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Socioeconomic status and hemodynamic recovery from mental stress

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Abstract

We assessed the changes in cardiac index and total peripheral resistance underlying blood pressure reactions and recovery from acute mental stress, in relation to socioeconomic status. A sample of 200 men and women aged 47–59 years was divided on the basis of occupation into higher, intermediate, and lower socioeconomic status groups. Blood pressure was monitored using the Portapres, and hemodynamic measures were derived by Modelflow processing of the arterial pressure waveform. Blood pressure increases during two stressful behavioral tasks were sustained by increases in cardiac index and total peripheral resistance. During the 45-min posttask recovery period, cardiac index fell below baseline levels, whereas peripheral resistance remained elevated. Peripheral resistance changes during recovery varied with socioeconomic status and blood pressure stress reactivity, with particularly high levels in reactive low status participants. Results are consistent with the hypothesis that disturbances of stress-related autonomic processes are relevant to the social gradient in cardiovascular disease risk.

Descriptors: Stress, Hemodynamics, Recovery, Socioeconomic status, Peripheral resistance

Acute blood pressure responses to mental stress are underpinned by increases in cardiac output, total peripheral resistance, or a combination of the two. Understanding these hemodynamic processes has greatly benefited from the development of noninvasive measures of stroke volume, cardiac output, and vascular resistance. Nevertheless, uncertainty remains about whether vascular or cardiac responses are more significant from the perspective of cardiovascular pathology. Early work developed the notion proposed by Obrist (1976) that cardiac hyperreactivity might be particularly significant because of parallels with the elevated cardiac output characteristic of the formative stages of hypertension. But established hypertension is predominantly sustained by raised systemic vascular resistance, and doubts have been raised over the transition between high cardiac output and high peripheral resistance (Fagard, Staessen, & Amery, 1997). Various lines of research suggest that raised peripheral resistance both at rest and in response to stress is related to enhanced cardiovascular disease risk (Fagard, Pardaens, Staessen, & Thijs, 1996). Peripheral resistance increases with age (Lakatta, 1993), as does peripheral resistance responsivity to mental stress (Jennings et al., 1997). Blood pressure responses to stress are maintained to a greater extent by increased vascular resistance in black than white hypertensives (Sherwood, May, Siegel, & Blumenthal, 1995). Young adults with two hypertensive parents in the Dutch Hypertension and Offspring Study showed larger vascular responses to a reaction time task than the comparison group (de Visser et al., 1995), and other studies of family history of hypertension have also implicated enhanced vascular resistance (Lovallo & al'Absi, 1998). Investigations of patients with coronary artery disease indicate that stress-induced reductions in left ventricular ejection fraction are inversely associated with changes in peripheral vascular resistance (Goldberg et al., 1996; Jain et al., 1998). An association between peripheral resistance, stress responsivity, and hostility has also been described (Davis, Matthews, & McGrath, 2000).

Research in this field has primarily focused on acute responses to mental stress, with less attention being paid to patterns of recovery. However, delayed poststress recovery appears to be associated with heightened disease risk (Hocking Schuler & O'Brien, 1997). The theory of allostasis places particular emphasis on disturbances of poststress recovery as manifestations of sustained dysfunction (McEwen, 1998). Acute mental stress has effects on vascular endothelial function and inflammatory cytokine release that are only apparent 30–120 min following challenge (Ghiadoni et al., 2000; Steptoe, Willemsen, Owen, Flower, & Mohamed-Ali, 2001). Animal work indicates that blood pressure elevations during poststress recovery are greater in vascular than cardiac responders (Muller, Le, Haines, Gan, & Knuepfer, 2001). Recently, it has been found that

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delayed heart rate recovery following physical exercise is an independent predictor of mortality in patients with coronary heart disease (Watanabe, Thamilarasan, Blackstone, Thomas, & Lauer, 2001).

Studies that have assessed cardiac output and total peripheral resistance during poststress recovery in humans have been confined to short periods of less than 5 min, and we have not identified any experiments that have measured cardiac or vascular indices for more than 10 min following stress termination (Anderson, Lane, Taguchi, Williams, & Houseworth, 1989; Boutcher, Nurhayati, & McLaren, 2001; Davis et al., 2000; de Visser et al., 1995; Gillin et al., 1996; Gregg, James, Matyas, & Thorsteinsson, 1999). The first aim of this study was therefore to characterize vascular and cardiac responses associated with blood pressure during recovery, with measures taken at 15–20 and 40–45 min after behavioral tasks. Individual differences in stress reactivity are potentially pathogenic, so we assessed whether high systolic blood pressure reactivity was associated with enhanced peripheral resistance adjustments during the recovery period.

These issues may be significant in the context of studies of the psychobiological processes underlying socioeconomic differences in cardiovascular disease risk. There is substantial evidence from across the developed world that low socioeconomic status as defined by occupation, education, or income is associated with an increase risk of coronary heart disease and stroke (Stansfeld & Marmot, 2002). The social gradient is partly accounted for by behavioral factors such as smoking, but socioeconomic differences persist after these factors are taken into account, suggesting that other processes are also involved (Lynch, Kaplan, Cohen, Tuomilehto, & Salonen, 1996). Disturbed psychophysiological responsivity may be an important mediating pathway (Steptoe & Marmot, 2002). One of the best established methods of assessing psychophysiological responsivity is standardized mental stress testing. However, studies assessing blood pressure and heart rate reactions during acute mental stress in adults have presented a mixed picture, with both positive and negative associations with socioeconomic status (Carroll, Davey Smith, Sheffield, Shipley, & Marmot, 1997; Carroll et al., 2000; Lynch, Everson, Kaplan, Salonen, & Salonen, 1998; Owens, Stoney, & Matthews, 1993). We have argued that this might be due to two factors: failure to ensure that behavioral stimuli elicit similar levels of engagement or involvement in people of varying social status, and the limiting of measurements to task periods (Steptoe & Marmot, 2002).

In the present study, we therefore compared both stress reactions and recovery in men and women systematically sampled across the social gradient, in relation to tasks that elicited similar levels of engagement, perceived difficulty, and controllability from the different social groups. In a companion paper, we have recently described how a lower socioeconomic status is associated with impaired posttask recovery of blood pressure, heart rate, and heart rate variability, after controlling for baseline levels, magnitude of task reactivity, age, and sex (Steptoe et al., 2002). In the present article, we describe the cardiac and vascular correlates of these changes in blood pressure, testing the hypothesis that low socioeconomic status would be associated with greater peripheral resistance during recovery. The study also illustrates the use of the Modelflow method of assessing cardiac output and peripheral resistance, as this technique has as yet had little application in psychophysiology, but which may prove to be a valuable complement to impedance electrocardiography.

Methods

Participants

Participants were drawn from the Whitehall II cohort, a sample of 10,308 London-based civil servants recruited in 1985–1988 when aged 35–55 years to investigate demographic, psychosocial, and biological risk factors for coronary heart disease (Marmot et al., 1991). This sample was used firstly because of the extensive clinical, biological, and behavioral data available on the participants, and secondly because grade of employment in the British civil service has been established as a marker of socioeconomic status, and is inversely related to coronary heart disease incidence and mortality (Marmot, Bosma, Hemingway, Brunner, & Stansfeld, 1997; Marmot, Shipley, & Rose, 1984). Employment grade in the British civil service correlates highly with income and educational attainment. Participants in this psychobiological substudy were recruited on the following criteria: white European origin, aged 45–59 years, based in the London area, not planning to retire for at least 3 years, no history or objective signs of coronary heart disease, and no previous diagnosis or treatment for hypertension. The age range was selected so as to ensure that participants were of working age. They were drawn equally from higher (administrative and professional), intermediate (senior executive officers), and lower (executive officers, clerical, office support) employment grades. Two hundred forty civil servants were recruited, and the response rate was 55%, being greater in higher than lower status participants. Invitations were based on employment status 5 years earlier, and by the time of the study, the position of some participants had altered due to promotion and job changes. Participants were classified on the basis of current occupation. Cardiovascular data were lost from 12 individuals due to equipment failure, and data across trials were incomplete in another 28. The final sample therefore numbered 200, made up of 75 higher grade (42 men, 33 women), 65 intermediate grade (34 men, 30 women), and 61 lower grade (31 men, 30 women) participants. There were no important differences between participants included in the analyses and those with incomplete data.

Equipment

Cardiovascular monitoring was carried out continuously from the finger using a Portapres-2, a portable version of the Finapres device that shows good reproducibility and accuracy for the measurement of blood pressure and heart rate in a range of settings (Castiglioni et al., 1999; Imholz et al., 1993). Cardiac output and stroke volume were determined from the Portapres using the aortic flow waveform method described by Wesseling, Jansen, Settels, and Schreuder (1993), and embodied in Modelflow 2.1 software (TNO, Amsterdam, the Netherlands). Stroke volume is calculated from the systolic area—the area under the arterial pressure wave between the onset of the blood pressure rise and the dichrotic notch—on a beat-by-beat basis corrected by a calibration factor that relates to aortic compliance. Peripheral vascular resistance was predicted from mean pressure and computed aortic flow. Good agreement has been obtained between Modelflow™ computations of stroke volume and cardiac output from intra-arterial and finger blood pressure measures, and between finger-based measures and thermodilution (Gratz et al., 1992; Jansen, Wesseling, Settels, & Schreuder, 1990; Jellema, Imholz, van Goudoever, Wesseling, & van Lieshout, 1996). Poorer agreement has been observed during exercise (Houtman, Oeseburg, & Hopman, 1999), and some investigators argue that the method is better suited to track changes in hemodynamics rather than absolute values (Nieminen, Koobi, & Turjanmaa, 2000).

Additional measures of blood pressure were obtained periodically using standard brachial sphygmomanometry with an A&D UA 779 electronics sphygmomanometer, an instrument that complies with American Association for the Advancement of Medical Instrumentation/British Hypertension Society criteria.

Behavioral Tasks

Mental stress was induced by two behavioral tasks. The first was a computerized color–word interference task as used in a number of previous psychophysiological studies (Manuck et al., 1996; Muldoon et al., 1992). This involved the successive presentation of target color words (e.g., *green*, *yellow*), printed in another color. At the bottom of the computer screen were four names of colors, again printed in incongruous colors. The task was to press a computer key that corresponded to the position at the bottom of the screen of the name of the color in which the target word was printed. The rate of presentation of stimuli was adjusted to the performance of the participant, to ensure sustained demands. The second task was mirror tracing, involving the tracing of a star with a metal stylus that could only be seen in mirror image (Owens et al., 1993). Each time the stylus came off the star a mistake was registered and a loud beep was emitted by the apparatus (Lafayette Instruments Corp., Lafayette, IN, USA). Participants were told that the average person completed five circuits of the star in the time available, and were asked to give accuracy priority over speed on both tasks.

Procedure

Participants were tested in either the morning or afternoon in a light- and temperature-controlled laboratory. They were instructed not to have drunk tea, coffee, or caffeinated beverages, or to have smoked for at least 2 hr prior to the study, and not to have consumed alcohol or exercised on the evening before or the day of testing. The study was approved by the UCL/UCLH Committee on the Ethics of Human Research.

Following instrumentation and the insertion of a venous cannula for the periodic collection of blood samples (not described here), the participant rested for 30 min. Cardiovascular data were recorded for the last 5 min of this period (baseline trial), and two measures using the standard arm cuff were also obtained. A rating was taken of subjective stress on a scale from 1 = *low stress* to 7 = *high stress*. The two behavioral tasks were then administered in random order. Each task lasted 5 min, during which blood pressure and heart rate were recorded continuously. Following each task, the participant rated task difficulty, involvement, degree of control, and feelings of stress on a series of 7-point scales from 1 = *low* to 7 = *high*. Five-minute recordings of blood pressure and heart rate were made between minutes 15 and 20 and 40 and 45 of the 45-min posttask period, during which the participant rested quietly, reading or watching nature videos. A final stress rating was obtained at the end of the recovery period.

Data Reduction and Statistical Analysis

Systolic pressure, diastolic pressure, heart rate, cardiac output, stroke volume, and total vascular resistance were averaged into 5-min means for baseline, the two tasks, and two recovery periods. Measures obtained during tasks were averaged to produce a mean task value. Cardiac output and stroke volume were transformed into cardiac index and stroke volume index by correcting for body surface area. Data were analyzed using repeated measures analysis of variance with sex and grade of employment as between-subject factors, and trial (baseline, tasks, recovery 1, recovery 2) as the within-subject factor. The Greenhouse–Geisser ε was applied where appropriate. The association between hemodynamic responses and blood pressure reactivity was analyzed by dividing the sample into low and high systolic pressure reactors on the basis of median split of changes between baseline and tasks.

The blood pressure, heart rate, and subjective results are detailed elsewhere, and will only be summarized in as much as they relate to the patterns of vascular and cardiac response in the study (Steptoe et al., 2002).

Results

The baseline characteristics of the sample are summarized in Table 1. The occupational grade groups did not differ in proportion of men and women or in body mass index. Despite the limited age range, there was a significant Grade $\times$ Sex interaction, $F(2,194) = 3.08$, $p < .05$. Lower grade men were slightly older than those in intermediate and higher grades, $F(2,104 = 6.26$, $p < .005$, whereas there were no differences among women. As expected, smoking was inversely associated with socioeconomic status among men, $\chi^2 = 4.10$, $p < .05$. Overall, 24 of the 93 women (25.8%) were taking hormone replacement therapy, but the proportion did not differ with socioeconomic status. There was a significant sex difference in cardiac index at baseline, with higher values in women than men, $F(1,194) = 11.6$, $p < .001$. There were no differences by grade of employment or sex in stroke volume index or peripheral vascular resistance. Portapres systolic and diastolic pressures were higher in men than women, $F(1,194) = 22.7$ and 8.07, respectively, $p < .005$, but did not differ by grade. This pattern was paralleled by brachial sphygmomanometer measures of blood pressure, with higher systolic and diastolic values in men, $F(1,194) = 22.5$ and 8.30, $p < .005$. Baseline heart rate did not differ by grade of employment or sex when measured with the Portapres, but there was sex difference in heart rate measured by sphygmomanometry, with higher levels in women, $F(1,194) = 5.08$, $p < .05$. Systolic and diastolic pressure were on average 2.6 and 2.8 mmHg higher at baseline when measured from the upper arm than the finger, $F(1,197) = 56.2$ and 104.4, respectively, $p < .001$. However, Portapres and sphygmomanometer measures at baseline were highly correlated, $r = .93$ for systolic pressure and .91 for diastolic pressure, $p < .001$.

Hemodynamic Responses during Stress and Recovery

Repeated measures analyses showed significant main effects of trial for cardiac index and peripheral vascular resistance, $F(3,582) = 239.8$ and 129.8. respectively, $\varepsilon = .76$ and .73, $p < .001$. These responses are summarized in Figure 1. There were significant increases in both cardiac index and total peripheral resistance during the task trials, averaging 6.6% for cardiac index and 20.1% for peripheral vascular resistance, $F(1,194) = 66.9$ and 226.4, respectively, $p < .001$. Subsequently, cardiac index fell to levels below baseline both in recovery 1 and 2, $F(1,194) = 198.9$ and 223.9, respectively, $p < .001$. By contrast, peripheral vascular resistance remained above baseline during

Table 1. *Baseline Characteristics of the Three Employment Grades*

	Higher ($n = 75$)		Intermediate ($n = 64$)		Lower ($n = 61$)	
Employment grade	Men	Women	Men	Women	Men	Women
N (%)	42 (56%)	33 (44%)	34 (53.1%)	30 (46.9%)	31 (50.8%)	30 (49.2%)
Age	52.1±2.6	51.2±2.2	51.9±2.3	52.3±2.9	53.9±2.8	52.0±2.7
BMI	25.9±3.0	25.8±4.4	26.5±3.9	24.9±4.0	25.6±3.0	25.8±4.3
Cigarette smokers	1 (2.4%)	2 (6.1%)	4 (12.1%)	3 (10.0%)	5 (16.1%)	2 (6.9%)
Cardiac index (l/min/m^2)	3.23±0.46	3.57±0.53	3.26±0.52	3.64±0.49	3.41±0.57	3.47±0.61
Stroke volume index (ml/beat/m^2)	49.4±6.6	52.4±6.7	52.0±11.3	54.5±8.5	52.3±7.8	52.8±10.1
Total peripheral resistance (dyne/cm^5/s)	749.2±137	689.4±179	736.8±189	667.3±150	730.3±156	790.3±234
Systolic pressure (mmHg)						
Manual	122.1±12.0	110.2±13.8	123.4±15.7	113.4±13.1	122.0±12.6	116.3±14.8
Portapres	120.2±10.9	110.8±13.3	119.5±14.5	108.0±13.0	118.8±12.2	113.7±13.1
Diastolic pressure (mmHg)						
Manual	74.9±8.1	70.6±10.3	76.2±9.8	71.5±9.8	74.9±9.6	72.4±9.0
Portapres	72.2±6.9	68.5±10.3	73.2±10.8	67.9±10.9	71.7±10.3	68.8±9.2
Heart rate (bpm)						
Manual	62.2±9.6	66.0±7.1	61.2±9.5	65.6±8.0	63.3±10.2	63.9±7.8
Portapres	64.7±8.7	66.9±6.8	62.5±9.6	67.3±7.3	65.0±10.4	64.6±6.9

Note: Means±standard deviations.

both recovery trials, $F(1,194) = 256.9$ and 318.3, respectively, $p < .001$. Peripheral vascular resistance did not differ in recovery 1 and during tasks, but by recovery 2, resistance was higher than during the tasks themselves, $F(1,194) = 516$, $p < .05$.

A different pattern was observed for stroke volume index. There was a main effect of trial, $F(3,579) = 27.1$, $\varepsilon = 0.82$ $p < .001$, but as can be seen in Table 2, this was due to a progressive reduction in stroke volume over trials. Thus the stroke volume during tasks was lower than at baseline, $F(1,194) = 6.11$, $p < .05$, and remained lower during recovery. Stroke volume during tasks was higher than the level during recovery trial 1, $F(1,193) = 13.2$ $p < .001$, whereas recovery trial 2 was lower again, $F(1,193) = 10.7$, $p < .001$. These hemodynamic response patterns did not differ with age or smoking status.

The blood pressure, heart rate, and subjective responses are briefly summarized in Table 2. Significant effects for trial were recorded for systolic and diastolic pressure, $F(3,579) = 293.8$ and 308.7, respectively, $\varepsilon = .64$ and .88, $p < .001$, and for heart rate, $F(3,576) = 284.9$, $\varepsilon = .70$, $p < .001$. The behavioral tasks elicited increases averaging 19.3% systolic pressure, 19.0% diastolic pressure, and 10.4% heart rate. During the recovery phase, systolic and diastolic pressure remained elevated above baseline both at 15–20 and 40–45 min, $p < .001$. Heart rate, by contrast, fell below baseline levels in both recovery trials, $p < .001$.

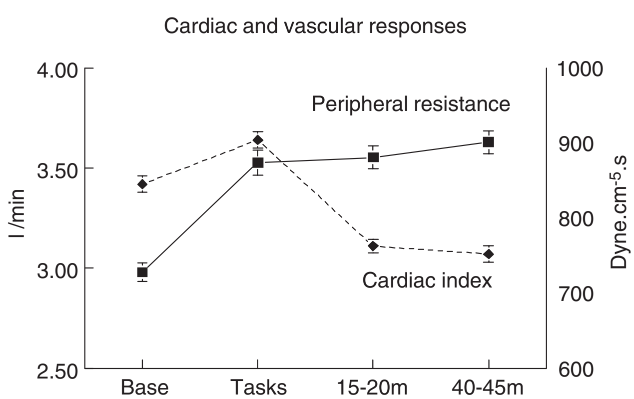

Figure 1. Mean levels of total peripheral resistance (dyne/cm^5/s) and cardiac index (l/min) at baseline, during the averaged task trials, and recovery 1 (15–20 min posttask) and recovery 2 (40–45 min posttask). Error bars are *SEM*.

Analyses of the subjective ratings indicated that participants found tasks to be difficult, engaging, uncontrollable, and moderately stressful (Steptoe et al., 2002). There were no differences by grade of employment or sex in task appraisal. Stress ratings (Table 2) showed an increase immediately following tasks, and a return to baseline by the end of recovery, with no differences between socioeconomic status groups, $F(2,452) = 628.2$, $\varepsilon = .66$, $p < .001$.

Socioeconomic and Sex Differences in Hemodynamic Response

There was no significant interaction between trial and grade or sex in the analysis of cardiac index. Total vascular resistance showed a Grade × Sex interaction, $F(2,194) = 3.3$, $p < .05$, and again no interaction with trial. Across all trials, there was no difference between grades in men. But among women, participants in the lower grade of employment had higher peripheral vascular resistance (934.7±244 dyne/cm^5/s) than those in the intermediate (820.2±188 dyne/cm^5/s) or higher (800.2±188 dyne/cm^5/s) grades, $F(2,90) = 3.74$, $p < .05$. These patterns were not affected by the use of hormone replacement treatment.

In the case of stroke volume index, the interaction between sex and trial was significant, $F(3,579) = 6.47$, $\varepsilon = .82$, $p < .001$. Post hoc analyses indicated that this resulted from a greater decrease in stroke volume index over trials in women and men. In women, stroke volume index declined from 53.2±8.5 at baseline to 49.4±8.2 ml/beat/m^2 in the second recovery trial, compared with 51.0±8.6 to 49.1±8.8 ml/beat/m^2 in men. There were no associations between hemodynamic measures and stress ratings or subjective appraisals of behavioral task performance.

Table 2. *Blood Pressure, Stroke Volume, Heart Rate and Subjective Responses to Tasks*

	Baseline	Tasks	Recovery 1 (15–20 min)	Recovery 2 (40–45 min)
Systolic blood pressure (mmHg)	115.3 ± 13.3	137.6 ± 19.8	120.9 ± 14.7	121.2 ± 15.5
Diastolic blood pressure (mmHg)	70.5 ± 9.8	83.9 ± 11.6	74.9 ± 10.8	75.3 ± 11.2
Heart rate (bpm)	65.2 ± 8.5	72.0 ± 10.0	63.0 ± 8.3	63.4 ± 8.1
Stroke volume index (ml/beat/m^2)	52.0 ± 8.6	51.4 ± 9.1	50.1 ± 8.7	49.2 ± 8.5
Stress rating (1–7)	1.43 ± 0.76	3.99 ± 1.42		1.38 ± 0.71

Note: Means ± standard deviations.

Hemodynamic Responses and Blood Pressure Reactivity

The median systolic pressure increase from baseline to task trials was 21.9 mmHg. Division by median split produced two groups with reactions to tasks averaging 12.1 ± 6.1 mmHg and 33.4 ± 9.2 mmHg. Systolic reactivity status did not vary by sex or grade of employment.

In the analysis of cardiac index, the interaction between systolic reactivity and trial was significant, $F(3,561) = 13.3$, $\varepsilon = .79$, $p < .001$. There was a larger increase in cardiac index during tasks in the high systolic reactors (averaging 0.43 l/m) than in the low systolic reactors (0.12 l/m). There were no further effects involving systolic reactivity status in the analysis of cardiac index. But in the case of peripheral vascular resistance, both the Grade × Systolic Reactivity, $F(2,187) = 3.08$, $p < .05$, and the Grade × Systolic Reactivity × Trial interactions were significant, $F(6,561) = 3.37$ $\varepsilon = .75$, $p < .01$. These interactions were decomposed by analyzing the effects of systolic reactivity separately for each grade of employment. The results are summarized in Figure 2. In the higher grade participants, systolic reactivity had no impact on peripheral vascular resistance. In the intermediate group, systolic reactivity groups varied in response to tasks, with larger increases in peripheral vascular resistance during tasks among high systolic reactors, $F(3,180) = 5.06$, $\varepsilon = .72$, $p < .01$. In the lowest socioeconomic group, there was a main effect of systolic reactivity, $F(1,57) = 8.24$, $p < .01$, with greater peripheral vascular resistance during all trials in the high and low systolic reactor groups. This is consistent with the notion that socioeconomic status moderates the impact of blood pressure reactivity on peripheral vascular resistance responses to stress.

There was no interaction between grade of employment and systolic reactivity in the analysis of heart rate. But the Grade × Systolic Reactivity × Trial interaction was significant for stroke volume index, $F(6,558) = 2.76$, $\varepsilon = .82$, $p < .025$. However, this interaction was not easily interpretable. There were no differences in stroke volume changes across trial in the different grades of high systolic reactors. Among low systolic reactors, there were nonsystematic variations in stroke volume index responses across grades of employment.

Discussion

The main findings in this study were that blood pressure adjustments during the poststress recovery period were predominantly sustained by increased total peripheral resistance, with cardiac output returning relatively rapidly to baseline levels, and that socioeconomic status interacted with blood pressure reactivity in determining raised vascular tone. The Modelflow technique for analyzing hemodynamic responses from Portapres recordings provided useful data concerning variations in stroke volume and computed cardiac output and total peripheral resistance. The method was developed using intra-arterial brachial pressure recordings, but has proved to operate effectively with noninvasive finger blood pressure data (Harms et al., 1999). Differences in stroke volume computed from intra-arterial brachial pressure and finger blood pressure average 2–3%, so there may have been some underestimation of absolute levels in

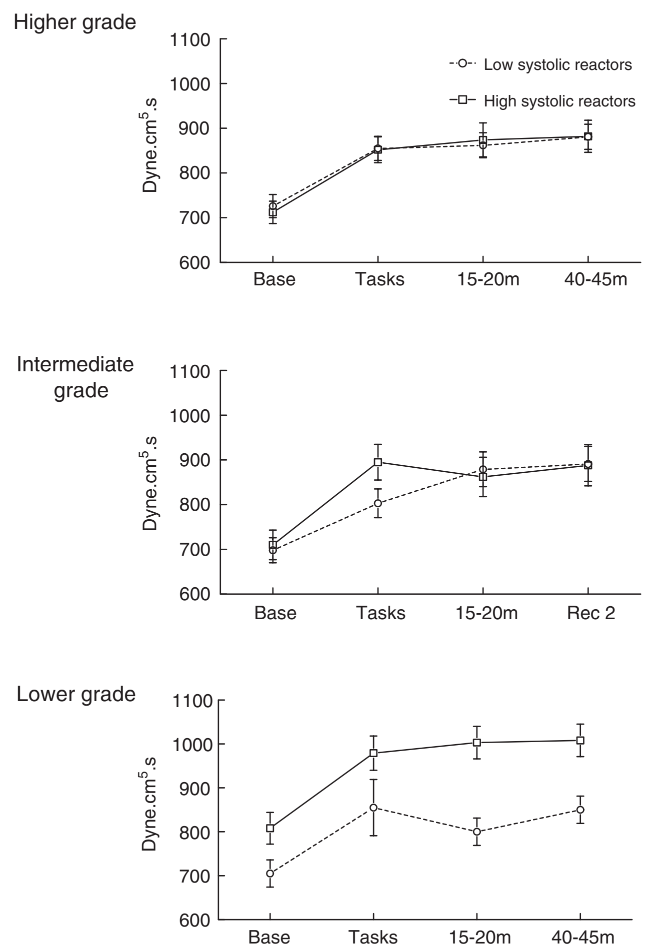

Figure 2. Total peripheral resistance (dyne/cm^5/s) in high and low systolic reactors in higher grade (top panel), intermediate grade (center panel) and lower grade (lower panel) of employment groups, recorded at baseline, during the averaged task trials, and recovery 1 (15–20 min posttask) and recovery 2 (40–45 min posttask). Error bars are *SEM*.

this study (Jellema, Imholz, Oosting, Wessling, & van Lieshout, 1999). Stroke volume estimates have proved relatively stable on repeated testing (Voogel & van Montfrans, 1997). The method has been used to investigate hemodynamic influences on cerebral blood flow, autonomic dysfunctions such as syncope, and the hemodynamic effects of hemodialysis (Bos et al., 2000; Diamant, Harms, Immink, van Lieshout, & van Montfrans, 2002; Freitas et al., 1999). Impedance cardiography was also carried out in our study, and it may prove possible in future analyses to carry out direct comparisons between these noninvasive indices of hemodynamic function.

The blood pressure and heart rate responses to the behavioral tasks were sustained by increases in both cardiac output and total peripheral resistance (Figure 1). A variable pattern has been observed in previous studies. Although some have shown that cardiac output and peripheral resistance both increase in response to behavioral tasks (de Visser et al., 1995; Lawler et al., 2001), others have recorded reductions in total peripheral resistance (Turner, Sherwood, & Light, 1991; Uchino, Uno, Holt-Lunstad, & Flinders, 1999). The hemodynamic changes in responses to tasks may vary with ethnic group and with psychological characteristics such as hostility (Davis et al., 2000; Sherwood et al., 1995). In addition, cardiac and vascular responder groups can be identified, so the overall pattern of hemodynamic response will depend on the proportion of each type included in the study (McCaffery, Muldoon, Bachen, Jennings, & Manuck, 2000). The likelihood of increased total peripheral resistance in response to stress rises with age (Jennings et al., 1997; Uchino et al., 1999). Our sample was in late middle-age, a critical period for the emergence of clinical coronary heart disease, so the vascular resistance changes may be particularly important. The decrease in stroke volume that we observed during tasks has been described in previous research (de Visser et al., 1995; Uchino et al., 1999).

Although blood pressure decreased during the poststress recovery period, average levels remained above baseline even after 45 min (Table 1). By contrast, heart rate and stroke volume fell below baseline during the recovery period. The residual elevation in blood pressure was therefore sustained by raised total peripheral resistance. Not only did peripheral resistance fail to decrease during recovery, it was actually greater after 40–45 min than during tasks themselves (Figure 1). Cardiovascular monitoring stopped after 45 min, so we do not know the complete time course of these responses. It will be important in future research to establish how long vascular resistance remains elevated following stress. In the light of recent data indicating that acute behavioral stress provokes delayed alterations in vascular endothelial function and in proinflammatory cytokine release (Ghiadoni et al., 2000; Steptoe et al., 2001), it appears that the impact of mental stress should be judged in terms of longer term adjustments as well as acute responses.

The phenomenon of sustained elevations in total peripheral resistance following mental stress has, to our knowledge, not been described before. This may be primarily because measurements of cardiac output and vascular resistance have not continued more than 10 min into recovery. However, the pattern resembles the shift in hemodynamic control of blood pressure adjustments that has been reported during sustained mental stress tests, with increased vascular resistance taking a more prominent role late in the stress period (Carroll & Roy, 1989). The mechanism underlying the increased vascular resistance is unknown, but it may relate to sustained changes in centrally mediated neurogenic vasoconstriction, or alternatively to disturbance of nitric-oxide-dependent endothelial function. The persistent elevation in blood pressure during recovery is associated with reduced heart rate variability, and with raised levels of inflammatory cytokines in the circulation (Steptoe et al., 2002).

The pattern of total peripheral resistance and cardiac output response varied with blood pressure reactivity. We selected systolic pressure increases with tasks as the index of stress reactivity differences for the following reasons. First, systolic pressure reactivity has been associated with a number of adverse cardiovascular outcomes, including higher future blood pressure (Light et al., 1999; Matthews, Woodall, & Allen, 1993), heightened left ventricular mass (Georgiades, Lemne, De Faire, Lindvall, & Fredrikson, 1997), the progression of atherosclerosis (Lynch et al., 1998), and the incidence of stroke (Everson et al., 2001). Second, systolic pressure reactivity has been related to noncardiovascular responses, such as immune dysfunction and cytokine production, that might be relevant to the inflammatory processes underlying coronary heart disease (Steptoe et al., 2001). Third, the socioeconomic status groups did not differ in systolic pressure reactivity. Consequently, socioeconomic differences in hemodynamic patterns were not secondary to overall differences in stress responsivity. High systolic pressure reactivity was positively associated with cardiac output during tasks, whereas total peripheral resistance showed an interesting interaction between blood pressure reactivity and socioeconomic status. Progressively lower socioeconomic status as defined by grade of employment appears to have been associated with increased disturbance in vascular regulation. There were no differences in total peripheral resistance responses in relation to systolic reactivity in the higher grade group (Figure 2). The intermediate grade of employment group showed differences in peripheral resistance only during the task period, whereas in the lower grade group, greater systolic reactivity was sustained by elevated total peripheral resistance during all trials.

This pattern is consistent with the notion that socioeconomic status may act as a trigger for the expression of individual differences in the adaptive capacity of the cardiovascular system. Socioeconomic status is inversely related to chronic work, financial, and neighborhood strain (Marmot et al., 1991; Steptoe & Feldman, 2001), whereas individual differences in blood pressure reactivity arise from a combination of genetic, early environmental, and adult lifestyle and psychosocial factors. We can speculate that in comparison with the adaptive pattern manifested by the higher socioeconomic status group, greater chronic stress in the lower status group led to expression of individual differences in reactivity in vascular processes throughout the study period. The intermediate grade group showed an intermediate pattern, with differences in vascular responses only being exhibited in the most stressful phase of the study, namely the task period.

The limitations of this study should be acknowledged. Participation was restricted to white middle-aged men and women, and hemodynamic responses may differ in other groups. The participation rate was 55%, so selection factors may have been operating. Cardiovascular monitoring only continued for 45 min poststress, and the overall time course of hemodynamic adjustments is not known. Nevertheless, the results complement our observation that poststress recovery in blood pressure and heart rate variability is inversely related to socioeconomic status, being most complete in high grade and most impaired in low grade of employment participants (Steptoe et al., 2002). The present findings suggest that in some lower social status individuals, this pattern of delayed blood pressure recovery is sustained by differences in vascular function. As suggested by the literature outlined in the Introduction, blood pressure stress responses may be particularly significant for disease if they are due to increased peripheral resistance. The disturbance in vascular resistance in reactive individuals may therefore be one of the mechanisms through which low socioeconomic status increases cardiovascular disease risk.

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