AMBULATORY MONITORING SYSTEM

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Abstract

This paper describes the Ambulatory Monitoring System (AMS) for measuring and scoring heart rate, heart rate variability, and the amount of body movement during normal daily activities. After a technical description of the system, results from a validation study are presented in which heart rate and heart rate variability measured with the AMS showed predictable variation with time of day, posture, physical activity and the type of activity that the subjects were engaged in. It is concluded that the Ambulatory Monitoring System is a valid system for non-invasive real-life monitoring of heart rate and heart rate variability.

1. Introduction

It has been widely assumed that exaggerated reactivity to laboratory stressors is a valid indicator of a tendency towards exaggerated reactivity in general, and that by measuring laboratory stress-reactivity we could index individual susceptibility to psychosomatic disease (Matthews, Weiss, Detre, Dembroski, Falkner, Manuck,& Williams, 1986). However, recent reviews have concluded that laboratory reactivity does not reflect cardiovascular activation in the field situation very well (Pickering & Gerin, 1990; van Doornen & Turner, 1992). In fact, the best correspondence between laboratory and real-life data is found when absolute levels of blood pressure (BP) and heart rate (HR) during the day are predicted from the resting level in the laboratory, rather than from reactivity. Even then, prediction is meagre at best (Harshfield, James, Schlussel, Yee, Blank & Pickering, 1988; Morales-Ballejo, Eliot, Boone & Hughes, 1988). This does **not** refute the idea that behavioral factors play an important role in cardiovascular disease or that the physiological stress-response stands at the basis of such stress-induced disease. The time scale of the physiological responses may be all important. So far, research has concentrated on the response amplitude during shortterm laboratory stressors. However, individual differences in susceptibility to stress-induced disease may not be found in these acute alarm reactions, lasting only minutes. Instead, the crucial link between stress and disease may lie in subsequent processes of adaptation or exhaustion that take up hours or days. Such processes will not be found in laboratory experiments, but can only be uncovered with the help of ambulatory monitoring in real life situations.

At the instrumentation department of the Faculty of Psychology and Pedagogics of the Free University of Amsterdam, the development of ambulatory physiological recording equipment has a history of about 10 years. Originally, a device was developed that consisted completely of discrete electronic components. With the first generation of single chip micro processors, containing nearly all necessary peripheral devices like timers, input/output ports and memory etc, the use of "intelligent" ambulatory monitoring devices became feasible for psychological research. For instance, Houtman (1990) used HGM1, a prototypic ambulatory HR monitoring device in combination with an Apple II personal computer to measure during lecturing. Barry, Moroney, Orlebeke & de Vries (1991) used an upgraded version of the HGM1 to measure orientation components in the galvanic skin response (GSR). Recently a new generation of processors became available on the market, containing more peripheral devices and memory and consuming less power. Along with it, a high level language compiler enabled efficient software development. With this processor, the current Ambulatory Monitoring Device was developed, measuring HR, heart rate variability (HRV), GSR, and body movement (Motility).

2. Description of the system

The complete Ambulatory Monitoring System consists of 1) an Ambulatory Monitoring Device (AMD), 2) a small light-weight device for the actual ambulatory recording, 3) AMSCOM, which is a communication/data evaluation program to run on your PC, and 4) an interface (AMS-i) to connect the AMD to a PC. The AMD contains a single chip micro processor, running its own software. Because of its small size and weight, the AMD can be worn unobtrusively underneath clothing leaving the freedom of movement of the subject intact and hardly visible to others. This way the AMD reliably measures physiological signals during daily life and work situations without disrupting the normal course of events.

2.1. The AMD Hardware

The AMD hardware consists of two major parts: a digital and an analog circuit board. Both have their own power supply to minimise processor noise in the analog circuitry. The outside dimensions of the AMD are 32*65*120 mm, and its weight is 225 g not including a 9V battery. For an impression see Figure 1.

Figure 1: An impression of the Ambulatory Monitoring Device.

The digital part of the AMD consists of a single chip micro processor (μP) and up to 512 kbyte of Random Access Memory (RAM) chips for internal data storage. An 8-bit autonomous counter functions as an accurate 1 millisecond clock. A 16 bit timer functions as analogue/digital converter (ADC) for GSR measurement. A built in ADC (10 bits) is used for the motility measurement, and for monitoring the battery voltage. For ECG recording one active electrode is placed at mid- sternum/left axillary, and another at the ninth rib, above the apex of the heart. A ground electrode is placed at equal distance of both active electrodes. The ECG signal is lead into a differential amplifier, with an input impedance higher than 1MΩ, and a CMRR of 96dB. The R-peak is detected with a level detector with automatic level adjustment, as described by Thakor, Webster and Thompkins (1980, 1983). The output of the level detector is connected to an interrupt request (IRQ) input of the μP. At each R-peak, a millisecond counter is read and reset, yielding the raw interbeat interval (IBI). The AMD stores each IBI, allowing spectral analysis with commercially available programs like CARSPAN (Mulder, 1988). Storing all IBI's continuously, however, will fill memory fast. To reduce the memory filling rate, raw IBI's are stored periodically during so called Beat-to-Beat Registration (BBR) periods. A BBR period can be initiated on a fixed or random time schedule. Furthermore, the subject can self-initiate a 5-minute BBR period at any time by pushing a button when a significant event takes place, for instance during a panic attack. The BBR has a default length of 5 minutes. From 5 minutes of IBI data, all relevant aspects of HRV can be derived. Longer BBR periods are less likely to be stationary, do not add information, but will consume considerable memory. While not in a BBR period, the AMD stores the IBI average over a default period of 30 seconds. This duration of this Averaging Recording (AP) period can range from 30 to 300 seconds.

The bodily movement (motility) of the subject is measured as the vertical acceleration of the subject which is an indicator of its physical load (Montoye, Washburn, Servais, Erlt, Webster and Nagle, 1981). The actual acceleration is measured as described in the same article by Montoye et al. (1981). Figure 2 is the block diagram of the accelerometer. It consists of an active acceleration sensor. Its output is amplified, rectified and led into a hardware integrator. Every 5 seconds this integrator is sampled and reset by the μP. The integrated values are averaged up to the set sample rate. Motility can be averaged over periods from 10 to 300 seconds. Motility measurement has a range of 0 to 4 gsec with a resolution of 0,008 gsec. To compare across subjects, we prefer to map motility on a ten point scale, using the subjects maximum and minimum scores as scaling criteria.

Figure 2: Block diagram of the accelerometer.

The GSR is measured with the 0,5V constant voltage method according to Lowry (1977). A block diagram of the circuit is shown in Figure 3. The GSR signal is amplified. The output of the amplifier is led to a one-shot puls width modulator (PWM). To sample the GSR, the PWM is started by the µP. The length of the PWM output puls is GSR dependent. This lenght can be measured with a higher resolution (13 bits) than the ADC available in the µP. The default sample rate is 500ms but can be set between 100 and 30000 milliseconds. The range of the GSR measurement is 1 to 100µS, at a resolution of 0.0125µS. The device is suited for the measurement of tonic levels as well as phasic activity.

The maximum recording duration depends on the quality of the battery and on sample rate setting. A full battery and the default settings allow 48h of recording (64 Kb RAM). With less memory consuming sample rate settings, the length of a registration period is determined by the battery capacity. With a full battery, data is retained after recording for at least 2 days.

Figure 3: Block diagram of the GSR circuit.

2.2. AMD software
The data collection part is controlled by an autonomous counter, incremented by the system clock. All timed processes, either peripheral devices or software functions, are started by this timer. When a specific peripheral device is ready, it is serviced by its own interrupt service routine.

The software is designed so that data collection can be started in the field from power up. When batteries are inserted in the AMD, all variables are initialised to default values (the default values are 'one time programmable', at production time of the AMD). The AMD is then ready for data collection. If an ECG signal is connected, the incoming IBI's are averaged and evaluated. If incoming IBI's are constant within a 12.5% of the average for 8 consecutive R-peaks, the storage of data in the AMD's internal RAM is started. At the start of internal data storage, the internal clock time is stored as well. During the evaluation period, the subject/experimenter gets audible feedback to check electrode connection. If for some reason during a registration the ECG signal disappears for more than 10 seconds, the AMD emits an audible alarm, stores the internal clock time in memory and holds internal data storage. The subject/experimenter should be instructed beforehand to check electrode connection in that event, and to resume the measurement in the same way as described for start of data storage. The time of these events is stored in memory as well and data storage is continued.

2.3. The AMS interface
To connect the AMD to your computer, an interface is needed. This interface, the AMS-i, has several purposes. Its most important function is the galvanic isolation of the PC and a possible subject connected to the AMD while performing online monitoring. The interface consists of a DC/DC converter, supplying power to the isolated part of the interface. The signal lines are isolated through optocouplers. The other function of the interface is adjusting the voltage levels of signal lines between the AMD and the PC. The AMD has a serial port, switching signal levels between 0 and 5 volt. The PC expects standard RS232 signal levels.

2.4 PC Software
The functioning of the AMD is determined by settings such as the sample rates for motility and GSR, the frequency and duration of BBR periods, etc.. These variables can be set with a PC running the communication program AMSCOM. Although the AMD's obvious purpose is to measure and store data for off-line processing, you can easily perform on-line monitoring, using the PC screen to display the incoming signals. After the AMD is filled with data, this data can be retrieved with AMSCOM, and stored on disk. The data can be converted to ASCII format to allow further processing with statistical software packages such as SPSS. Using the graphical display option allows the demarcation and labeling of certain time periods in the recorded data. A VGA card is necessary for this option. In Figure 4 a sample printout of a graphical display is shown. The data is displayed in two windows: In the upper window, the overview window, the whole recording is shown (i.e. from time 10:53 on day 1 to 14:53 on day 2). In the lower window, the zoom window, a user selected section of the upper window is shown. In the overview window, a H and a C, printed close together, indicate a hold and continue of data

storage (in the zoom window this period will be clearly visible as a gap in the recording). With a cursor, the user can set the begin and end times of an activity performed by the subject, and assign a text label and a numerical code to these time periods. In the zoom window of figure 4 the time period from 9:44 to 11:20 is labelled as "meeting at work", and its code is 20 (the code could mean something like: "sitting quietly"). Note that for presentation purposes HR notation was favored over IBI notation. The statistics section top-right show the mean, standard deviation and extreme of the HR. These statistics are saved in a separate file, together with the name and code of the period, as well as its begin and end time. These files can be used in further analyses that need to account for the subject's activity at the time of measurement.

Figure 4: An example of the representation and score posibilities of data.

3. A field study

A sample study was undertaken to examine HR responses to various real-life situations, and to determine the influence of posture and activity on HR-derived parameters. A group of 48 healthy sedentary males (aged 27 to 37) wore the AMD during one work day and one weekend day. The order of work and weekend days was randomized. The AMS was set to record the average HR and Motility over half-minute periods, and to record one beat-to-beat registration every hour. In addition, the subjects were asked to initiate BBR's themselves during two or three periods of quiet sitting without talking on the evening of the weekend day. HR and HRV values from these latter periods were considered to represent the home baseline. Apart from the AMD, subjects wore the SpaceLabs Model 90202 Ambulatory Blood Pressure Monitor (SL). Shoulder belts were used to carry the weight of both monitors and a belt around the waist was used to keep the monitors on the left and right hips respectively. On the first day, recording started around 9 o'clock when subjects had the AMD attached by an experimenter who demonstrated the procedure for attaching the electrodes and the blood pressure cuff. Recording ended around 11 o'clock when subjects removed the equipment before going to bed. On the second measurement day, subjects attached both AMD and SL themselves, with the help of a written instruction. Measurements on the second day ran from about 8 in the morning to about 11 at night. The subjects were instructed to keep a diary of their activities, in which they indicated the type of activity (e.g. reading, discussing, bicycling), the bodily posture(s) during the activity (lying, sitting / standing, standing / walking, etc.), and the amount of physical strain they had experienced (4-point scale).

After data-storage, the graphical option of the AMSCOM program was used to combine the information from the activity diary with the recordings of motility and HR. The following algorithm was used: all activities that subjects had entered in the diary were labelled by a text that indicated the type of activity (see table 3) and a code that indicated posture and movement (see table 4). The motility data were used to improve the accuracy of the timing of begin and end of the various activities. For instance, if subjects indicated to have walked to their car and drove home in the interval from 17.15 to 18.00, motility data could be used to accurately set the begin and end of walking (e.g. 17.15 to 17.23) and the begin and end of driving (e.g. 17.23 to 18.05).

For each of the activity and posture coded time periods, mean (HR), standard deviation (SD30), maximum (HR-max) and minimum (HR-min) were computed over all half-minute averages that fell within a single period. The SD30 reflects the variability in average HR across the 30 second segments and can be used as an index of real-life reactivity. The time series of IBI's from the BBR were selected from the raw data with an auxiliary program that checks stationarity and corrects IBI's by the method of Rompelman (1986). Frequency domain analysis of the IBI's was done with the CARSPAN program, that is based on sparse Discrete Fourier Transformation and that yields a power-frequency spectrum from 0.02 to 0.50 Hz (Mulder, 1988). Averaged powers in three frequency bands were deemed of interest: total power over all frequency bands (0.02-0.50: TOTAL), power in the frequency band around the intrinsic BP oscillations (0.05-0.15: BLOOD) and the power in the high frequency band, that reflects vagal influences on the heart only (0.16-0.40: HIGH). We will only look at the self-initiated BBR during periods of quiet sitting without talking on the evening of the weekend day.

The SpaceLabs was set to measure BP every 20 minutes with an automatic retry after 3 minutes if the first measurement failed. Subjects were instructed not to move during measurement and to keep their arm still. For comparison of the SpaceLabs with the AMD, all SpaceLabs data were paired to two minu-tes of AMD-derived HR data that lay directly before the start of the BP measurement. Assignment of SpaceLabs data to classes of activity was similar to that of the AMD. For instance, if a meal had lasted from 12.30 to 12.46 then the SL measure of 12.35 was counted as a BP recorded during "sitting / eating". It was then paired to the average HR, SD30 and Motility of the period from 12.33 to 12.35 for cross-instrument comparison.

On a separate day, all subjects visited the laboratory for determination of baseline BP, HR and HRV. These were measured at the end of a 15 minute period sitting in a dimly lit sound shielded cabin. Laboratory measurements were done in the same week as the ambulatory monitoring.

3.3 Results

A total of 1376 hours were recorded on the 43 subjects. Two subjects failed to attach the SpaceLabs correctly, yielding their blood pressure data unusable. A total of 78 hours of HR recording were lost due to AMD-malfunction. All subjects managed to attach the AMD correctly, but faulty batteries and lose electrodes caused a loss of data in three subjects. Heart rate and BP values over all remaining subjects (N=43) are shown in table 2. Separate values are given for work and weekend days, and these days were further subdivided in three time intervals of 5 hours each. As expected, the highest HR and BP values were seen at work and the lowest values were found late in the evening of the rest day. In addition, variability of the average HR over 30-second fragments was substantially higher during the work day.

Table 2: HR, Motility and SD30 over all subjects (N=43), measured with the AMD and systolic (SBP) and diastolic blood pressure (DBP) measured with the SpaceLabs. Separate values are given for work and weekend days, and these days were further subdivided in three time intervals of 5 hours each.

	Ambulatory Monitoring Device				SpaceLabs ABP			
	HR (bpm)	Motility	SD30 (bpm)		SBP (mmHg)	DBP (mmHg)	HR (bpm)	
Overall	75.6	2.3	5.4		126.9	78.0	77.4	
Weekend day	74.1	1.9	5.7		126.3	77.2	76.5	
Work day	77.1	2.5	5.1		128.4	79.7	80.4	
08.00-13.00 h Work		77.5	2.7	5.8		129.4	79.2	79.1
13.00-18.00 h Work		82.2	2.5	6.1		129.3	80.5	84.9

18.00-23.00 h Work		74.0	1.9	5.1		125.5	78.4	75.7
08.00-13.00 h Weekend	75.3	1.4	3.8		129.1	79.9	77.4	
13.00-18.00 h Weekend	77.0	2.4	5.1		125.1	76.6	78.0	
18.00-23.00 h Weekend	72.1	1.8	3.3		124.7	76.2	73.9	

Heart rate measured with the SpaceLabs monitor was systematically higher than HR recorded with the AMD. However, AMD-derived HR over a two minute period just before each BP measurement showed excellent correlation with HR values measured with the SpaceLabs ($r=0.92$, $p<0.0001$). From these results it appears that HR may be increased a few beat in anticipation of BP recording. This is not surprising, since oncoming measurements are signalled with a warning beep. Most likely, the continuous HR as measured with the AMD is more typical of average HR than the HR yielded by the SpaceLabs.

It is clear that even with the rudimentary classification of table 2 some effect of daily activities can be found on cardiovascular parameters. However, for detailed analyses of ambulatory data it is necessary to label individual activities with the help of the activity diaries. After processing the diaries with the AMSCOM program, a total of 2104 labelled time periods resulted, with an average duration of 39 minutes (min: 3 minutes, max: 360 minutes). To reduce data, the activities were reclassified into 10 classes of similar activities that took place in roughly the same social situation or with the same amount of movement. Table 3 gives 6 of these classes of activities with the corresponding HR and SD30 and BP (Capitals). For each class, one or more of the most frequent occurring activities in that class are listed as well. The effects of different activity classes on the cardiovascular parameters were analyzed by using one-way ANOVA with Tukey post-hoc comparison of the means. For HR, significant differences were seen between all classes. Peak HR's were found during discussions at work, speeching, lecturing, shopping and bicycling. Excepting heavy physical activity, highest SBP and DBP were found during social interaction.

Table 3: HR, Motility and BP readings averaged over classes of activity (Capitals) and over examples of single activities belonging to those classes. AMD-derived HR and Motility give the average HR and Motility over all 30 second fragments that belonged to any of the time periods of the activity (class) in all subjects. HRmin, HRmax and SD30 give the average of the minimum, maximum and standard deviation of the 30-second HR fragments recorded during those periods. SpaceLabs-derived SBP, DBP, and HR give the average of all BP measurements in all subjects that occurred during a particular activity. Note that the capitalised activity classes are listed in the order of ascending HR.

		Ambulatory Monitoring Device					SpaceLabs ABP			
		HR (bpm)	SD30 (bpm)	HRmin (bpm)	HRmax (bpm)	Motility	SBP (mmHg)	DBP (mmHg)	HR (bpm)	
02 RELAXATION		69.4	3.1	63.9	76.4	0.73	123.6	73.9	71.4	
e.g.	Reading in free time	70.4	4.0	63.1	78.8	0.59	120.9	71.7	73.7	
	Watching television	69.8	2.9	64.6	76.1	0.78	123.7	71.5	73.1	
06 INTELLECTUAL WORK		72.9	3.7	66.6	81.7	0.92	124.3	77.1	74.1	
e.g.	Reading at work	72.2	2.9	67.3	78.9	0.69	121.6	72.3	74.8	
	Clerical work	76.0	4.0	67.2	81.2	1.30	125.9	78.5	76.2	
05 SOCIAL INTERACTION		78.6	5.3	69.1	92.3	1.96	130.5	81.2	79.7	
e.g.	Talking with partner or friend		68.7	3.6	62.1	76.9	1.42	126.4	78.1	78.3
	Work-related talking	81.3	5.6	71.7	95.4	1.92	131.3	81.6	82.8	
	Speeching/lecturing		85.7	6.0	68.2	100.5	2.44	136.9	86.8	87.2
09 WALKING		80.7	7.8	68.3	95.9	3.61	131.0	81.7	82.7	
e.g.	Walking (transportation)	80.3	7.9	68.0	95.6	3.61	131.8	81.9	79.4	
	Shopping		85.8	5.4	74.7	100.5	4.52	130.7	83.4	83.0
11 HOUSEWORK		82.5	6.8	69.1	99.3	3.21	125.8	78.1	80.1	
e.g.	Household activities		84.1	6.9	69.1	101.8	3.47	125.8	78.2	80.3
12 MODERATE/HEAVY WORK		99.8	12.2	71.7	123.9	6.77	130.1	81.4	93.1	
e.g.	Bicycling	101.5	12.1	72.2	124.0	9.20	132.9	83.2	95.1	

From table 3 it is clear that HR and SD30 increased linearly with Motility. This was confirmed by a significant correlation of Motility with both HR (r=0.53, p<0.001) and SD30 (r=0.70, p<0.001) across all time periods. However, correlation coefficients between HR and Motility within each of the classes of activity listed in table 3 were significant only during walking (HR:r=0.43, p<0.001) and social interaction (HR:r=0.42, p<0.001). On the one hand this is not surprising: no relationship may exist between vertical acceleration and HR during reading and talking. Nonetheless, it is surprising that no significant correlation was found between vertical acceleration and HR during light physical house-work, particulary since the Motility index provided good visual guidance in finding begin and end times of changes in posture an physical activity during interactive scoring. Overall these findings suggest that Motility of the AMD reliably detects changes in posture and physical activity, but that it does not quantify the intensity of physical activity very well.

In table 4 Motility values were combined with diary information on posture and intensity of physical activity to reclassify all time periods in 10 distinct classes of posture / physical activity. Classification of physical activities as heavy or moderately intense depended on the effort score filled out by the subject and on the content of the activity. For instance, gardening could be light (power mowing, planting seeds) or heavy (digging, hand mowing) and similar distinctions were made for household activities (mopping vs dish washing) and repair work (engine or car repair vs repair of electrical appliances).

Table 4: HR and BP readings averaged over different postures / physical activities. Variable labels as in table 3.

	Ambulatory Monitoring Device					SpaceLabs ABP		
	HR (bpm)	SD30 (bpm)	HRmin (bpm)	HRmax (bpm)	Motility	SBP (mmHg)	DBP (mmHg)	HR (bpm)
Supine	70.1	3.21	63.5	80.7	0.75	111.1	70.5	71.7
Sitting	71.5	2.96	66.1	78.2	0.74	125.9	77.3	75.4
Sitting with occasional movement	74.4	4.65	66.5	85.4	2.07	128.2	79.9	78.4
Sitting with occasional standing and / or walking	75.4	7.47	64.4	94.8	2.54	130.0	79.7	76.1
Standing	78.4	5.49	68.0	94.2	2.63	126.1	80.5	84.3
Standing with occasional walking	79.0	7.22	67.6	94.6	2.92	129.8	79.4	78.4
Walking	85.3	9.17	70.0	103.6	5.16	128.4	80.1	81.6
Moderate Physical Work	91.2	7.28	67.2	121.1	6.09	135.1	84.1	92.1
Bicycling	101.5	10.11	72.2	125.0	7.02	133.4	83.5	96.8
Heavy Physical Work	103.2	12.28	72.4	128.8	7.22	138.2	81.2	102.1

There was a clear increase in HR, SD30 and blood pressure from activities in sitting to activities in standing positions. Further increases were seen when subjects were walking occasionally or continuously and the highest values were found during bicycling and various forms of heavy physical activity (stair climbing, carrying loads etc.). It should be clear from table 4 that posture and physical activity are important determinants of average ambulatory HR and BP values. In general tables 2, 3 and 4 show that interpretation of overall "24-hour HR / BP levels" without correction for physical (posture, activity), metabolic (smoking, eating, coffee) and behavioral influences (alone / company, work / rest) is hazardous at best.

A final issue that was addressed was the correspondence of HR and HRV measured in the laboratory to ambulatory HR and HRV measured with the AMS. For this purpose we studied the laboratory baseline in relationship to the ambulatory HR recorded during self-initiated beat-to-beat registration on the evening of the weekend day (Table 5). T-tests showed that home-derived basal level of HR was higher than laboratory baselines, and that short-term HRV in all three frequency bands was lower at home (p's<0.01). This suggests that the parasympathetic dominance over sympathetic control of heart rate was larger in the laboratory than at home. Correlation between laboratory and ambulatory baseline levels were generally significant, with the exception of spectral power in the BLOOD and HIGH bands. The meagre relationship between laboratory and ambulatory data that was found for HR, HRV and blood pressure underscores the need for the development of powerful ambulatory tools.

Table 5: Comparison between basal HR, BP, and short-term HRV measured during supine laboratory recording and during quiet sitting without talking on a weekend day. In accordance with van Dellen, Aasman, Mulder & Mulder (1985) the spectral values are expressed in 'squared modulation index'-units.

	Laboratory basal	Ambulatory basal	Correlation between Laboratory and Ambulatory baselines
SBP	123.4 (±10.1)	122.0 (±8.2)	0.58*
DBP	75.8 (±6.2)	70.9 (±5.4)	0.68*
HR	62.1 (±7.1)	71.7 (±6.4)	0.49*
SD30	2.7 (±1.1)	3.1 (±1.1)	0.52*
TOTAL	5323 (±1200)	3700 (±1900)	0.35*
BLOOD	1759 (±1525)	1500 (±980)	0.11
HIGH	1100 (±710)	623 (±501)	0.32

3.4 Discussion

Various algorithms have been used in the literature to determine the contribution of real-life stimuli to variability in ambulatory HR and blood pressure. For instance, to test the effect of work-stress, the overall level throughout the work-day has been compared with the baseline level measured on the evening of the same day, on a separate weekend day, or during quiet sitting in the laboratorium or at sleep (Harshfield, James, Schlussel, Yee, Blank & Pickering, 1988; Unden, Orth-Gomer & Elofsson, 1991). Three of these methods were used in the present study and the results suggest that the AMD can easily be used to obtain such indices of work-related cardiovascular activation. No monitoring during sleep was done, because of the obtrusiveness of the SpaceLabs blood pressure recorder (There seems to be no trouble in night time recording with the AMD. In two ongoing studies, HR during sleep is being monitored with the AMD, and so far no major discomfort has been reported by a total of 17 subjects) .

The main problem with a rudimentary classification of activities in work / rest is that the contribution of physical activity to ambulatory parameters remains unclear. Nonetheless, this study, as well as others (Gellman, Spitzer, Ironson, Llabre, de Carlo Passin, Weidler & Schneiderman, 1990) have shown the need to control for posture and physical activity, particularly when one is interested in uncovering psychosocial effects on cardiovascular regulation. One approach to this problem has been to select only minutes without physical activity (Pollak, 1991). Selection of time periods without physical activity can easily be performed with the AMS, by using the Motility score as a guideline. However, removing physical activity may seriously reduce the ecological validity of ambulatory parameters. Although a large part of the day was spent sitting by our subjects, they engaged in some form of physical activity at least 6 hours a day. Other, less sedentary, subject groups may be even more active, and lots of data would have to be discarded if periods with physical activity had to be removed. A second approach to deal with physical activity is autoregressive correction for the amount of body movement. Anastasiades & Johnston (1990) used concurrently measured EMG for this purpose, since they found very high correlation between EMG and HR. It is unclear whether such "movement-corrected" HR can be meaningfully interpreted. In any case: the imperfect correlation between HR and Motility suggests that statistical removal of body movement recorded with an accelerometer is not a good idea.

We prefer the approach followed in tables 2 to 5: a detailed list of daily activities is constructed from the diaries and the motility recordings. These are then reclassified into 10 to 15 classes including similar activities, and all data are summed per subject per class. Depending on the research questions and the subjects studied, activity classes can be based on the content of activity alone, on the posture and intensity of physical work or on a mixture. Naturally, psychophysiologists will want to concentrate on the effects of cognitive and emotional load during work-related activities rather than on the effects of physical activity. The classification scheme in this study should, therefore, be seen as one of many possible schemes. We expect that consensus on classification will rapidly develop as more ambulatory monitoring data become available. Nonetheless, two other studies have found classes of activity that are remarkable similar to ours (Turjanmaa, Tuomisto, Fredrikson, Kalli, & Uusitalo, 1991; Hedges, Krantz, Contrada & Rozanski, 1990). Based on the activity classes chosen, we may conclude that the AMS is a valid instrument for detecting daily influences on HR and HRV. It detects differences in posture and physical activity, and it also showed sensitivity to psychosocial influences of work-related stressors. Although one may criticize the low sample frequency of HR by the SpaceLabs, cross-instrument comparison with SpaceLabs was highly satisfactorily.

In contrast to available commercial apparati, the AMS measures HRV as well as HR level and combines these directly to an index of physical activity and diary data. Two disadvantages remain in using the AMS and the strategy followed in this sample study. Firstly, scoring the individual time periods interactively is a time consuming procedure. Even with the highly optimized interface provided by the AMSCOM program, average time to label an individual time period is 25 seconds. This meant that the labelling of 2104 time periods took a trained research assistant 18 hours to complete. Hopefully, future consensus on classification systems will speed up this process. The second disadvantage of AMS recording is the fact that it yields only an incomplete view on the physiological processes that may be involved in stress reactions. The addition of beat-to-beat recording certainly presents an improvement over the mere recording of HR that is done by most commercial apparati. With the AMD it is possible to get estimates of parasympathetic as well as sympathetic cardiac drive, since power in the HIGH band reflects parasympathetic tone only whereas power in the BLOOD band reflects both sympathetic and parasympathetic influences. However, using the HIGH band as an index of vagal tone should be done preferably when respiratory frequency can be statistically controlled (Grossman, Stemmler & Meinhardt, 1990). In addition, the BLOOD band is very sensitive to posture (Pagani, Lombardi, Guzzetti, Rimoldi, Furlan & Pizzinelli, 1986), which makes it far less reliable as an indicator of cardiac sympathetic drive than a parameter like the Pre Ejection Period from Impedance Cardiography (Newlin & Levenson, 1979). In short, we should try to develope an ambulatory monitoring device that combines measurement of HR and HRV with the measurement of ventilation as well as impedance cardiographic data.

At present we are still far from that goal but we believe that investment in that endeavour is warranted. Ambulatory monitoring has clear practical and theoretical merits. Through ambulatory monitoring the developments in laboratory cardiovascular stress-research of the past decade can be put to use in health care by allowing objective measurement of physical and emotional load of stress at the work site, with minimal interference on normal activity. This can be used, for instance, to evaluate the effectiveness of health-interventions like corporate fitness programs. Psychosomatic theory, in turn, will benefit from ambulatory monitoring because it yields far more realistic data than laboratory stressors on physiological coping with real-life stress.

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