac Function and Remodeling in Sarcomeric versus Non-sarcomeric HCM**

Clinical characteristics and objective measures of cardiac function and remodeling have been characterized in prior genotype-phenotype studies. These studies have reported differences in sex, age at diagnosis, presence of co-morbidities, LV wall thickness and LV gradient, consistent with those reported here.3,8–10 We provide new information regarding differences in cardiopulmonary exercise testing. Overall, patients had a mild to moderate reduction in exercise capacity. When adjusting for age, sex, body-size and effort, 11,12 patients with sarcomeric HCM had a 10% lower exercise capacity (maximum oxygen uptake) compared to patients with non-sarcomeric HCM. This could suggest that while the overall functional limitation might appear similar between these two groups, inherent biological differences lead to a differential impact on the ability to respond to the increased demands during physical exertion and could contribute to more pronounced exercise limitation in sarcomeric HCM.

**Patients with Non-sarcomeric HCM Have a Higher Burden of Comorbidities**

Consistent with prior studies, we observed that patients with non-sarcomeric HCM were more likely to have classic cardiovascular comorbidities and an obstructive phenotype.3,8,9,19 However, we add to this knowledge base by providing detailed information on the timing and downstream effect of LV obstruction. We found that the age-specific incidence of LV obstruction in non-sarcomeric HCM to be at least 40% higher than in sarcomeric HCM across all examined age-groups. Overall, the age-standardized incidence rate was twice as high in non-sarcomeric HCM. We confirm that obesity is an independent risk factor for developing obstructive physiology, with an 80% higher rate of obstruction in obese patients and a larger effect in patients with non-sarcomeric HCM.20 Notably, while LV obstruction has previously been associated with an higher risk of ventricular arrhythmias, stroke and death, 21 we did not find LV obstruction to be linked to these outcome after adjustment for age and sex.

Hypertension and specifically elevated diastolic blood pressure has been identified as an important exposure leading to HCM in patients with non-sarcomeric disease. 22,23 In accordance with this, the prevalence of hypertension was almost twice as high in non-sarcomeric HCM. However, the impact of hypertension on progression of HCM has not been investigated previously. In this study, hypertension was associated with developing LV obstruction but no significant associations with other adverse cardiovascular outcomes in time-to-event analysis was found after adjusting for age and sex.

**Adverse Cardiovascular Outcomes and HCM-Related Mortality are Higher in Sarcomeric HCM**

Patients with sarcomeric HCM had a higher prevalence of atrial and ventricular arrhythmias and LV systolic dysfunction. Overall, the age-standardized incidence rates were approximately 33% higher in patients with sarcomeric HCM for both atrial fibrillation, ventricular arrhythmias and LVSD. Notably, both atrial fibrillation and LV systolic dysfunction were important precursors of adverse cardiovascular outcomes, and had a larger disease modifying effect in patients with sarcomeric HCM. This suggests that healthcare providers should pay particular attention to these outcomes in patients with sarcomeric HCM, both since they are amenable to medical intervention but also since they suggest a poorer long-term prognosis24,25.

The cumulative incidence of the composite ventricular arrhythmia outcome was higher in sarcomeric HCM during follow-up. Investigation of age-specific incidence rates revealed that the largest relative difference in incidence was observed in patients older than 65.

Finally, patients with sarcomeric HCM had an HCM-related mortality rate double that of non-sarcomeric HCM. Age-specific analysis revealed that HCM-related mortality diverges in the two groups from age 45 onwards. The largest relative difference in HCM-related mortality in patients between the age of 46 and 55, where the rate is 3.7 times higher in patients with sarcomeric HCM.

**Clinical Implications**

The findings from this study have important implications for clinical practice and future research in HCM. Non-sarcomeric HCM was characterized by a higher burden of cardiovascular risk factors and LV obstruction, and these patients may benefit from aggressive management targeting hypertension control and risk factor modification. On the other hand, patients with sarcomeric HCM were more likely to die of HCM-related causes, progress to LV systolic dysfunction and experience cardiac arrhythmias.

Patients with sarcomeric HCM, may benefit from more intensive screening for and surveillance of ventricular and atrial arrhythmias and LV dysfunction, particularly given the adverse nature of these outcomes.12,24,25 Current risk stratification algorithms for sudden cardiac death in HCM do not include genetic information26–28. However, in this study carrying a LP/P genetic variant in a sarcomere gene was associated with a standardized incidence ratio of 1.35 for a composite ventricular arrhythmia outcome, and notably with the highest relative and absolute difference in elderly patients (>65 years). Furthermore, LV systolic dysfunction was also identified to be a risk factor for ventricular arrhythmias with a HR> 2 in both sarcomeric and non-sarcomeric HCM. These findings suggest that implementing information regarding genetic substrate and LV ejection fraction into future models could improve model performance and better guide management decisions regarding primary prevention ICD. Future research should aim to further investigate the underlying mechanisms contributing to the observed differences in disease progression and outcomes between patients with sarcomeric and non-sarcomeric HCM. Advancements in comprehensive genetic profiling and comprehensive phenotyping may provide further insights into the complex interplay between genetic variants, clinical characteristics, and disease progression in HCM.

**Limitations**

Several limitations should be acknowledged in this study. First, our sample was limited to patients followed at high-volume referral centers, and our cohort primarily consists of probands and individuals with Caucasian ancestry and does not fully represent the general population of patients with HCM. Second, the study had a pragmatic, real-world, partially retrospective observational design, and therefore, is subject to a potential selection and information bias. Third, although we attempted to control for potential confounders through various adjustments, there may be residual confounding that could impact the results of the study. Fourth, in time-to-event analysis we chose to use age (left-truncated at time of first SHaRe visit) as the time-scale. Using standard follow-up from time of first visit as the time-scale would yield different results in assessing associations between different exposures and downstream outcomes. Finally, we did not have comprehensive data on the use of guideline-directed medical therapy and the potential impact of drugs on cardiovascular co-morbidities or occurrence of outcomes could not be evaluated.

**Conclusion**

In conclusion, our study provides insights into the clinical characteristics and natural history in patients with sarcomeric and non-sarcomeric HCM, contributing to our understanding of the heterogeneity within HCM. We identified distinct differences in clinical characteristics, temporal progression, and outcomes which underscore the importance of genetic characterization in guiding risk stratification, surveillance, and management strategies. Continued research in this field will further refine our understanding of HCM pathophysiology and pave the way for personalized approaches to patient care.

**ACKNOWLEDGEMENTS:**

The authors are grateful for the dedicated work of the site data managers. The authors express deep gratitude to the patients and patient families who live with HCM.

**FUNDING SOURCES:**

SHaRe receives unrestricted research support from Bristol Myers Squib, Pfizer, and Cytokinetics. CSem is the recipient of a National Health and Medical Research Council (NHMRC) Practitioner Fellowship (#1154992). JSW is supported by the Sir Jules Thorn Charitable Trust [21JTA], Medical Research Council (UK), British Heart Foundation [RE/18/4/34215], the National Institute for Health and Care Research (NIHR) Imperial College Biomedical Research Centre, and the NIHR Royal Brompton Cardiovascular Biomedical Research Unit. CRV was supported by grants from The Research Foundations at Rigshospitalet, Knud Højgaards Fond and Reinholdt W. Jorck og Hustrus Fond

**CONFLICT OF INTEREST AND DISCLOSURES:**

CRV, JCS, TDR and CSEM declare no relevant disclosures or competing interests.

CYH is a consultant for and receives research funding from Bristol Myers Squib, Pfizer, Cytokinetics, Tenaya, and Biomarin. VNP receives research funding from BioMarin and consults for Nuevocor and Viz.ai. NKL is a consultant for Bristol Myers Squibb, Pfizer, Cytokinetics, Tenaya and Sarepta and receives research funding from Pfizer. SS isa consultant for Bristol Myers Squibb and Cytokinetics. MM is a consultant for Bristol Myers Squibb and Cytokinetics. JSW has consulted for MyoKardia (now Bristol Myers Squibb), Foresite Labs, and Pfizer. DJA is a consultant for Dinaqor.

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**Table 1:** Clinical characteristics of the cohort at time of initial SHaRe visit.

| Characteristic | SARCOMERIC HCM N= 2,715 | NON-SARCOMERIC HCM  N = 2,739 | p-value |
| --- | --- | --- | --- |
| **Demographic information** |  |  |  |
| Female | 1,144 (42%) | 939 (34%) | <0.001 |
| Age at HCM diagnosis | 37.5 (22.5 to 50.5) | 53.2 (41.2 to 63.0) | <0.001 |
| Age at initial visit to a SHaRe site | 43 (28, 55) | 56 (45, 66) | <0.001 |
| Family proband | 2,154 (80%) | 2,627 (98%) | <0.001 |
| **Race** |  |  | <0.001 |
| White | 2,356 (87%) | 2,227 (81%) |  |
| Black | 72 (2.7%) | 134 (4.9%) |  |
| Asian | 82 (3.0%) | 98 (3.6%) |  |
| Other or Not Reported | 205 (7.6%) | 280 (10%) |  |
| **Clinical findings** |  |  |  |
| Systolic blood pressure | 120 (110 to 130) | 130 (118 to 140) | <0.001 |
| Diastolic blood pressure | 71 (65 to 80) | 76 (70 to 82) | <0.001 |
| Body mass index | 26.3 (23.1 to 30.0) | 28.1 (25.0 to 32.3) | <0.001 |
| Body surface area | 1.92 (1.73 to 2.11) | 2.00 (1.83 to 2.18) | <0.001 |
| **Echocardiography findings** |  |  |  |
| Maximal LV wall thickness | 18.0 (14.5 to 22.0) | 17.0 (14.0 to 20.0) | <0.001 |
| LV internal diameter in diastole | 43 (39 to 48) | 45 (40 to 49) | <0.001 |
| Indexed LV internal diameter in diastole | 22.7 (20.0 to 25.4) | 22.2 (19.8 to 24.9) | 0.001 |
| LV internal diameter in systole | 26 (22 to 30) | 27 (22 to 31) | <0.001 |
| Indexed LV internal diameter in systole | 13.5 (11.3 to 16.1) | 13.2 (11.2 to 15.4) | 0.003 |
| **Co-morbidities and medical history** |  |  |  |
| Hypertension | 518 (19%) | 1,054 (38%) | <0.001 |
| Atrial fibrillation | 357 (13%) | 357 (13%) | 0.9 |
| Syncope | 282 (10%) | 263 (9.6%) | 0.3 |
| Stroke | 68 (2.5%) | 85 (3.1%) | 0.2 |
| Family history of sudden cardiac death | 486 (18%) | 197 (7.2%) | <0.001 |
| History of cardiac arrest | 70 (2.6%) | 45 (1.6%) | 0.016 |
| New York Heart Association class III-IV | 196 (7.2%) | 244 (8.9%) | 0.022 |
| LV systolic dysfunction (LVEF<50%) | 101 (3.7%) | 48 (1.8%) | <0.001 |
| Severe LV systolic dysfunction (LVEF<35%) | 22 (0.8%) | 10 (0.4%) | 0.031 |
| **ESC risk score** |  |  | <0.001 |
| High (>6% per 5 years) | 172 (11%) | 76 (4.8%) |  |
| Moderate (4-6% per 5 years) | 215 (13%) | 122 (7.8%) |  |
| Low (<4% per 5 years) | 1,216 (76%) | 1,374 (87%) |  |
| Unknown | 1,112 | 1,167 |  |
| n (%); Median (25% to 75%) | | | |
|  | | | |

| **Table 2:** All-cause and cause-specific mortality in sarcomeric and non-sarcomeric hypertrophic cardiomyopathy | | | |
| --- | --- | --- | --- |
| **CHARACTERISTIC** | **SARC(+)**, N = 2,715 | **SARC(-)**, N = 2,739 | **P-VALUE** |
| All-cause mortality | 281 (10%) | 260 (9.5%) | 0.3 |
| Causes of death |  |  | <0.001 |
| *Non-cardiovascular death* | 93 (33%) | 147 (57%) |  |
| *Heart failure* | 77 (27%) | 24 (9.2%) |  |
| *Sudden cardiac death* | 58 (21%) | 28 (11%) |  |
| *Not Recorded* | 25 (8.9%) | 22 (8.5%) |  |
| *Other cardiovascular death* | 21 (7.5%) | 25 (9.6%) |  |
| *Malignancy* | 7 (2.5%) | 14 (5.4%) |  |

**Figure 1:**

**Legend:** Relative risk of the occurrence of 15 cardiovascular features (y-axis) in patients with sarcomeric versus non-sarcomeric hypertrophic cardiomyopathy (HCM). The relative risk ratio is given on the x-axis and the filled dots denote the point-estimate of the relative risk while the error-bars give the confidence intervals. On the right the overall prevalence of each feature is given separately for each group.

**Figure 2**



**Legend:** Density plots, showing the distribution of age (x-axis) at time of occurrence of each of six adverse outcomes associated with hypertrophic cardiomyopathy. Patients have been stratified into two groups according to whether they had sarcomeric (pink) or non-sarcomeric HCM (blue). The y-axis gives the raw number of patients associated with each outcome in a 5 year-period. The dots denote the median age of HCM diagnosis in the two groups.

**Figure 3:**



**Legend:** Heatmap showing the time-adjusted hazard ratios of being diagnosed with one of 8 cardiovascular features (x-axis) predicated on of the presence of one of the 7 pre-defined exposures (y-axis). Hazard ratios larger than 1 are shown with Bonferroni corrected 95% confidence intervals if Bonferroni corrected p <0.05 (i.e. uncorrected p <0.0009). Colors indicate the level of statistical significance. Hazard ratios are adjusted for sex and if a significant interaction was observed stratified analysis was performed.

**Figure 4:**



the significance of the association with darker red indicating a lower p-value.

**Figure 5**

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**Legend:** Incidence of hypertrophic cardiomyopathy (HCM) related mortality in patients who are genotype-positive (pink) versus -negative (blue) for sarcomere variants. Panel **A.** Cumulative incidence since first SHaRe evaluation, including numbers at risk by year. Panel **B.** Age-specific incidence rates, including total person-years at risk in each age-group. The age-standardized incidence rate (ASI) has been added as the final group. The standardized incidence ratio (SIR) has been added for each age-group at the bottom of the plot. HCM-related mortality includes sudden cardiovascular death, heart failure related death, and death due to stroke.

**SUPPLEMENTAL MATERIAL**

**Supplemental results**

*LV obstruction*

During 17,154 person-years of follow-up in 2456 patients, the cumulative incidence of LV obstruction was almost twice as high in patients with non-sarcomeric HCM versus sarcomeric HCM (**Supplementary Figure 1A**). Age-specific incidences of LV obstruction was higher in patients with non-sarcomeric HCM across all age-groups (**Supplementary Figure 1B**). Since patients with non-sarcomeric HCM had a higher burden of cardiovascular risk factors, we performed Cox regression adjusted for age at HCM diagnosis, sex, presence of hypertension or obesity and being a proband. Patients with non-sarcomeric HCM had an adjusted HR of 1.59 (CI: 1.32-1.92) for the presence of obstructive physiology.

*Cardiac arrhythmias*

The incidence of atrial fibrillation was evaluated over 29,923 person-years of follow-up in 4270 patients without atrial fibrillation at baseline. The cumulative incidence of atrial fibrillation was similar in non-sarcomeric and sarcomeric HCM during follow-up (log-rank p =0.078) (**Figure 2a**). To account, for factors associated with developing atrial fibrillation, we performed multiple Cox proportional hazards models adjusting for age, obesity and hypertension. In this analysis, having sarcomeric HCM was associated with a HR of 1.41 (CI: 1.18 to 1.67, p=0.0001) for developing atrial fibrillation. Next, we calculated the age-specific incidence of atrial fibrillation and found this to be significantly higher in patients with sarcomeric HCM across all evaluated age-groups (**Figure 2c**), with an age-standardized incidence ratio of 1.34 (CI: 1.21 to 1.47, p <0.0001) for atrial fibrillation in sarcomeric HCM (27 [CI 24-30] versus 21 [CI: 19-24] per 1000 person-years).

The incidence of the composite ventricular arrhythmia outcome was evaluated over 35,703 person-years of follow-up in 4726 patients, without ventricular arrhythmias at baseline. The cumulative incidence was higher in sarcomeric HCM during follow-up (p =0.004) (**Figure 2b**). The age-specific incidence of the composite ventricular arrhythmia outcome was numerically higher in patients with sarcomeric HCM, across all evaluated age-groups (**Figure 2d**), with the most pronounced difference in patients older than 65 years. Overall, the age-standardized incidence rate in sarcomeric and non-sarcomeric HCM was 7.6 (CI 6.4-8.9) versus 5.4 (CI: 4.1-7.0) per 1000 person-years. This corresponds to a standardized incidence ratio of 1.35 (CI: 1.15 to 1.59, p <0.001) for ventricular arrhythmias in sarcomeric HCM.

*Left ventricular systolic dysfunction*

The incidence of LV systolic dysfunction was evaluated over 38,410 person-years of follow-up in 4939 patients with LVEF>50% at baseline. The cumulative incidence of LV systolic dysfunction was similar during follow-up (p =0.120) (**Supplementary Figure 2a**). However, the age-specific incidence rates of LV systolic dysfunction were numerically higher in patients with sarcomeric HCM (**Supplementary Figure 2b**) with an age-standardized incidence rate of LV systolic dysfunction of 14 (CI 12-16) versus 10 (CI: 8-12) per 1000 person-years. This corresponds to a standardized incidence ratio of 1.33 (CI: 1.17 to 1.50, p <0.001) in sarcomeric HCM.

**Supplementary Figure 1**



**Legend:** Incidence of obstruction in patients who are genotype-positive versus -negative for sarcomere variants. **A.** Cumulative incidence of obstruction since first SHaRe evaluation, including numbers at risk by year. **B.** Age-specific incidence rates of obstruction, including total person-years at risk in each age-group.

**Supplememtary Figure 2**

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**Legend:** Incidence of arrhythmias in sarcomeric versus non-sarcomeric HCM, excluding patients diagnosed with these events prior to or at initial SHaRe visit. Panel **A** shows the cumulative incidence of atrial fibrillation during follow-up, including numbers at risk, in sarcomeric (Sarc+, pink) and non-sarcomeric (Sarc-, blue) HCM. Overall, the cumulative incidence is similar between the two groups, with a trend towards a higher rate in non-sarcomeric HCM. Panel **B** shows the age-specific incidence rates of atrial fibrillation during follow-up, including accumulated years at risk, in the two groups. Incidence rates are numerically higher for patients with sarcomeric HCM in all investigated groups, reaching statistical significance in the three youngest age-groups, and with a highly significant increased age-standardized incidence (ASI) in sarcomeric HCM (shown in grey area). Panel **C**, shows the cumulative incidence of the composite ventricular arrhythmia outcome since first SHaRe evaluation, in sarcomeric and non-sarcomeric HCM, showing that there is a higher cumulative incidence in sarcomeric HCM. Panel **D.** Shows the age-specific incidence rate of the composite ventricular arrhythmia outcome, including total person-years at risk in each age-group. The age-standardized incidence rate has been added as the final group. Overall, the largest difference in incidence of this outcome occurs in the group of patients older than 65 years.

**Supplementary Figure 3**



**Legend:** Incidence of left ventricular systolic dysfunction in patients who are genotype-positive versus -negative for sarcomere variants. **A.** Cumulative incidence of obstruction since first SHaRe evaluation, including numbers at risk by year. **B.** Age-specific incidence rates of obstruction, including total person-years at risk in each age-group.

**Supplementary Figure 4**



**Legend:** Incidence of cardiovascular mortality in patients who are genotype-positive (pink) versus -negative (blue) for sarcomere variants. Panel **A.** Cumulative incidence since first SHaRe evaluation, including numbers at risk by year. Panel **B.** Age-specific incidence rates, including total person-years at risk in each age-group. The age-standardized incidence rate (ASI) has been added as the final group. The standardized incidence ratio (SIR) has been added for each age-group at the bottom of the plot.