Is Pulse Pressure Useful in Predicting Risk for Coronary Heart Disease?

The Framingham Heart Study

Stanley S. Franklin, MD; Shehzad A. Khan, BS; Nathan D. Wong, PhD; Martin G. Larson, ScD; Daniel Levy, MD

Background—Current definitions of hypertension are based on levels of systolic blood pressure (SBP) and diastolic blood pressure (DBP), but not on pulse pressure (PP). We examined whether PP adds useful information for predicting coronary heart disease (CHD) in the population-based Framingham Heart Study.

Methods and Results—We studied 1924 men and women between 50 and 79 years of age at baseline with no clinical evidence of CHD and not taking antihypertensive drug therapy. Cox regression, adjusted for age, sex, and other risk factors, was used to assess the relations between blood pressure components and CHD risk over a 20-year follow-up. The association with CHD risk was positive for SBP, DBP, and PP, considering each pressure individually; of the 3, PP yielded the largest \( \chi^2 \) statistic. When SBP and DBP were jointly entered into the multivariable model, the association with CHD risk was positive for SBP (HR, 1.22; 95% CI, 1.15 to 1.30) and negative for DBP (HR, 0.86; 95% CI, 0.75 to 0.98). Four subgroups were defined according to SBP levels (<120, 120 to 139, 140 to 159, and \( \geq 160 \) mm Hg). Within each subgroup, the association with CHD risk was negative for DBP and positive for PP. A cross-classification of SBP-DBP levels confirmed these results.

Conclusions—in the middle-aged and elderly, CHD risk increased with lower DBP at any level of SBP \( \geq 120 \) mm Hg, suggesting that higher PP was an important component of risk. Neither SBP nor DBP was superior to PP in predicting CHD risk. (Circulation. 1999;100:354-360.)

Key Words: blood pressure ■ hypertension ■ coronary disease

Current guidelines for the diagnosis and management of hypertension have defined cardiovascular risk by the elevation of systolic blood pressure (SBP) and/or the elevation of diastolic blood pressure (DBP).1–3 However, the principal components of blood pressure consist of both a steady component (mean arterial pressure, MAP) and a pulsatile component (pulse pressure, PP). Major determinants of MAP are ventricular ejection and peripheral vascular resistance.4–6 PP, the difference between SBP and DBP, is also made up of 2 major components—1 due to ventricular ejection interacting with the viscoelastic properties of the large arteries (direct) and the other due to wave reflection (indirect).4–6 The rise in SBP and PP in middle-aged and elderly subjects is due primarily to an increase in large-artery stiffness and an associated increase in wave reflection amplitude.6

Currently, there is increasing evidence that PP, in middle-aged and older subjects, is an independent predictor of risk of coronary heart disease (CHD), compared with MAP.7–11 We recently reported on the age-related change of PP and MAP in persons not receiving antihypertensive therapy and without clinical CHD.12 From age 30 to 50 years, SBP and DBP track together in a nearly parallel manner; however, after age 60 years, DBP decreases, while SBP continues to rise. This age-related phenomenon accounts for the large increase in PP after age 60 years and for the underestimation of peripheral vascular resistance in older persons by the MAP equation.12 Because of the inaccuracy of calculated MAP, it may be preferable to compare PP with SBP or DBP in evaluation of blood pressure predictors of CHD risk.

Therefore, the first goal of the present study, using the previous Framingham Heart Study cohort,12 was to compare various blood pressure components (PP, SBP, and DBP) individually as predictors of risk for CHD. The second goal was to examine the joint influence of any 2 blood pressure components on CHD risk and to determine whether PP adds to the predictive value of either SBP or DBP for CHD events.

Methods

The Framingham Heart Study is a prospective, population-based cohort study of cardiovascular disease incidence and risk factors.
which began in 1948 with the enrollment of 5209 men and women 28 to 62 years old. Participants undergo biennial examinations, which include an extensive cardiovascular history and physical examination, 12-lead ECG, and various blood chemistries. Morbidity and mortality are monitored by biennial clinic examinations and by review of interim hospitalizations. A panel of 3 experienced investigators reviews all new cardiovascular events. Detailed descriptions of the study design have been published.13,14

Study Sample

Subjects selected for this study had measurements of HDL cholesterol as part of a complete lipid profile. The earliest examination at which HDL cholesterol was measured served as the baseline examination for each subject; usually this was the 10th biennial examination, but for some it was the 11th or 12th. Study subjects were between 50 and 79 years old at baseline to be eligible. They had no history or clinical evidence of CHD, and they were not receiving antihypertensive medication. Three hundred thirty-five subjects were excluded because of concurrent antihypertensive therapy, and 2 subjects were excluded because of concurrent antihypertensive medication. Three hundred thirty-five subjects were excluded because of concurrent antihypertensive therapy at baseline, which may have influenced baseline blood pressure readings and thus their relation to CHD risk. Ninety-four percent, ie, 1924 of the original 2036 subjects in our previous study,12 qualified for the present investigation; 112 subjects were excluded because of missing covariates.

Blood Pressure Measurement

Readings of SBP and DBP were taken in the supported left arm of the seated subject, after 5 minutes of quiet rest, with a mercury-column sphygmomanometer with cuff-size adjustment based on arm circumference. Readings were recorded to the nearest even number. SBP was recorded at the first appearance of Korotkoff sounds, and palpation was used to check auscultatory systolic readings. DBP was recorded at the disappearance (phase V) of Korotkoff sounds. Baseline SBP and DBP each were the average of 2 separate measurements taken by the examining physician; in 2.1% of subjects, only 1 reading was available at the baseline examination.

End Points

The end point used in this study was incident CHD (fatal or nonfatal). A subject was considered to have incident CHD if he or she fulfilled published criteria15 for angina pectoris, coronary insufficiency (angina pectoris lasting ≥20 minutes and accompanied by ischemic ECG changes), myocardial infarction, or death from CHD occurring since the baseline examination. Follow-up time was defined from the date of the baseline examination to the date of the first CHD event or to the date of last contact free of CHD, up to the date of the 20th biennial examination.

Data Analysis

The relations of CHD hazard ratios (HRs) to single (SBP, DBP, or PP) and dual (SBP-DBP, PP-SBP, and PP-DBP) blood pressure components, as continuous variables, were evaluated by Cox proportional hazards regression.16 HRs, estimated as the exponent (e) raised to the power of the respective regression coefficient, were determined, along with 95% confidence limits, for a 10 mm Hg increment in blood pressure component and per 1-SD increment. Models were adjusted for age, sex, body mass index, cigarettes smoked per day, glucose intolerance (defined as clinical diagnosis of diabetes mellitus, definite or trace glycosuria [Clinistix or Combus-tix], or casual blood glucose values of ≥120 mg/dL), and the total cholesterol/HDL ratio. SAS statistical software (SAS Institute) was used.17

The dual influences of SBP and DBP (model 1) and SBP and PP (model 2) were also examined by Cox proportional hazards regression with SBP grouped in 4 discrete categories and PP and DBP plotted as continuous variables. The SBP groups were based on JNC VI criteria:16 group 1, <120 mm Hg (optimal systolic blood pressure); group 2, 120 to 129 mm Hg (normal and high normal systolic blood pressure); group 3, 140 to 149 mm Hg (stage 1 systolic hypertension); and group 4, ≥160 mm Hg (stages 2 and 3 systolic hypertension).

The relative risks for new CHD events for the 4 SBP categories as defined above and within specific DBP groupings (<70, 70 to 79, 80 to 89, and ≥90 mm Hg) were also examined by Cox regression, with adjustment for age, sex, and the other risk factors as specified above. Each group pairing of SBP and DBP was compared with a reference group with SBP <120 mm Hg and DBP <70 mm Hg with an HR of 1.0.

Secondary analyses were done to examine for sex differences and for potential bias that could affect the prediction of CHD risk from baseline blood pressure components: (1) an interaction term for sex was added to the model to test for sex differences; (2) subjects excluded from the study because of previous antihypertensive therapy at baseline were added to the study cohort to test for hypertension selection bias; and (3) postbaseline hypertension treatment was added as a time-dependent covariate to test for possible influence on the prediction of CHD risk from baseline blood pressure.

Results

Demographic and Clinical Characteristics

The sample comprised 830 men and 1094 women (Table 1). The mean follow-up time was 14.3 years, during which 433 subjects developed CHD. Of the initial CHD events, 187 were angina pectoris or coronary insufficiency, 182 were myocardial infarction with survival beyond 1 day, and 64 were CHD deaths. Subjects who developed new CHD events had higher levels of total serum cholesterol, lower levels of HDL cholesterol, and a higher prevalence of glucose intolerance (women only) at baseline than those who did not experience CHD. All blood pressure components (SBP, DBP, and PP) were higher in women subjects who experienced new CHD events than in those free of such events. Correlations among blood pressure components were r=0.87 for SBP-DDP, r=0.86 for SBP-DBP, and r=0.21 for PP-DBP.

Single Blood Pressure Component Models

The HRs associated with a 10 mm Hg increment in blood pressure were as follows: PP, 1.23 (P<0.001); SBP, 1.16 (P<0.001); and DBP, 1.14 (P<0.05), respectively, after adjustment for other risk factors. The HRs per 1 SD were PP, 1.38; SBP, 1.35; and DBP, 1.14 (Table 2).

Dual Blood Pressure Component Models

The combination of SBP (positive) and DBP (negative) (model 1) showed a modest incremental contribution from DBP (χ²=5.2, P<0.05) above and beyond SBP, but the combination of SBP and PP (model 2) or PP and DBP (model 3) showed no incremental value of SBP or DBP, respectively, in predicting CHD once PP was included in the model. These conclusions were unaltered when standardized HRs were considered (Table 2).

Table 3 shows CHD HRs for blood pressure components within the 4 SBP groups. Model 1 demonstrated that the slope of the inverse relation of DBP (HR per 10 mm Hg, 0.84 to 0.87; P<0.05), as a continuous variable, to CHD risk was similar (Wald χ²=5.6, 3 df, P=0.13) across all categories of
SBP. In this model, SBP provided further contribution to CHD risk (HR per 10 mm Hg, 1.25; 95% CI, 1.11 to 1.41) over and above DBP. Likewise, model 2 indicated that the positive slope of the relations of PP (HR, 1.12 to 1.20; $P_{0.05}$), as a continuous variable, to CHD risk was similar (Wald $X^2_{5.6, 3 df}$, $P_{0.13}$) across all categories of SBP. In this model, there was no added value of SBP in predicting CHD risk over and above PP (HR, 1.05; 95% CI, 0.90 to 1.23). These findings remained similar when standardized HRs were calculated.

The joint influences of SBP and DBP on CHD risk are plotted in Figure 1. For any level of SBP, subjects with lower DBP, ie, higher PP (moving leftward along each line) had greater CHD risk; alternatively, for any level of DBP, those with higher SBP and PP (moving upward from line to line) had greater risk. Figure 2 shows the joint influences of SBP and PP on CHD risk. For any given level of SBP $\leq 130$ mm Hg (group 2, 3, or 4), subjects with higher PP, ie, lower DBP (moving rightward along each line) had a considerable increase in CHD risk. By contrast, for any given

### TABLE 1. Demographic and Clinical Characteristics of Subjects at Index Examination According to Sex and Subsequent CHD Status*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No CHD (n=576)</td>
<td>CHD (n=254)</td>
</tr>
<tr>
<td>Age, y</td>
<td>61.1±7.9</td>
<td>61.5±7.4</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>26.7±3.5</td>
<td>26.8±3.6</td>
</tr>
<tr>
<td>Total cholesterol, mg/dL</td>
<td>217.5±40.1</td>
<td>223.7±40.6†</td>
</tr>
<tr>
<td>HDL cholesterol, mg/dL</td>
<td>47.0±14.4</td>
<td>44.0±11.6‡</td>
</tr>
<tr>
<td>Cigarettes/day, n</td>
<td>7.8±12.8</td>
<td>8.1±12.8</td>
</tr>
<tr>
<td>Glucose intolerance, %</td>
<td>10.6</td>
<td>12.6</td>
</tr>
</tbody>
</table>

Blood pressure, mm Hg

| PP                         | 54.7±14.1      | 59.2±15.3‡     | 55.9±15.2      | 62.8±20.2‡  |
| SBP                        | 134.6±19.2     | 140.7±19.2‡    | 133.5±20.0     | 142.1±23.9‡ |
| DBP                        | 79.9±9.9       | 81.4±9.9†      | 77.6±9.8       | 79.3±10.9   |

BMI indicates body mass index.

*Comparison of characteristics between CHD and no CHD, with values expressed as mean±SD or percentage.
†$P_{0.05}$, ‡$P_{0.001}$ vs those without CHD.

### TABLE 2. Cox Proportional Hazards Regression Models Relating Incidence of CHD to Single and Dual Blood Pressure Components of SBP, DBP, and PP

<table>
<thead>
<tr>
<th></th>
<th>Coefficient, $\beta$</th>
<th>SE*</th>
<th>Likelihood Ratio, $X^2$</th>
<th>Hazard Ratio/10 mm Hg (95% CI)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single blood pressure components,§ mm Hg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>0.20</td>
<td>0.03</td>
<td>41.4</td>
<td>1.23 (1.16–1.30¶)</td>
</tr>
<tr>
<td>SBP</td>
<td>0.15</td>
<td>0.02</td>
<td>36.9</td>
<td>1.16 (1.11–1.21¶)</td>
</tr>
<tr>
<td>DBP</td>
<td>0.13</td>
<td>0.05</td>
<td>6.5</td>
<td>1.14 (1.03–1.26¶)</td>
</tr>
</tbody>
</table>

Dual blood pressure components,§ mm Hg

| Model 1              |                      |     |                          |                                 |
| SBP                  | 0.20                 | 0.03 | 35.6                     | 1.22 (1.15–1.30¶)                |
| DBP                  | −0.15                | 0.07 | 5.2                      | 0.86 (0.75–0.98¶)                |
| Model 2              |                      |     |                          |                                 |
| PP                   | 0.15                 | 0.07 | 5.2                      | 1.17 (1.02–1.33¶)                |
| SBP                  | 0.04                 | 0.05 | 0.7                      | 1.04 (0.94–1.16¶)                |
| Model 3              |                      |     |                          |                                 |
| PP                   | 0.20                 | 0.03 | 35.6                     | 1.22 (1.15–1.30¶)                |
| DBP                  | 0.04                 | 0.05 | 0.7                      | 1.04 (0.94–1.16¶)                |

*Associated with a 10 mm Hg increment in the corresponding blood pressure component.
†Likelihood ratio statistics are for each blood pressure variable added to a model that contains covariates and (a) no other blood pressure variable, or (b) one other blood pressure variable.
§Adjusted for age, sex, body mass index, cigarettes smoked per day, glucose intolerance, and total cholesterol/HDL.
¶$P_{0.05}$, ‖$P_{0.001}$.
level of PP $\geq$50 mm Hg, subjects with a parallel increase in SBP and DBP (moving upward from line to line) had only a minimal increase in CHD risk. For example, a 20 mm Hg increase in PP for SBP group 2, 3, or 4 was associated with a much greater increase in CHD risk than a 20 mm Hg increment in PP for SBP group 1.

Table 4 shows the hazards for CHD by cross-classification of SBP and DBP, using SBP $<120$ mm Hg and DBP $<70$ mm Hg as the reference group. At all levels of DBP, the hazards for CHD rose with increasing SBP groups. Conversely, for all SBP groups $\geq 120$ mm Hg, the hazards for CHD rose with decreasing DBP (with the sole exception of the group SBP 140 to 159 and DBP 80 to 89 mm Hg).

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Secondary Analyses
When an interaction term for sex was introduced into the model, there was no significant difference in predicting CHD risk for men compared with women ($P=0.29$ for PP, $P=0.23$ for SBP, and $P=0.81$ for DBP). None of the blood pressure components were predictive of CHD risk in the subjects (n = 303) excluded from the study because of concurrent antihypertensive therapy at baseline examination ($P=0.45$ for PP, $P=0.63$ for SBP, and $P=0.73$ for DBP). When treated and untreated subjects were combined (n = 1924+303 = 2227), PP and SBP remained predictors of CHD risk ($\chi^2$=36.0 and 31.6, respectively) and DBP was of borderline significance ($\chi^2$=4.3). When postbaseline antihypertensive therapy was added as a time-dependent covariate, the magnitude of the prediction of CHD risk did not change significantly for baseline PP and SBP ($\beta$-coefficients of 0.19 for PP and 0.14 for SBP, both adjusted per 10 mm Hg) or for the baseline dual model of SBP-DBP ($\beta$-coefficients of 0.19 for SBP and $-0.17$ for DBP, both adjusted per 10 mm Hg), similar to the $\beta$-coefficients estimated earlier (Table 2).

Discussion
The principal new information provided by this study was that in middle-aged and older individuals, CHD risk was inversely related to DBP at any given SBP of $\geq 120$ mm Hg, consistent with the hypothesis that higher PP is an important component of risk. Moreover, neither SBP nor DBP was superior to PP in predicting CHD risk. There was a far greater increase in CHD risk with increments in PP without a change in SBP than with increments in SBP without a change in PP. An increase in PP with fixed SBP occurs solely as a function of declining DBP; this is a consequence of a rise in large-artery stiffness. An increase in SBP with fixed PP occurs when there are parallel increases in SBP and DBP; this is a consequence of a rise in peripheral vascular resistance.

An elevated DBP has long been associated with increased CHD risk. A negative association of DBP with CHD risk has been recognized only recently. Most of the early studies assessing blood pressure as a risk factor for CHD were based on young individuals, in whom SBP and DBP tend to track together and in whom both are strongly associated with CHD risk. With advancing age, there is a decline in DBP and in the role of DBP in predicting CHD risk.
present sample, however, with a mean age of 61.2 years, DBP when considered alone remained positively (but weakly) associated with CHD risk. In contrast, when DBP and SBP were considered jointly, an inverse relation between DBP and CHD risk became apparent. Similar trends for the association of PP with CHD events were reported in 3 previous publications, with mean sample ages of 51.6, 53.1, and 59.5 years, respectively.9 –11

Hemodynamic Implications
As large-artery stiffness increases in middle-aged and elderly subjects, SBP rises and DBP falls, with a resulting increase in PP.18 The normally present higher gradient of peripheral to central arterial PP (amplification) found in young subjects gradually decreases with aging as a result of the augmentation of central PP by early wave reflection.21,22 Therefore, brachial artery cuff measurement of PP in the elderly, in contrast to the young, becomes a more accurate indicator of central PP and an improved predictor of CHD risk.

As vascular resistance rises, there is a proportional increase in SBP and DBP in young individuals. With the onset of middle age, however, SBP rises more than DBP, resulting in elevation of PP.12,18 Thus, DBP rises with increased peripheral arterial resistance and falls with increased central artery stiffness; the relative contributions of these 2 opposing forces determine DBP and ultimately PP.

Normally, PP and SBP are highly correlated because both blood pressure components rise with increases in vascular resistance and large-artery stiffness. When assessed individually, however, increments in PP at a fixed SBP were associated with a greater risk for CHD than were increments in SBP at a fixed PP. From these findings, we can hypothesize that CHD risk is related more to the pulsatile stress caused by large-artery stiffness during systole than to the steady-state stress due to small-vessel resistance during diastole.23–25 Similarly, our data show that not all hypertensive subjects with the same elevation in SBP have the same CHD risk; those with lower DBP, and therefore wider PP, have greater CHD risk, possibly due to greater pulsatile stress.

Clinical Implications
Our analysis showed only slight favoring of PP over SBP in predicting CHD risk, presumably because of the overall strong concordance of SBP with DBP. In dual-component models, however, neither SBP nor DBP had additional value in predicting CHD risk over and above the contribution of PP. Further support favoring PP over SBP in subjects with discordantly low DBP was provided by a cross-classification matrix of SBP and PP using 4 discrete levels of SBP. This approach enabled us to examine the effect of discordant SBP-DBP pairings on CHD risk. At any SBP ≥120 mm Hg, with only 1 exception, DBP was inversely associated with CHD risk.

These results support the conclusion that in subjects with identical levels of SBP, those with isolated systolic hypertension are at greater risk for CHD than those with combined systolic-diastolic hypertension. This may have important

Figure 1. Joint influences of SBP and DBP on CHD risk. CHD HRs were determined from level of DBP within SBP groups. HRs were set to a reference value of 1.0 for SBP of 130 mm Hg and DBP of 80 mm Hg and are plotted for SBP values of 110, 130, 150, and 170 mm Hg, respectively. Probability values were for β-coefficients for model 1, Table 3. All estimates were adjusted for age, sex, body mass index, cigarettes smoked per day, glucose intolerance, and total cholesterol/HDL.

Figure 2. Joint influences of SBP and PP on CHD risk. CHD HRs were determined from level of PP within SBP groups. HRs were set to a reference value of 1.0 for SBP of 130 mm Hg and PP of 50 mm Hg and are plotted for SBP values of 110, 130, 150, and 170 mm Hg, respectively. Probability values were for β-coefficients for model 2, Table 3. All estimates were adjusted for age, sex, body mass index, cigarettes smoked per day, glucose intolerance, and total cholesterol/HDL.
From these findings, we cannot determine whether the association between PP and CHD events is causal or whether elevated PP is a marker for the underlying vascular disease, which predisposes to CHD. It is premature to suggest that current treatment recommendations should be modified on the basis of our observational data. Our study, however, may be useful in generating hypotheses that can be tested directly in clinical trials and in identifying high-risk hypertensive subjects who may benefit from more aggressive control of their blood pressure.

### Study Strengths and Limitations

In this study, we quantified the contributions of PP and SBP to CHD risk in both normotensive and hypertensive subjects followed up for up to 20 years. These findings were established in a cohort of subjects who were free of clinical CHD at baseline and who were not receiving antihypertensive therapy.

There are potential limitations regarding the interpretation of our data. There may have been a selection bias resulting from the exclusion of 335 subjects receiving antihypertensive therapy at baseline, which represented 30% of the hypertensive population in this cohort. When treated and untreated subjects were combined, however, SBP and PP remained significant predictors of CHD risk, and DBP was of borderline significance. These results are consistent with a previous study of combined treated and untreated hypertensive patients that showed a positive association between PP and myocardial infarction.

Because elevated DBP was the main criterion for treating hypertension until the early 1980s, this may have resulted in a higher prevalence of isolated systolic hypertension in the present study. However, our selection process, which may have eliminated the most severe hypertensives on treatment, would presumably result in a more representative population of normotensives, those with borderline blood pressure, and predominantly untreated stage 1 and 2 hypertensives. Stages 1 and 2 compose 94% of the hypertensive population. Furthermore, the results of this study have no bearing on accelerated or malignant hypertension, an acute or subacute process with an entirely different pathophysiology and clinical course.

Although a postbaseline treatment bias is possible, we found little evidence to support this conclusion. When a time-dependent covariate term for antihypertensive therapy was used in the model, there was no evidence that postbaseline treatment diminished the prediction of CHD events by baseline PP, SBP, or by baseline dual components of SBP and DBP. Any follow-up treatment effect in our study should bias results toward the null, because a previous Framingham Heart Study publication has shown a substantial reduction in CHD mortality with long-term hypertension therapy. Therefore, our findings may underestimate the utility of PP in predicting CHD risk.

The value of the single office PP, shown in this study to be predictive of CHD risk, may not be accurate in the individual subject. The averaging of multiple blood pressure readings taken on several visits or the use of ambulatory monitoring will improve accuracy and precision. Last, because the original Framingham sample consisted almost exclusively of whites, the majority of whom were middle class, results may not apply to other ethnic or socioeconomic groups.

In summary, PP provides important predictive value for CHD events in normotensive and untreated hypertensive middle-aged and elderly adults. PP may be the most reliable blood pressure indicator of risk when high-normal SBP or systolic hypertension is accompanied by normal or low DBP. Our data suggest that CHD events are more related to the pulsatile stress of large-artery stiffness during systole (as reflected in a rise of PP) than the steady-state stress of resistance during diastole (as reflected in a parallel rise in SBP and DBP). Indeed, at similar elevations of SBP, subjects with isolated systolic hypertension are at greater risk for CHD.
events than those with combined systolic-diastolic hypertension. For middle-aged and older persons, these new findings call into question the prevailing belief that elevations of SBP and DBP contribute equally to CHD risk.

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References


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