

Differing prognostic value of pulse pressure in patients with heart failure with reduced or preserved ejection fraction: results from the MAGGIC individual patient meta-analysis

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Received 3 August 2013; revised 14 October 2014; accepted 27 November 2014; online publish-ahead-of-print 23 January 2015

Aims

Low pulse pressure is a marker of adverse outcome in patients with heart failure (HF) and reduced ejection fraction (HF-REF) but the prognostic value of pulse pressure in patients with HF and preserved ejection fraction (HF-PEF) is unknown. We examined the prognostic value of pulse pressure in patients with HF-PEF [ejection fraction (EF) \geq 50%] and HF-REF.

Methods and results

Data from 22 HF studies were examined. Preserved left ventricular ejection fraction (LVEF) was defined as LVEF \geq 50%. All-cause mortality at 3 years was evaluated in 27 046 patients: 22 038 with HF-REF (4980 deaths) and 5008 with HF-PEF (828 deaths). Pulse pressure was analysed in quintiles in a multivariable model adjusted for the previously reported Meta-Analysis Global Group in Chronic Heart Failure prognostic variables. Heart failure and reduced ejection fraction patients in the lowest pulse pressure quintile had the highest crude and adjusted mortality risk (adjusted hazard ratio 1.68, 95% confidence interval 1.53–1.84) compared with all other pulse pressure groups. For patients with HF-PEF, higher pulse pressure was associated with the highest crude mortality, a gradient that was eliminated after adjustment for other prognostic variables.

Conclusion

Lower pulse pressure (especially $<$ 53 mmHg) was an independent predictor of mortality in patients with HF-REF, particularly in those with an LVEF $<$ 30% and systolic blood pressure $<$ 140 mmHg. Overall, this relationship between pulse pressure and outcome was not consistently observed among patients with HF-PEF.

Keywords

Pulse pressure • Heart failure • Reduced ejection fraction • Preserved ejection fraction • Mortality

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Introduction

Elevated pulse pressure is an established marker of adverse outcome in healthy individuals as well as patients with certain types of cardiovascular disease, especially those with hypertension.^{1–3} More recently, lower pulse pressure has emerged as an independent predictor of mortality in patients with heart failure (HF).^{4–9} This has been demonstrated in patients across the spectrum of symptom severity, and in patients with acute as well as chronic HF. However, studies to date have included only patients with heart failure and reduced left ventricular ejection fraction (HF-REF). Patients with heart failure and preserved left ventricular ejection fraction (HF-PEF) more often have a history of hypertension than patients with HF-REF, and therefore, may be more likely to have an elevated pulse pressure. However, the range of pulse pressures in patients with HF-PEF, compared with HF-REF, is unknown, as is the prognostic importance of pulse pressure in HF-PEF.

We used data from 22 HF studies included in the Meta-Analysis Global Group in Chronic Heart Failure (MAGGIC) to explore these questions.

Methods

Study design

The design and results of the MAGGIC meta-analysis are described elsewhere.¹⁰ Briefly, observational studies and randomized controlled trials of patients with established HF published up to 2008 were identified via online databases using the keywords: prognosis, outcome, HF, left ventricle, and preserved. Studies were included if they enrolled patients with HF, reported outcome (all-cause mortality), and did not use left ventricular ejection fraction (LVEF) as criterion for entry to the study. The University of Auckland Human Subjects Ethics Committee approved the original meta-analysis and the study complied with the Declaration of Helsinki. All patients provided written informed consent to participate in the individual studies.

Of 56 potential studies that were identified, investigators from 31 studies provided data on a pre-defined set of variables including demographics, medical history, medical treatment, symptom status, clinical variables, laboratory variables, and duration of follow-up. All-cause death was the only outcome available. Preserved LVEF was defined as $\geq 50\%$. Blood pressure (BP) measurement was taken over the brachial artery with a standard sphygmomanometer and recorded at the baseline study visit (at an outpatient visit, at randomization, or during hospitalization depending on the study design). Pulse pressure was defined as the difference between systolic and diastolic pressure. The principal outcome was all-cause mortality at 3 years from hospital discharge or baseline study visit.

Statistical analysis

Measurements of systolic and diastolic BP were available for patients in 22 of the 31 studies included in the MAGGIC meta-analysis. This analysis was performed using data from these 22 studies (the full list of MAGGIC studies is contained in Appendix section and those included in this article are identified by *). Pulse pressure results were analysed in quintiles and Cox proportional hazards models were used to estimate the hazard of pulse pressure according to HF-PEF or HF-REF, adjusted for the previously reported MAGGIC prognostic variables: age, gender, ischaemic aetiology, atrial fibrillation (AF), hypertension, and diabetes.

Mortality curves are similarly adjusted for the MAGGIC prognostic variables. To further investigate the relationship with ejection fraction (EF), those in the HF-REF group with a continuous measure of EF were stratified as <30 or $30–49\%$, and the adjusted model was repeated in these groups. To investigate the independent prognostic significance of pulse pressure and systolic BP, the main model was repeated using these as continuous variables. The relationship between pulse pressure and outcome in the presence of systolic blood pressure (SBP) was evaluated with an interaction term for both HF-PEF and HF-REF. Further analyses were performed in both EF groups, stratifying on SBP $<140/\geq 140$ mmHg, using quintiles of pulse pressure. Sensitivity analyses were performed: (i) with New York Heart Association (NYHA) Class (III vs. III/IV), (ii) with medications [angiotensin-converting enzyme (ACE) inhibitor/angiotensin receptor antagonist, digoxin, and spironolactone], (iii) excluding those patients with AF, and (iv) for acute HF vs. chronic HF. A P -value of <0.05 was considered statistically significant. Analyses were performed using SAS v9.2 (SAS Institute, Inc.).

Results

Baseline characteristics according to pulse pressure, overall

The 22 studies included 27 046 patients of whom 22 038 (81.5%) had HF-REF. Complete data for 25 465 patients were available for the multivariable analysis. Overall, the mean (SD) age was 65 (12) years, 71% were male and median [inter-quartile ratio (IQR)] LVEF was 34% (26, 45). Mean (SD) BP was 131 (23)/77 (12) mmHg, resulting in a mean (SD) pulse pressure of 54 (18) mmHg. *Table 1* shows the baseline characteristics of all patients according to quintiles of pulse pressure. There were many differences between patients according to pulse pressure value. Higher pulse pressure was associated with older age, female sex, history of hypertension, history of diabetes mellitus, higher systolic BP, and higher LVEF. These differences were most marked in the highest pulse pressure quintile, compared with the other quintiles. Those with a lower pulse pressure were more likely to be male and younger, to have had a previous myocardial infarction, to have a lower systolic and diastolic BP, reduced LVEF and to be treated with an ACE inhibitor or angiotensin receptor blocker, spironolactone, and digoxin; they were less likely to have a history of diabetes and hypertension (*Table 1*). There was no difference in β -blocker prescribing according to pulse pressure.

Baseline characteristics according to pulse pressure, by left ventricular ejection fraction stratum

Of the 27 046 patients, 5008 (18.5%) patients had HF-PEF. The proportion of patients with HF-PEF increased with the higher quintiles of pulse pressure: for example, 9% of the lowest quintile of pulse pressure had HF-PEF compared with 33% in the highest quintile (*Table 1*). The mean (SD) pulse pressure was 52 (6) and 62 (4) mmHg for patients with HF-REF and HF-PEF, respectively. *Table 2* shows the baseline characteristics according to quintiles of pulse pressure and stratified according to HF-REF or HF-PEF. The differences in baseline characteristics overall, described above, were also apparent within each LVEF stratum.

Table 1 Baseline characteristics according to groups defined by quintiles of pulse pressure

| Pulse pressure (mmHg) | Whole group | ≤39 | 40–49 | 50–55 | 56–68 | ≥69 | P-value (test for trend) |
|--------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------------------|
| n (22 studies) | 25 465 | 4106 | 5957 | 4944 | 5352 | 5106 | <0.001 |
| Age, years (SD) | 65 (12) | 60 (12) | 63 (12) | 65 (11) | 67 (11) | 70 (10) | <0.001 |
| Women (%) | 30 | 21 | 25 | 28 | 32 | 42 | <0.001 |
| Medical history | | | | | | | |
| Hypertension | 47 | 32 | 38 | 44 | 54 | 66 | <0.001 |
| Myocardial infarction | 51 | 53 | 54 | 52 | 51 | 44 | <0.001 |
| Atrial fibrillation | 16 | 15 | 16 | 17 | 17 | 16 | 0.019 |
| Diabetes | 26 | 20 | 22 | 25 | 30 | 33 | <0.001 |
| Ischaemic aetiology | 60 | 59 | 63 | 61 | 61 | 57 | <0.001 |
| Medication | | | | | | | |
| ACEi or ARB | 69 | 76 | 73 | 70 | 65 | 63 | <0.001 |
| β-Blocker | 43 | 43 | 45 | 43 | 43 | 42 | 0.039 |
| Diuretic | 79 | 82 | 79 | 80 | 77 | 80 | 0.009 |
| Spironolactone | 19 | 28 | 21 | 18 | 16 | 14 | <0.001 |
| Digoxin | 45 | 50 | 47 | 46 | 42 | 39 | <0.001 |
| Clinical status | | | | | | | |
| NYHA class (I or II/III or IV) | 60/40 | 54/46 | 62/38 | 61/39 | 61/39 | 61/39 | |
| Heart rate (b.p.m.) | 78 (17) | 80 (17) | 78 (16) | 77 (16) | 77 (16) | 77 (17) | <0.001 |
| SBP (mmHg) | 131 (23) | 106 (12) | 118 (12) | 128 (12) | 128 (12) | 160 (19) | <0.001 |
| DBP (mmHg) | 77 (13) | 75 (11) | 75 (11) | 77 (12) | 77 (12) | 79 (15) | <0.001 |
| Pulse pressure (mmHg) | 54 (17) | 31 (5) | 42 (3) | 51 (2) | 51 (2) | 80 (12) | <0.001 |
| LVEF %, median (IQR) | 34 (26, 45) | 28 (21, 27) | 32 (24, 40) | 34 (26, 44) | 34 (26, 44) | 41 (31, 54) | <0.001 |
| HF-PEF (%) | 19 | 9 | 13 | 17 | 22 | 33 | <0.001 |
| All-cause deaths, n (%) | 5684 (22) | 1071 (26) | 1250 (21) | 1033 (21) | 1130 (21) | 1200 (24) | 0.029 |

Values in parentheses are standard deviations for continuous variables or percentages for discrete variables.

ACEi, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; b.p.m., beats per minute; DBP, diastolic blood pressure; HF-PEF, heart failure with preserved ejection fraction; LVEF, left ventricular ejection fraction; NYHA, New York Heart Association; SBP, systolic blood pressure.

Distribution of pulse pressure by left ventricular ejection fraction stratum

The proportion of patients with a pulse pressure <45 mmHg differed considerably between those with HF-REF and HF-PEF (Table 2). Of the 22 038 patients with HF-REF, 8802 (39.9%) had a pulse pressure <45 mmHg. Of 5008 patients with HF-PEF, 1025 (20.5%) had a pulse pressure <45 mmHg. Conversely, 19.8 and 39.6% of patients with HF-REF and HF-PEF, respectively, had a pulse pressure >65 mmHg.

All-cause mortality

During 3 years follow-up, there were 4980 (23%) and 828 (17%) deaths among patients with HF-REF and HF-PEF, respectively. There was a highly significant interaction between the EF category (reduced/preserved) and the relationship between pulse pressure and mortality ($P < 0.0001$).

In patients with HF-REF, crude mortality was highest in patients in the lowest pulse pressure quintile although mortality differed little across the other quintiles before adjustment for other prognostic factors (Table 2). Mortality in Q1 (lowest) to Q5 (highest pulse pressure) was 27, 21, 23, 22 and 24%, respectively. However, after

adjustment, there was a clear gradient in the risk of death according to pulse pressure quintile with the highest risk in patients with the lowest pulse pressure (Table 3, Figures 1 and 2). Compared with patients in the highest quintile, those in the lowest pulse pressure quintile had a 68% higher adjusted relative risk of death [95% confidence interval (CI) 53–84%].

Analyses that further stratified the HF-REF group into those with EF <30 and 30–49% indicated that the increase in mortality associated with low pulse pressure was particularly prominent among patients with EF <30% (see Supplementary material online, Tables S1 and S2). For the patients with EF <30%, mortality was significantly higher for patients with a pulse pressure <54 mmHg. When analysed as continuous variables, both pulse pressure and systolic BP were independent predictors of mortality (data not shown). However, there was a significant interaction between pulse pressure and systolic BP ($P < 0.0001$), and hence the size and direction of the hazard ratio (HR) for each variable is difficult to interpret. To explore this further, a stratified analysis based on SBP <140/≥140 mmHg was conducted and this showed that patients with both a lower systolic BP (<140 mmHg) and lower pulse pressure seemed to fare particularly badly (Table 5).

Table 2 Baseline characteristics according to groups defined by quintiles of pulse pressure, in patients with reduced and preserved EF

| Pulse pressure (mmHg) | HF-REF | | | | | P-value (test for trend) | HF-PEF | | | | | P-value (test for trend) |
|--------------------------------|-------------|-------------|-------------|-------------|-------------|-----------------------------|-------------|-------------|-------------|-------------|-------------|-----------------------------|
| | ≤39 | 40–45 | 46–53 | 54–64 | ≥64.5 | | ≤45 | 46–55 | 56–64 | 65–78 | 79–164 | |
| n (22 studies) | 3750 | 4455 | 4011 | 4324 | 4118 | | 966 | 978 | 938 | 962 | 963 | |
| Age, years (SD) | 60 (12) | 62 (12) | 65 (11) | 67 (10) | 69 (10) | <0.001 | 65 (13) | 67 (12) | 69 (11) | 71 (10) | 73 (10) | <0.001 |
| Women (%) | 19 | 22 | 25 | 26 | 34 | <0.001 | 39 | 45 | 46 | 53 | 61 | <0.001 |
| Medical history | | | | | | | | | | | | |
| Hypertension | 31 | 34 | 42 | 50 | 60 | <0.001 | 47 | 56 | 64 | 71 | 78 | <0.001 |
| MI | 55 | 57 | 56 | 56 | 51 | <0.001 | 33 | 34 | 30 | 32 | 30 | 0.030 |
| Atrial fibrillation | 14 | 15 | 15 | 16 | 14 | 0.456 | 26 | 26 | 24 | 24 | 17 | <0.001 |
| Diabetes | 20 | 21 | 25 | 30 | 32 | <0.001 | 19 | 23 | 28 | 30 | 35 | <0.001 |
| Ischaemic aetiology | 60 | 65 | 63 | 65 | 62 | <0.001 | 50 | 51 | 48 | 48 | 49 | 0.219 |
| Medication | | | | | | | | | | | | |
| ACEi or ARB | 79 | 78 | 76 | 72 | 70 | <0.001 | 44 | 44 | 44 | 42 | 53 | 0.001 |
| Beta-blocker | 42 | 44 | 44 | 43 | 42 | 0.369 | 46 | 45 | 42 | 43 | 41 | 0.016 |
| Diuretic | 83 | 80 | 81 | 79 | 81 | 0.047 | 72 | 73 | 74 | 75 | 78 | 0.001 |
| Spironolactone | 29 | 22 | 20 | 18 | 14 | <0.001 | 17 | 13 | 14 | 15 | 10 | <0.001 |
| Digoxin | 51 | 50 | 50 | 46 | 44 | <0.001 | 30 | 31 | 28 | 31 | 27 | 0.108 |
| Clinical status | | | | | | | | | | | | |
| NYHA class (I or II/III or IV) | 54/46 | 59/41 | 60/40 | 61/39 | 60/40 | <0.001 | 67/33 | 69/31 | 65/35 | 62/38 | 63/37 | <0.001 |
| Heart rate (b.p.m.) | 80 (17) | 77 (16) | 77 (16) | 77 (16) | 78 (17) | <0.001 | 77 (18) | 76 (17) | 77 (18) | 75 (17) | 77 (20) | <0.001 |
| SBP (mmHg) | 106 (12) | 116 (11) | 126 (12) | 136 (12) | 156 (18) | <0.001 | 115 (14) | 129 (12) | 131 (20) | 150 (13) | 172 (22) | <0.001 |
| DBP (mmHg) | 75 (11) | 75 (11) | 76 (12) | 77 (12) | 79 (14) | <0.001 | 77 (12) | 78 (12) | 79 (13) | 79 (13) | 80 (17) | <0.001 |
| Pulse pressure (mmHg) | 31 (5) | 41 (2) | 50 (1) | 59 (3) | 77 (11) | <0.001 | 38 (6) | 51 (2) | 60 (2) | 70 (3) | 92 (14) | <0.001 |
| LVEF %, median (IQR) | 27 (20, 34) | 30 (23, 37) | 32 (24, 38) | 33 (26, 39) | 34 (27, 41) | <0.001 | 58 (53, 63) | 58 (53, 64) | 59 (54, 64) | 59 (54, 66) | 60 (55, 66) | <0.001 |
| All-cause deaths, n (%) | 1017 (27) | 952 (21) | 919 (23) | 971 (22) | 1007 (24) | 0.046 | 128 (13) | 142 (14) | 153 (16) | 175 (18) | 220 (22) | <0.001 |

In contrast to the patients with HF-REF, crude mortality among patients with HF-PEF was highest in those in the *highest* pulse pressure quintile and there appeared to be a gradient in crude mortality across the other quintiles before adjustment for other prognostic factors (Table 2). Crude mortality in Q1 (lowest) to Q5 (highest pulse pressure) was 13, 14, 16, 18 and 22%, respectively. After adjustment, however, the gradient in risk according to pulse pressure quintile in patients with HF-PEF was largely eliminated (Table 4, Figures 1 and 2). Compared with patients in the highest quintile, those in quintiles 2, 3, and 4 had an adjusted HR of ~1.0. Those in the lowest quintile

had an adjusted HR of 1.16 (95% CI 0.92, 1.45). In a similar manner to the analysis for patients with HF-REF, we explored this further with a stratified analysis based on SBP <140/≥140 mmHg, which showed that there was no significant interaction between the pulse pressure (quintiles) and the BP groups (Table 5).

When NYHA class was included in the model (see Supplementary material online, Tables S3 and S4), higher NYHA class (III/IV) was associated with worse outcome [HF-REF: HR 1.87 (95% CI 1.76, 2.00); HF-PEF HR 1.99 (95% CI 1.69, 2.34)]. In patients with HF-REF, low pulse pressure remained an independent predictor of death even taking account of NYHA class. The relationship between pulse pressure and mortality was not altered when analyses were repeated with the addition of ACE inhibitor/angiotensin receptor antagonist, digoxin, and spironolactone treatment.

When analyses were re-run excluding patients with AF: the results for those with HF-REF were similar to the main analyses (see Supplementary material online, Tables S5 and S6). The results for those with HF-PEF demonstrate that those patients with the lowest pulse pressure quintile were at increased risk (HR for lowest quintile of pulse pressure 1.33, 95% CI 1.02, 1.73).

Table 3 Multivariable model by quintiles of pulse pressure in 20 658 patients with HF-REF—adjusted for the Meta-Analysis Global Group in Chronic Heart Failure variables

| Variable | HR (95% CI) | P-value |
|-------------------------|-------------------|---------|
| Pulse pressure (mmHg) | | |
| ≥ 64.5 | 1 | |
| 54–64 | 1.02 (0.93, 1.11) | 0.749 |
| 46–53 | 1.15 (1.05, 1.26) | 0.003 |
| 40–45 | 1.23 (1.12, 1.35) | <0.001 |
| ≤ 39 | 1.68 (1.53, 1.84) | <0.001 |
| Age (per year increase) | 1.04 (1.03, 1.04) | <0.001 |
| Gender (male) | 1.21 (1.13, 1.29) | <0.001 |
| Atrial fibrillation | 1.21 (1.12, 1.32) | <0.001 |
| Hypertension | 0.99 (0.93, 1.05) | 0.608 |
| Ischaemic aetiology | 1.12 (1.05, 1.19) | 0.001 |
| Diabetes | 1.47 (1.38, 1.56) | <0.001 |

Acute heart failure vs. chronic heart failure

The multivariable models were repeated for patients with acute HF only (see Supplementary material online, Tables S7 and S8). A very similar pattern of findings was apparent although, with the reduced numbers (4746 patients compared with 25 465 for the main models) and power in this subset, mortality was significantly higher only in the lowest pulse pressure quintile in patients with HF-REF. Interestingly, in patients with acute HF-PEF, there was an increased risk with pulse pressure < 56 mmHg, although the lowest quintile group (≤45 mmHg) was of borderline significance (P = 0.049). The multivariable analyses were also performed for patients with

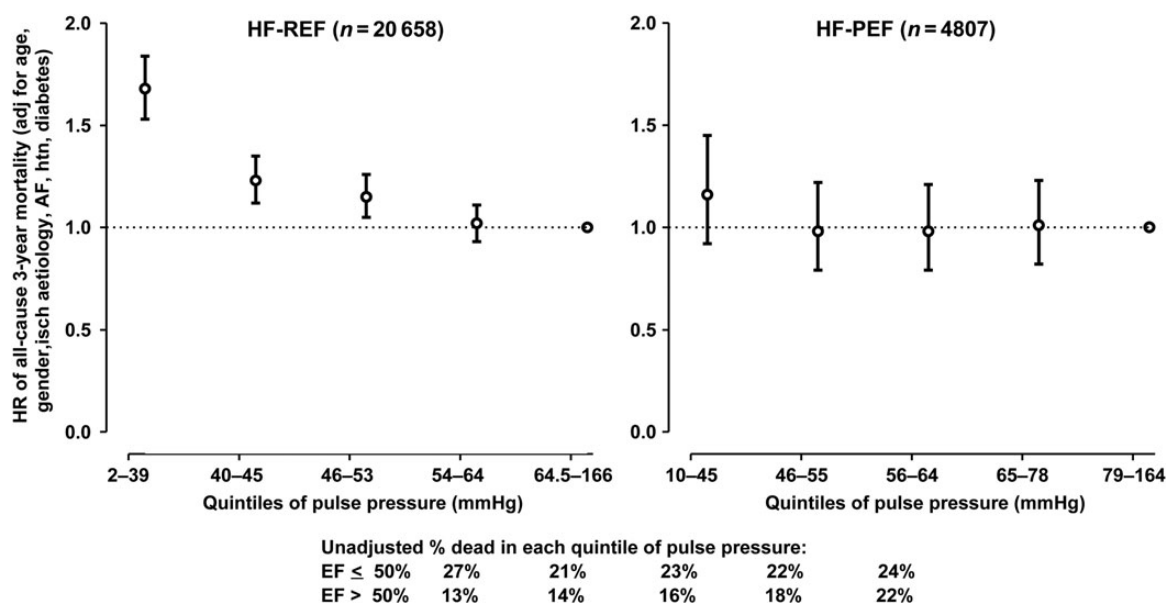


Figure 1 Quintiles of pulse pressure by ejection fraction group. Adjusted for age, gender, hypertension, atrial fibrillation, ischaemic aetiology, and diabetes.

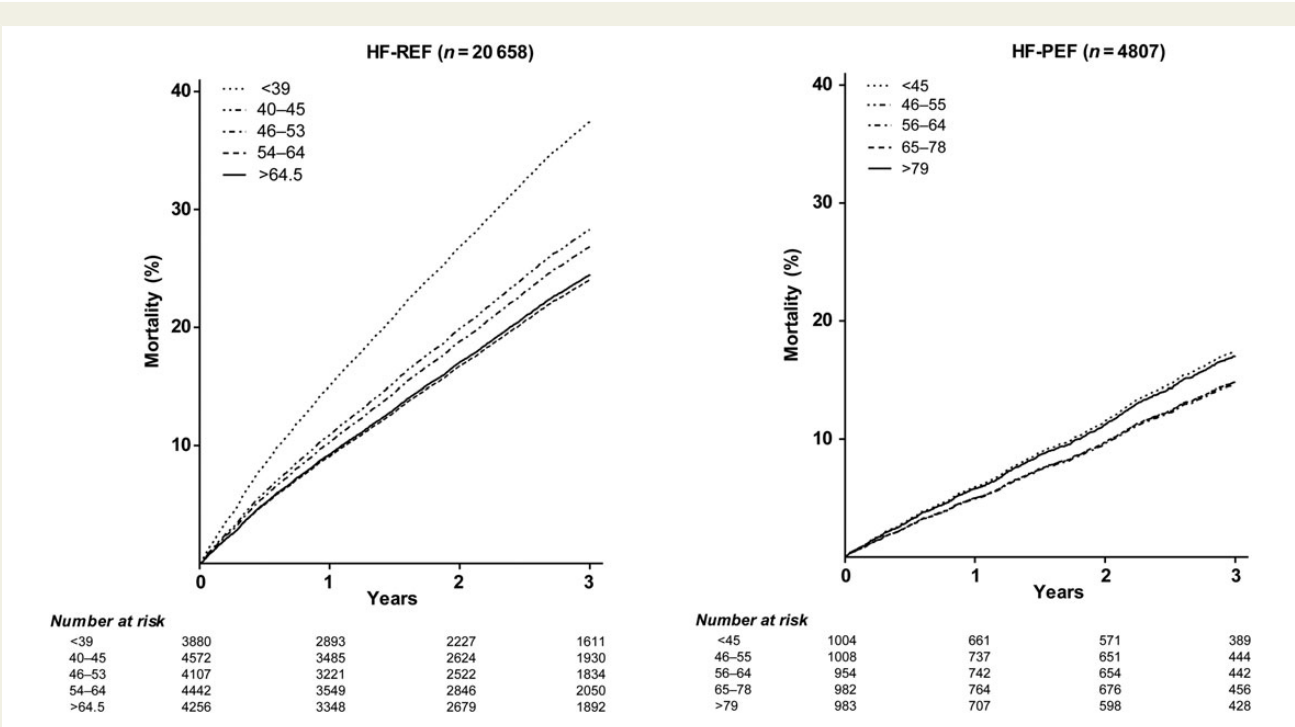


Figure 2 Mortality curves of pulse pressure quintiles by ejection fraction group. Adjusted for age, gender, hypertension, atrial fibrillation, ischaemic aetiology, and diabetes. The curves for the pulse pressure groups of the middle three quintiles (46–55, 56–64, and 65–78 mmHg) overlap, with lower mortality compared with the highest and lowest quintiles.

Table 4 Multivariable model by quintiles of pulse pressure in 4807 patients with HF-PEF—adjusted for the Meta-Analysis Global Group in Chronic Heart Failure variables

| Variable | HR (95% CI) | P-value |
|-------------------------|-------------------|---------|
| Pulse pressure (mmHg) | | |
| ≥ 79 | 1 | |
| 65–78 | 1.01 (0.82, 1.23) | 0.959 |
| 56–64 | 0.98 (0.79, 1.21) | 0.836 |
| 46–55 | 0.98 (0.79, 1.22) | 0.857 |
| ≤ 45 | 1.16 (0.92, 1.45) | 0.219 |
| Age (per year increase) | 1.06 (1.05, 1.07) | <0.001 |
| Gender (male) | 1.36 (1.18, 1.57) | <0.001 |
| Atrial fibrillation | 1.15 (0.96, 1.37) | 0.130 |
| Hypertension | 1.00 (0.86, 1.17) | 0.977 |
| Ischaemic aetiology | 1.04 (0.90, 1.20) | 0.609 |
| Diabetes | 1.61 (1.39, 1.87) | <0.001 |

chronic HF only (see Supplementary material online, Tables S9 and S10). The findings were consistent with the overall model.

Discussion

This large meta-analysis is the first study to describe the range of pulse pressure and evaluate the prognostic significance of pulse pressure in

patients with HF-PEF, as well as patients with HF-REF. The physiological influences on pulse pressure in HF are complex and appear to be dependent on EF, with left ventricular function and stroke volume playing an important role in HF-REF. This is in contrast to HF-PEF where the major influence on pulse pressure is probably arterial stiffness. As has been described previously, HF-REF patients in the lowest pulse pressure quintile had the highest crude and adjusted mortality risk, compared with all other pulse pressure groups. However, the relationship among patients with HF-PEF differed: while the highest pulse pressure quintile had the highest crude mortality, this difference did not persist in the multivariable analyses.

Association between lower pulse pressure in HF-REF and increased mortality

Paradoxically, the relationship between pulse pressure and mortality appears to be reversed in HF-REF compared with that seen in patients with other cardiovascular diseases and among individuals in the general population where a high pulse pressure has consistently been linked to adverse outcomes. In populations where high pulse pressure predicts mortality risk, the cause of high pulse pressure is thought to be reduced aortic elasticity secondary to arteriosclerosis and the increased risk possibly reflects widespread arteriosclerotic disease.^{11,12} However, a different pathophysiological process is evident in HF-REF where a lower pulse pressure is not an index of arterial stiffness but represents reduced cardiac function and lower stroke volume. This has recently been confirmed in an analysis from the Eplerenone Post-Acute Myocardial Infarction Heart Failure Efficacy and Survival Study (EPHESUS).¹³ In a sub-study in these patients with HF-REF after myocardial infarction, pulse

Table 5 Analyses of quintiles of pulse pressure for HF-REF and HF-PEF, stratified by systolic blood pressure—adjusted for the Meta-Analysis Global Group in Chronic Heart Failure prognostic variables

| HF-REF | | | HF-PEF | | |
|-----------------------------|-------------------|---------|----------------------------|--------------------|---------|
| Quintile of pulse pressure | HR (95% CI) | P-value | Quintile of pulse pressure | HR (95% CI) | P-value |
| SBP < 140 mmHg (n = 14 039) | | | SBP < 140 mmHg (n = 2234) | | |
| 1 | 1.50 (1.20, 1.88) | <0.001 | 1 | 0.95 (0.58, 1.53) | 0.823 |
| 2 | 1.10 (0.88, 1.38) | 0.407 | 2 | 0.73 (0.47, 1.15) | 0.172 |
| 3 | 1.06 (0.85, 1.33) | 0.610 | 3 | 0.67 (0.43, 1.05) | 0.083 |
| 4 | 0.98 (0.77, 1.23) | 0.833 | 4 | 0.81 (0.52, 1.26) | 0.347 |
| 5 | 1.0 | | 5 | 1.0 | |
| SBP ≥ 140 mmHg (n = 6619) | | | SBP ≥ 140 mmHg (n = 2573) | | |
| 1 | 0.88 (0.39, 2.00) | 0.764 | 1 | 5.66 (0.68, 47.42) | 0.110 |
| 2 | 1.07 (0.79, 1.44) | 0.662 | 2 | 1.08 (0.50, 2.31) | 0.853 |
| 3 | 0.92 (0.77, 1.09) | 0.322 | 3 | 1.06 (0.73, 1.55) | 0.753 |
| 4 | 0.89 (0.79, 1.00) | 0.048 | 4 | 0.90 (0.71, 1.14) | 0.373 |
| 5 | 1.0 | | 5 | 1.0 | |

Quintiles 1–5 indicate low to high pulse pressure.

pressure was more dependent on left ventricular function and was not a marker of aortic stiffness, as measured by carotid-femoral pulse wave velocity. Low proportional pulse pressure (pulse pressure/systolic BP) has previously shown a correlation with a low cardiac index and stroke volume index in patients with advanced HF-REF.¹⁴ However, the paradox in patients with HF-REF does not seem to be explained solely by measures of systolic function as studies of patients with asymptomatic left ventricular systolic dysfunction (LVSD)^{15,16} have shown high pulse pressure to be predictive of mortality risk. This seems to indicate that the transition to symptomatic HF-REF in some way reverses the usual relationship between pulse pressure and outcome. Lower pulse pressure has also been associated with higher B-type natriuretic peptides (BNPs) in advanced HF-REF.⁵ An additional finding in this study is that the risk associated with low pulse pressure in patients with HF-REF is especially marked in those with a lower SBP. The relationship between severity of LVSD, SBP, and outcome is complex. There is a U-shaped association between SBP and outcome in patients with less severe LVSD whereas in patients with more severe LVSD the relationship is linear, with lower SBP associated with increased mortality risk.¹⁷ One possible (but speculative) explanation for our finding of increased mortality risk in those with low pulse pressure and lower SBP is that both of these together identify patients with a particularly low stroke volume who are at greatest mortality risk.

Pulse pressure in HF-PEF and outcome: a reverse pattern compared with HF-REF

The relationship between pulse pressure and mortality appears to be completely different among patients with HF-PEF. Analysis of crude mortality showed the reverse pattern to that observed in HF-REF, with the highest risk in those with the highest pulse pressure. At first sight this might seem to make sense as patients with HF-PEF are 'phenotypically' more similar to subjects with hypertension, or even elderly individuals in the general population, both of which have worse outcomes with higher pulse pressure. A recent analysis from the Aldosterone Receptor Blockade in Diastolic Heart Failure trial showed that higher pulse pressure was associated with higher E/E' , an index of increased left ventricular filling pressure and more severe diastolic dysfunction.¹⁸ Higher pulse pressure may be a crude surrogate of increased arterial stiffness. Increased arterial stiffness increases afterload and cardiac work and mechanistically there is a plausible link between high pulse pressure and the development of HF-PEF. However, the association between increasing pulse pressure and increasing mortality was eliminated by adjustment for other prognostic variables (whereas the association between pulse pressure and mortality was strengthened by adjustment in HF-REF). The loss of this association highlights the complexity of the condition of HF-PEF and the prognostic importance of the underlying comorbidities in the outcomes for patients with HF-PEF. The difference between crude and adjusted risk seemed to reflect the high proportion of women (61% vs. 39%) and patients with diabetes (35% vs. 19%) in the highest pulse pressure quintiles compared with the lowest pulse pressure quintiles, two of the most powerful prognostic variables in these patients. The highest quintile also had a particularly low proportion of patients with AF and high proportion of patients with hypertension, although these were not significant predictors

of mortality. Several of the prognostic variables included in the multivariable model are recognized determinants of arterial stiffness (e.g. age, sex, history of hypertension, and diabetes) and thus adjustment for these may have eliminated the significance of pulse pressure as a surrogate for arterial stiffness in HF-PEF. For patients with HF-PEF, therefore, higher pulse pressure may reflect more arterial stiffness and truly related to higher mortality. In a recent retrospective analysis of results from the Digitalis Investigator Group (DIG) trial,¹⁹ there was a significant J-shaped relationship between pulse pressure and mortality. Interestingly in our more contemporary population of patients with HF-PEF, we found the crude mortality was highest among patients in the highest quintile (Table 2). However, there was no difference across the quintiles on multivariable analysis. However, in two sub-groups of patients with HF-PEF (acute HF and patients without AF), lower pulse pressure was an independent predictor of mortality. While sub-group findings must always be interpreted with caution, lower pulse pressure in these patients may also be an index of lower stroke volume. Reduced stroke volume has previously been reported in HF-PEF²⁰ and this may explain the J-shape relationship between pulse pressure and mortality seen in the retrospective analysis from the DIG trial.¹⁹ These findings should be explored further in future, larger studies.

The finding of a low prevalence of AF in the highest pulse pressure quintile is curious, if not paradoxical. Higher pulse pressure is a predictor of incident AF in the general population and in patients with certain types of cardiovascular disease.^{21,22} Yet we saw the opposite in relation to prevalence in patients with HF-PEF. This does not seem to be explained by difficulty in measuring pulse pressure in patients with AF as no such variation in prevalence of AF was found according to pulse pressure quintile in patients with HF-REF.

Limitations

This meta-analysis incorporated data from a large number of observational studies and randomized clinical trials, and therefore, BP measurements were not performed in a standardized fashion. Another limitation resulting from the use of a large number of observational studies and randomized clinical trials is the lack of standardization of HF diagnosis. As previously described, the variables that were incorporated into the multivariable model were selected due to their clinical relevance and because they were available in the majority of patients. Other variables, which may have prognostic significance, were not included due to the amount of missing data. Therefore, the multivariable model did not include established biomarkers, such as renal function, sodium, and haemoglobin or powerful contemporary biomarkers such as BNP. Future work should incorporate such biomarkers to evaluate the incremental prognostic value of pulse pressure. Pulse pressure may change within short time intervals and mean pulse pressure over several measurements, rather than a single measurement, may provide additional prognostic information. Central pulse pressure has been demonstrated to be a stronger prognostic marker than brachial pulse pressure in patients with hypertension²³; however, this has never been measured in any large-scale trial in HF and was not available from any of the studies included in our analyses. A recent sub-study of EPHEsus¹³ found aortic pulse wave velocity, measured by carotid-femoral pulse wave velocity, to be predictive of increased risk of cardiovascular death. The latter, a marker of increased aortic stiffness, was not

available in this study but should be included in future research. Finally, the only clinical outcome available in the majority of studies was all-cause mortality and we were not able to look at non-fatal outcomes.

Conclusions

Pulse pressure is a simple, inexpensive, and readily available clinical index. This non-invasive test provides useful prognostic information for patients with HF-REF (particularly in those with an LVEF < 30%) where lower pulse pressure (especially < 53 mmHg) independently predicts mortality, particularly in patients with lower systolic BP (< 140 mmHg). The prognostic utility of pulse pressure among patients with HF-PEF appears more complex, with higher pulse pressure appearing to be predictive of crude but not adjusted mortality. Future analyses evaluating the incremental prognostic value of pulse pressure, in addition to powerful contemporary biomarkers in HF, are required to determine if this simple clinical sign has a role in HF risk stratification. Such studies should include patients with HF-PEF as well as HF-REF.

Supplementary material

Supplementary material is available at *European Heart Journal* online.

Funding

The work was partly supported by project grants from the New Zealand Heart Foundation, the University of Auckland, and the University of Glasgow. K.K.P. is supported by a Research Fellowship from the Heart Foundation of New Zealand and R.N.D. holds the New Zealand Heart Foundation Chair of Heart Health.

Conflict of interest: none declared.

Appendix

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