The diagnostic value of finger systolic blood pressure and cold-provocation testing for the vascular component of hand–arm vibration syndrome in health surveillance

K. Poole, J. Elms and H. J. Mason

Background
Hand–arm vibration syndrome (HAVS) is a complex condition with vascular, sensorineural and musculoskeletal components. A number of quantitative tests have been used for assisting in the diagnosis of HAVS and grading disease severity.

Aims
To investigate and compare the diagnostic value of finger systolic blood pressure (FSBP) and rewarming of finger skin temperature (FST) following cold-provocation testing, in the assessment of vascular HAVS.

Methods
Twenty-four individuals with vascular HAVS (Stockholm Workshop stage 2 or 3V) and 22 control subjects underwent FSBP measurements at 30, 15 and 10°C and monitoring of FST following immersion of the hands in water at 15°C for 5 min.

Results
There was a significant reduction in median FSBP% in the vascular HAVS group in the change in FSBP from 30 to 15°C adjusted for brachial blood pressure (FSBPC%). There was no difference in the median time for FST to rewarm by 4°C between HAVS cases and controls. The sensitivity and specificity of FSBP to discriminate between the groups varied between 44 and 61% and 91 and 95%, respectively. The sensitivity and specificity for the time for FST to rewarm by 4°C were 71 and 77%.

Conclusions
There is little evidence that the described form of finger rewarming after cold-provocation testing is a useful diagnostic test for vascular HAVS, although it may have some moderate influence in ruling out vascular problems. Based on our data, the FSBP may also have limited use in confirming a positive diagnosis of vibration-induced vascular problems. The higher specificity of the FSBP test suggests it may have some value in ruling out the vascular component of HAVS. The data from this study do not confirm the diagnostic power of FSBP for the vascular component of HAVS reported by a few other investigators.

Key words
Cold provocation; finger systolic blood pressure; HAVS.

Introduction
Hand–arm vibration syndrome (HAVS) is a complex condition with vascular, sensorineural and musculo-
A number of quantitative physiological tests have been used in the diagnosis of HAVS and grading its severity. The occurrence in HAVS cases of cold-induced blanching suggests that digital blood vessels may be hyper-responsive to cold stimuli and, consequently, vascular tests have focused on measuring this phenomenon. The most commonly applied test involves immersion of the hands in cold water for a period of time and then measuring the recovery of fingertip skin temperature (FST), which is a surrogate for blood flow [1], as a measure of the vasodilatory responsiveness of the digital blood vessels after the cold stimulus. Defining the diagnostic power of such tests is difficult, as there has been wide variation in both the nature of the cold challenge and the outcome parameter used [2–7]. It has been reported that this technique may be useful for discriminating on a group basis between those with and without vibration-induced vascular problems, but may lack the necessary sensitivity and specificity to distinguish between such individuals [5,8,9]. Furthermore, the diagnostic usefulness of a specific form of the technique widely applied in the UK for medico-legal compensation claims, has been questioned [10–12].

Measurement of finger systolic blood pressure (FSBP) under cold provocation has also been used for the investigation of the vascular component of HAVS, although not as widely as FST measurements. FSBP is related to the tone of the digital blood vessels, so that during cold provocation the blood vessel constricts and FSBP falls [13,14]. It has been suggested that FSBP during cold provocation may be a more useful and reproducible diagnostic test [4,7] than FST rewarming measurements after cold provocation [15]. Changes in FSBP with cold provocation have been shown to be related to finger blanching [16,17]. It has been shown to have high specificity, suggesting that it may be a useful diagnostic test in ruling out vascular abnormality [7,17], but its sensitivity has tended to be lower, suggesting that it may not be suitable as a screening tool [7].

The aims of this study were to compare the diagnostic abilities of a standardized FST technique after cold provocation of 15°C for 5 min [18,19] and FSBP measurements for assessing abnormal vascular responses to cold in HAVS.

Population and methods
Twenty-four male HAVS cases referred to the Health and Safety Laboratory (HSL) for health surveillance purposes and staged at Stockholm Workshop stage 2 V or 3 V, were invited to re-attend for FSBP measurements. They had undergone a standard FST rewarming test within the original HAVS assessment. All testing was performed at a room temperature of 22°C (±2°C). Twenty-two male HSL staff who had not been exposed to vibration occupationally and were not experiencing any symptoms consistent with primary Raynaud’s phenomenon, were studied as a control group. No subject was taking any vasoactive therapy.

FST measurements were carried out by a standardized methodology [11,18,19]. Essentially, calibrated thermocouples were attached to the fingertips of both hands, which were gloved in thin plastic during the cold challenge. A settling period of 2 min was applied with the hands at approximately heart level, followed by immersion of both hands in water at 15°C for 5 min. The subjects then removed their hands from the water, the gloves were removed and the hands kept at heart level to rewarm for 10 min. Continuous monitoring of skin temperatures during the settling, hand-immersion and rewarming periods were recorded. The time for FST to increase by 4°C (T14°C) after cold challenge was used as the outcome parameter.

The FSBP test used commercial instrumentation (ISVR, Southampton). Essentially, water-perfusible cuffs were placed around the mid-phalanx of each finger on the right hand with a separate air cuff around the thumb as a reference measurement. Mercury strain gauges were positioned at the base of the fingernail of cuffed fingers. The subjects were tested seated with their hands at approximately heart level. The tips of the fingers were then squeezed to remove blood volume and perfusion cuffs were inflated to a suprasystolic pressure to prevent arterial inflow, while the cuffs were perfused with thermostated water. After 5 min of ischaemia, the cuff pressure was reduced at a rate of 2 mmHg/s. The brachial blood pressure in the left arm was also recorded using an automatic oscillatory system (Omron 705CP). The procedure was performed with circulating water at 30, 15 and 10°C. FSBP was calculated as the cuff inflation pressure at which arterial inflow returned to the finger for 30°C (FSBP30), 15°C (FSBP15) and 10°C (FSBP10). Percentage changes (FSBP%) from 30 to 15°C and from 30 to 10°C were calculated according to the following formulae [17]:

\[
\text{FSBP\% A} = \left(\frac{\text{FSBP}_{15\text{C}} \times 100}{\text{FSBP}_{30\text{C}}} - \frac{\text{FSBP}_{10\text{C}} \times 100}{\text{FSBP}_{30\text{C}}} - \frac{\text{FSBP}_{10\text{C}} \times 100}{\text{FSBP}_{15\text{C}}}\right) / \left(\frac{\text{FSBP}_{30\text{C}} - \text{FSBP}_{15\text{C}}}{\text{FSBP}_{30\text{C}} - \text{FSBP}_{10\text{C}}}\right)
\]

\[
\text{FSBP\% B} = \left(\frac{\text{FSBP}_{10\text{C}} \times 100}{\text{FSBP}_{30\text{C}}} - \frac{\text{FSBP}_{10\text{C}} \times 100}{\text{FSBP}_{15\text{C}}}\right) / \left(\frac{\text{FSBP}_{30\text{C}} - \text{FSBP}_{15\text{C}}}{\text{FSBP}_{30\text{C}} - \text{FSBP}_{10\text{C}}}\right)
\]

\[
\text{FSBP\% C} = \left(\frac{\text{FSBP}_{15\text{C}} \times 100}{\text{FSBP}_{30\text{C}}} - \frac{\text{FSBP}_{15\text{C}} \times 100}{\text{FSBP}_{10\text{C}}}\right) / \left(\frac{\text{ASP}_{30\text{C}} - \text{ASP}_{15\text{C}}}{\text{ASP}_{30\text{C}} - \text{ASP}_{10\text{C}}}\right)
\]

\[
\text{FSBP\% D} = \left(\frac{\text{FSBP}_{10\text{C}} \times 100}{\text{FSBP}_{30\text{C}}} - \frac{\text{FSBP}_{10\text{C}} \times 100}{\text{FSBP}_{15\text{C}}}\right) / \left(\frac{\text{ASP}_{30\text{C}} - \text{ASP}_{15\text{C}}}{\text{ASP}_{30\text{C}} - \text{ASP}_{10\text{C}}}\right)
\]

\[
\text{FSBP\% E} = \frac{\text{FSBP}_{15\text{C}} \times 100}{\text{FSBP}_{30\text{C}}}
\]
FSBP% F = \frac{(FSBP_{t,10°C} \times 100)}{FSBP_{t,30°C}}

FSBP% G = \frac{(FSBP_{t,15°C} \times 100)}{ASP_{15°C}}

FSBP% H = \frac{(FSBP_{t,10°C} \times 100)}{ASP_{10°C}}

where FSBP = finger systolic blood pressure, t = test finger, ref = reference finger (thumb) and ASP = systolic blood pressure measured in the arm.

Non-parametric statistical tests were used to analyse the data which differed significantly from a normal distribution. Receiver operating characteristics (ROC) analysis was used to establish the optimum cut-off that minimized the false positive and negative results for distinguishing between groups and the sensitivity and specificity of tests. A disease prevalence of 40%, similar to that seen in our referral centre, was used to derive the positive and negative predictive values (PPV and NPV). The diagnostic accuracies of different test outcome metrics were investigated by comparison of the areas under the ROC curves.

In addition to investigating the diagnostic power to distinguish between normal subjects and those with a high Stockholm Workshop vascular stage, the ability of tests to detect reported blanching on a specific finger was also assessed.

Results

Table 1 presents information regarding age, room temperature, time between assessment and FSBP testing and years of vibration exposure. The HAVS referrals were slightly older than the controls at the time of testing (P = 0.06). The room temperatures when the tests were performed were the same for both groups.

The median Griffin score for each finger on the right hand for the HAVS referrals was identical (median = 3). Therefore, in the following analysis, results for only one finger (middle finger on the right hand chosen arbitrarily) or an average of all fingers on the right hand are shown.

For each outcome parameter the median value on the right middle finger was lower in the HAVS referral group than the controls, but with considerable overlap between groups. After correcting for multiple comparisons using the Bonferroni correction these differences were only significant for FSBP% C (P = 0.018; Figure 1) rather than other FSBP parameters or FST T4°C. The variability in the measurements was large with some individuals showing blood vessel closure and an FSBP of zero. An FSBP of zero was measured in the middle finger in one laboratory control at 10°C and three HAVS cases at 15 and 10°C (Figure 1).

ROC analysis was performed to calculate the optimum cut-off and diagnostic accuracy of each FSBP parameter (Table 2). Sensitivities ranged between 43.5 and 60.9% and specificities between 90.5 and 95.2% on the middle finger and were similar for averages of outcome metrics across fingers (Table 3). The calculated PPV and NPV for

### Table 1. General information about the control and HAVS referrals groups

<table>
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<tr>
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<th>Controls</th>
<th>HAVS referrals</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>43.3 (10.0)</td>
<td>48.7 (7.9)</td>
</tr>
<tr>
<td>Room temperature (°C)</td>
<td>22.7 (0.9)</td>
<td>22.7 (0.8)</td>
</tr>
<tr>
<td>Time between assessment and FSBP (years)</td>
<td>–</td>
<td>0.7 (0.6)</td>
</tr>
<tr>
<td>Vibration exposure (years)</td>
<td>–</td>
<td>26.8 (8.2)</td>
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<td>Currently using vibrating tools in workplace (%)</td>
<td>–</td>
<td>46</td>
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Values shown in table are mean and (SD).

Figure 1. Comparison of each FSBP% parameter and T4°C in the two groups. Scatterplots showing each value of FSBP (%) and time to rewarm by 4°C measured on the middle finger of the right hand for the controls and HAVS referrals. Measurements of FSBP at 15°C are shown in A and at 10°C in B. The values for time to rewarm by 4°C are shown in C. The black horizontal line represents the median for each group.
The FSBP showed maxima of 88 and 77.6%, respectively, with different parameters having little effect on the calculated values. FSBP% C gave the greatest area under the ROC curve, but was not statistically significantly different to any of the other parameters. The time to rewarm by 4°C for FST had a higher sensitivity and lower specificity than FSBP, but the area under the ROC curve was not statistically significant from that for FSBP parameter C ($P = 0.651$; Figure 2).

The diagnostic power of the tests to identify the presence of reported blanching on the middle finger did not show any improvement. For example, for FSBP% C on the middle finger the sensitivity was 60%, specificity was 84.1%, PPV was 71.5%, NPV was 75.9% and the area under the ROC curve was 0.73 (confidence interval of 0.60–0.83). The corresponding values for sensitivity, specificity, PPV and NPV for FST using $T_4^\circ C$ were 68, 71, 61 and 77%, respectively.

### Discussion

This study has compared the diagnostic value of two techniques for assessing vascular responsiveness to cold in HAVS cases. The FSBP test investigates arterial tone during the cold challenge, while the FST test investigates vasodilatory changes after cold challenge. The techniques have been compared for their abilities to discriminate between controls and individuals with Stockholm Workshop stage 2 or 3V. Although using relatively small cohorts, care was taken to obviate subject misclassification and tests were performed under carefully controlled conditions by the same experienced HAVS investigators.

| Table 2. Diagnostic accuracy of FSBP parameters and $T_4^\circ C$ on the middle finger to distinguish between laboratory controls and stage 2/3V HAVS |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
| FSBP (%) | Cut-off | Sensitivity | Specificity | Positive predictive value | Negative predictive value | ROC area (95% CI) |
| A | $\leq 62.4$ | 43.5 | 95.0 | 85.3 | 71.6 | 0.73 (0.58, 0.86) |
| B | $\leq 79.5$ | 47.6 | 95.2 | 87.0 | 73.2 | 0.67 (0.51, 0.80) |
| C | $\leq 79.5$ | 59.1 | 90.5 | 80.5 | 76.8 | 0.78 (0.62, 0.89) |
| D | $\leq 74.0$ | 52.4 | 95.2 | 88.0 | 75.0 | 0.70 (0.54, 0.83) |
| E | $\leq 68.7$ | 47.8 | 95.2 | 87.0 | 73.2 | 0.73 (0.58, 0.86) |
| F | $\leq 70.3$ | 47.6 | 95.2 | 87.0 | 73.2 | 0.71 (0.55, 0.84) |
| G | $\leq 57.3$ | 60.9 | 90.5 | 81.0 | 77.6 | 0.72 (0.56, 0.84) |
| H | $\leq 56.7$ | 52.4 | 90.5 | 78.6 | 74.0 | 0.70 (0.54, 0.83) |
| $T_4^\circ C$ | $>276$ | 70.8 | 77.3 | 67.5 | 79.9 | 0.69 (0.54, 0.82) |

| Table 3. Diagnostic accuracy of FSBP parameters and $T_4^\circ C$ (average over all fingers on right hand) to distinguish between laboratory controls and stage 2/3V HAVS |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
| FSBP (%) | Cut-off | Sensitivity | Specificity | Positive predictive value | Negative predictive value | ROC area (95% CI) |
| A | $\leq 74.7$ | 60.9 | 80.0 | 67.0 | 75.4 | 0.72 (0.56, 0.84) |
| B | $\leq 61.1$ | 42.9 | 90.5 | 75.0 | 70.4 | 0.68 (0.52, 0.81) |
| C | $\leq 80.9$ | 63.6 | 85.7 | 74.8 | 78.0 | 0.75 (0.60, 0.87) |
| D | $\leq 92.9$ | 85.7 | 57.1 | 57.1 | 85.7 | 0.72 (0.56, 0.85) |
| E | $\leq 78.2$ | 60.9 | 85.7 | 74.0 | 76.7 | 0.71 (0.55, 0.84) |
| F | $\leq 68.3$ | 52.4 | 90.5 | 78.6 | 74.0 | 0.71 (0.55, 0.84) |
| G | $\leq 61.7$ | 56.5 | 85.7 | 72.5 | 74.7 | 0.70 (0.54, 0.83) |
| H | $\leq 71.6$ | 61.9 | 71.4 | 59.1 | 73.8 | 0.69 (0.53, 0.82) |
| $T_4^\circ C$ | $>261$ | 75.0 | 77.3 | 68.8 | 82.3 | 0.73 (0.58, 0.85) |

Figure 2. ROC curves for discrimination between the two groups for FSBP% and $T_4^\circ C$ on the middle finger of the right hand.
The FST cold-provocation test of 15°C for 5 min, that has been most notably used in the UK Department of Trade and Industry (DTI) compensation scheme for coalminers [19], was found to give a wide range of results in normal subjects. The median time to rewarm by a set temperature failed to show a statistically significant difference between cases and controls (Figure 1). The sensitivity and specificity in this study of FST using T4°C as outcome measure were relatively low at 70.8 and 77.3%, respectively. We also found that this technique was no better at discriminating between individuals who did or did not report blanching on an individual finger and that averaging rewarming rates across fingers of the hand did not significantly aid the diagnostic power. Concerns about the FST in this format have been raised in medico-legal populations [10,11,19]. Overall, it would appear that the FST technique in the form used in this study is not useful in the diagnosis of individuals staged according to the Stockholm Workshop Scale and does not confirm self-reported blanching.

Other investigators, using a variety of provocation challenges as part of a FST test [2,7,20–29], have reported variable sensitivities and specificities (sensitivity 22–73% and specificity 43–100%) and it has been suggested that more complex assessment of the cold-challenge–rewarming profile may be more diagnostically useful [5,28,30].

The measurement of FSBP during cold provocation has been proposed as a suitable test for identifying the cold-induced digital vasospasm of HAVS. A number of published studies of FSBP performed under a number of conditions have detailed its sensitivity and specificity (see Table 4). The reported sensitivities appear somewhat variable, although Bovenzi's Italian group [17], which has investigated considerable numbers, has reported consistently high sensitivities. Reported specificities are less variable and generally high. FSBP is usually calculated as the percentage difference between the baseline and cold-challenge digital pressure measurements, corrected for changes in systemic blood pressure measured either in a reference finger or brachially. Failure in digital arterial reopening (i.e. FSBP0%) has also been used as a diagnostic criterion [17,31,32]. Some investigators have used body cooling in addition to local cooling of the digits, which would certainly lead to greater digital vasospasm via a central sympathetically driven response [4,31]. The FSBP has been less widely used and reported on than variants of the FST test.

In this study there was a tendency for the median FSBP% to be lower in the HAVS group compared to the

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<th>Table 4. Summary of publications reporting sensitivity and specificity for FSBP measurements in hand–arm vibration syndrome</th>
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<td>Ref.</td>
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Abbreviations: VWF, vibration white finger; VE, vibration exposed; FSBP(0), finger systolic blood pressure of 0 mmHg; SWS, Stockholm Workshop Scale; Room temp., room temperature; Sens., sensitivity; Spec., specificity; PPV, positive predictive value; NPV, negative predictive value.
controls, but only the FSBP% C parameter showed significant differences between groups. ROC analysis suggested that the test does have an ability to distinguish between laboratory controls and stage 2/3V on a group basis. However, no specific means of calculating a FSBP result was significantly better than the others. We have concerns about the use of a reference finger or thumb in FSBP measurement, given the possibility for occult vascular damage on any reference digit and prefer a brachial blood pressure reference. Our data show that this is as satisfactory as other methods of referencing.

Our calculated sensitivities for FSBP parameters appear to be relatively low (43.5–60.9%) and generally lower than those reported in the literature (Table 4), but our calculated specificities were high (90.5–95.2%). Some investigators have measured FSBP in the supine position rather than the seated position that we used. Although there is no published evidence for the effects of such an experimental difference, it may be a contributory factor through subtle postural changes influencing the autonomic nervous system control of peripheral blood pressure. We found FSBP was not significantly better at predicting blanching on a specific finger, nor that averaging across fingers of a hand helped its discriminative power. Obvious differences with Bovenzi’s studies remain as the postural position during measurement, differences in the FSBP equipment used and that Bovenzi tested a single finger based on anamnesis of worst finger, while we have largely reported on the middle finger. The last difference may not be important as our group largely had similar severity across all fingers of the hand.

Other investigators have also used the measurement of an FSBP0% (i.e. no reopening) as their diagnostic criteria for VWF [17,31,32]. This was detected in this study for one control and three HAVS cases and therefore would not improve diagnostic ability.

Comparison was made of the ROC analyses between FST and FSBP. There was little difference between the areas under the ROC curves for these measurements. However, our calculated NPV and PPV suggest that FSBP is relatively more useful in ruling in a diagnosis of vibration-induced vascular problems, whereas both tests are largely equivalent in ruling out the diagnosis.

In conclusion, using the specific test conditions applied in this study, there is little evidence that FST after cold provocation is a useful diagnostic test for vascular HAVS. This study does not necessarily indicate that an FST-based test may not be diagnostically useful in some form, but possibly that the nature of the cold challenge or the simplistic use of a single outcome metric is not appropriate. The sensitivity of FSBP in the present study was found to be lower than that reported in some studies. The cause of this difference is unclear and makes definite conclusions on the value of FSBP test within a diagnostic strategy problematic.

References
4. Kurozawa Y, Nasu Y, Nose T. Diagnostic value of finger


