Twenty four hour intermittent, ambulatory blood pressure monitoring

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SUMMARY Blood pressure and heart rate were measured every 30 minutes during the day and every hour during the night in 43 children (20 girls and 23 boys, aged 10 to 16) with a portable automated monitor. The apparatus was better accepted in girls than in boys, and the failure rate was lower during the day. The overall failure rate was 22%, which corresponds with comparable studies in adults. During the night blood pressure and heart rate fell by 10% and 14% of the daytime values, respectively. Mean (SD) blood pressure was significantly higher in boys than in girls (126/72 (17/8) v 109/64 (9/5) mm Hg) and measurements correlated positively with age, body weight, and height of the subjects. Heart rate was not significantly influenced by gender or age. A positive correlation between heart rate and blood pressure was found when expressed as standard normal deviations or hourly variations. In children intermittent monitoring of ambulatory blood pressure and heart rate is a suitable method for measuring individual diurnal patterns.

Intermittent, ambulatory 24 hour blood pressure and heart rate recording is increasingly used in adults for diagnostic and therapeutic purposes.¹ A circadian rhythm has been shown, with its nadir in the early morning hours, a bimodal curve during the day, and peaks in the late morning and early evening hours.¹⁻³ This rhythm remains constant and is sometimes even enhanced in benign hypertension; other conditions such as pregnancy associated hypertension, malignant hypertension, pheochromocytoma, autonomic neuropathy, and some depressive disorders may affect it.¹⁻³ Casual office or clinic readings are higher than values obtained by ambulatory blood pressure and heart rate devices, and recent data suggest that cardiovascular risks are more accurately predicted by ambulatory blood pressure readings.¹ This technique is often used in the evaluation, diagnosis, and treatment of hypertension and the evaluation of hypotensive states and syncope.

Intermittent, ambulatory 24 hour blood pressure and heart rate recording has not been used in children until now, mainly for technical reasons. The first available devices measured blood pressure and heart rate intra-arterially thus practically preventing their use in children. The first non-invasive technology was semiautomated, and required the patient to activate the cuff with an inflation bulb; a considerable degree of patient cooperation was

essential to allow such a device to be effective. Another disadvantage was that no readings could be obtained while the subject was asleep.³⁻⁵ We report here the results of intermittent, ambulatory 24 hour blood pressure and heart rate recordings in a relatively small sample of volunteer children, using a fully automated device, developed by Instruments for Cardiac Research. Validation studies in normotensive or hypertensive adults showed good agreement between this and other non-invasive systems with simultaneous intra-arterial or mercury sphygmomanometric determination, and a fairly good patient acceptance and reproducibility.^{1 3 6 7}

Subjects and methods

Forty three volunteers, 20 girls and 23 boys, with a median age of 13½ years (range 10 to 16) were investigated. All were healthy and were not taking any drugs (including hormonal contraception). The ranges of body weight and height were 31 to 64 kg (mean 44.5) and 1.47 to 1.67 m (mean 1.57) for girls and 28 to 69 kg (mean 48.2) and 1.43 to 1.83 m (mean 1.61) for boys. The body mass index, calculated by dividing the body weight by the height squared, ranged from 13.1 to 26.0 kg/m² (median 18.2) in boys and from 14.0 to 22.7 kg/m² in girls (median 17.9). The pubic hair development of the boys ranged from prepubertal to stage 5 according

to Tanner (median stage 3). The pubic hair development of the girls was not assessed. The boys were recruited in a nearby school and seen on a regular school day (when there was no gymnastic lesson or other sporting activity) in the outpatient clinic where the monitor and the questionnaire were explained and a short clinical examination was performed. Unfortunately, it proved difficult to recruit sufficient girls from the same source, therefore girls from another school were enrolled in the study and for logistic reasons the measurements were performed during the weekend at their homes.

The recorder, SPM 5200 (weight 1.6 kg), was hung over the shoulder by means of a comfortable strap. The apparatus consisted of the inflating pump with its batteries, a microprocessor controlling inflation and deflation of the cuff, and a storing unit for the blood pressure and heart rate readings. If Korotkov sounds were not detected accurately by the piezoelectric microphone the system reverted automatically to an oscillometric recording method. The first and the last sound were taken as systolic and diastolic blood pressures, respectively. Mean blood pressure was calculated as the sum of the diastolic plus one third of the pulse pressure. Conditions preventing measurement within 90 seconds and measurement failure due to excessive noise production or battery failure were indicated by code on the visual display. A more detailed description of the system is given by Turm and Graney.³ The monitor was programmed to measure blood pressure and heart rate every 30 minutes from 6.00 am to 5.59 pm (day) and every 60 minutes from 6.00 pm to 5.59 am (night). To increase the number of available blood pressure and heart rate readings and the motivation of the children to enter the study they were allowed to take additional measurements by operating a manual control switch. Exceptionally, programmed measurements could be manually cancelled and postponed if they occurred at a time when it was impossible for the child to hold his or her arm in a suitable position for measurement. The time spent in bed and inconvenience caused by the apparatus were assessed from a questionnaire. Seventeen of the 23 boys started monitoring between 3 pm and 5 pm; in all other subjects the time of starting the 24 hour registration was evenly distributed over the day. The cuff was attached to the non-dominant arm with the microphone taped over the brachial artery. Cuff size was 8 or 12 cm in width, according to the recommendations of Leumann *et al.*⁸ Measurements that produced a systodiastolic blood pressure difference of less than 20 mm Hg were regarded as erroneous and therefore not used for further analysis. Simultaneous mercury column and monitor readings on opposite arms were

performed in 12 boys. No significant difference between the two methods was found; the mean differences were 0.45 mm Hg (-5.5 to $+6.5$) for systolic blood pressure and -2.0 mm Hg (-6.5 to -4.5) for diastolic blood pressure. No calibration on the individual subject was performed.

The data obtained from the recorder, the statements from the questionnaires, and the clinical data were analysed by the software package SAS, version 5.08 (SAS Institute Inc, Cary, North Carolina, United States). Analysis of variance, based on general linear models, was applied to study the influence of age, body weight, height, body mass index, and sex of the subjects, and of day, night, bed, or hook up time on the 24 hour course of blood pressure and heart rate. The coefficients of variation for nocturnal and diurnal blood pressure or heart rate were calculated separately. The interaction between blood pressure and heart rate was studied by relating absolute values, standard normal deviations,⁹ and hourly differences. The circadian rhythm of blood pressure or heart rate was mathematically assessed using a cosine function¹⁰ and Fourier analysis. Significance was assumed when $p < 0.05$.

Results

The acceptance of the apparatus was very good during the day; a considerable inconvenience was reported only when the children played sport and dressed and undressed. One girl and three boys were particularly disturbed by the weight of the monitor. Inconveniences were more pronounced in bed. Four boys removed the cuff because they could not fall asleep and 17 boys and 10 girls woke up, most of them repeatedly, when the cuff was inflated. Of the measurements 22% (boys 25%, girls 18%) were incomplete: 50% of these were due to the fact that the measurement could not be completed within 90 seconds; this might have been caused by improper placement of the cuff, loose connections between cuff and monitor, or an air leak in the system. In 25% excessive noise was produced due to movements of the arm; battery failure occurred only once (2%). The remaining 23% of the failed determinations were without explanation. In addition to the incomplete readings, 2.3% of measurements were deleted because the difference between systolic and diastolic blood pressure was less than 20 mm Hg. Almost all readings (97%) were performed by the auscultatory method. The boys stopped and restarted a considerable number of the measurements with the manual control switch: 22% of the total measurements were cancelled; 36% of the finally performed readings had been triggered

Table Mean (SD) values of blood pressure and heart rate recorded over 24 hours and separately of day and night in 20 girls and 23 boys

	Blood pressure (mm Hg)			Heart rate (beats/minute)
	Systolic (mean (SD))	Diastolic (mean (SD))	Mean	
24 Hours				
All	118 (16)	68 (7)	85 (9)	81 (7)
Girls	109 (9)	64 (5)	79 (5)	80 (7)
Boys	126 (17)	72 (8)	90 (9)	81 (7)
	p<0.001	p<0.001	p<0.001	
Daytime				
All	123 (18)	71 (7)	88 (9)	85 (8)
Girls	113 (11)	68 (5)	83 (5)	86 (7)
Boys	130 (21)	74 (8)	93 (11)	86 (8)
	p<0.001	p<0.001	p<0.001	p<0.001
Night time				
All	110 (12)	64 (10)	79 (9)	75 (9)
Girls	102 (7)	60 (6)	74 (6)	73 (7)
Boys	117 (14)	68 (12)	85 (11)	75 (9)
	p<0.001	p<0.001	p<0.001	p<0.001

manually. By contrast, in girls only 2% of the measurements were cancelled and 17% manually triggered.

The table shows the mean values of blood pressure and heart rate recorded over 24 hours and separately during the day and night. A significant sex difference was noted with regard to blood pressure ($p<0.001$) but not for heart rate. Systolic,

mean, and diastolic blood pressure, and heart rate were appreciably lower ($p<0.001$) during the night compared with diurnal readings. In girls the mean nocturnal blood pressure and heart rate were 11% and 13% lower, respectively, than diurnal recordings. The corresponding nocturnal decreases for boys were 9% and 15%, respectively. The coefficient of variation (mean (SD)) for systolic, mean,

Fig 1 Hourly blood pressure and heart rate recordings during 24 hours in 20 girls and 23 boys.

and diastolic blood pressure, and for heart rate were 11.0 (5)%, 10.6 (5)%, 13.7 (6)%, and 20.5 (7)% during the day, and 11.1 (5)%, 11.2 (4)%, 15.5 (6)%, and 20.9 (11)% during the night. No difference was observed between girls and boys.

When studied by analysis of variance, systolic, mean, and diastolic blood pressure and heart rate were significantly influenced by whether the readings were taken during the day or night and by whether the subjects were in bed ($p<0.001$). Sex, age, body weight, and height influenced blood pressure measurements ($p<0.001$) but not heart rate. The time of starting the 24 hour recording significantly influenced the course of heart rate in boys ($p<0.05$) but not in girls; its influence on blood pressure was not significant. The correlation between absolute values of heart rate and systolic, mean, and diastolic blood pressure was not significant. A positive and significant correlation between

heart rate and blood pressure, however, was found using standard normal deviations ($p<0.001$) or the hourly variations ($p<0.05$). No correlation was found between body mass index and blood pressure or heart rate.

Fig 1 shows the course of the hourly mean (SEM) values of systolic and diastolic blood pressure and heart rate over 24 hours. Systolic and diastolic blood pressure and heart rate reached their nadir at about 4.00 am, increasing thereafter to a first peak around mid-day. In the early afternoon a slight decrease occurred, after which a second peak was attained. In the boys blood pressure and heart rate values peaked at 4.00 pm, while the course in the girls was smoother. The fitting of a cosine function to the course of the mean hourly values of systolic and diastolic blood pressure and of heart rate (fig 2) showed a good synchronisation of systolic and diastolic blood pressure, with changes in the heart

Fig 2 Mathematical transformation of the 24 hour values for systolic and diastolic blood pressure and heart rate in 43 children. The left panel shows the cosine curve fitting. The corresponding formulae, in which t signifies the hour of the day, are: systolic blood pressure = $118 + 8.8 \cos(t + 2.3)$; diastolic blood pressure = $68 + 6.3 \cos(t + 2.3)$; heart rate = $81 + 10.6 \cos(t + 2.4)$. The right panel shows the Fourier analysis. The corresponding formulas are: systolic blood pressure = $118 - 6.2 \cos t - 6.1 \sin t + 1.4 \cos 2t - 1.3 \sin 2t + 0.7 \cos 3t + 0.8 \sin 3t$; diastolic blood pressure = $68 - 4.5 \cos t - 0.4 \sin t - 1.3 \sin 2t + 0.2 \cos 3t + 0.5 \sin 3t$; heart rate = $81 - 8.0 \cos t - 7.2 \sin t + 0.6 \cos 2t - 1.9 \sin 2t + 0.8 \cos 3t + 0.5 \sin 3t$.

rate slightly preceding those in blood pressure. A slightly better approximation of the circadian rhythm could be achieved using a Fourier analysis.

Discussion

When compared with other widely available automated recorders, the Instruments for Cardiac Research monitor SPM 5200 has the advantage of a relatively low weight and low noise production. It does not need electrocardiographic leads for the registration of heart rate and displays error codes rather than artefactual readings.⁵⁻⁷ All these characteristics make this monitor a suitable recorder for measuring ambulatory blood pressure in children, and for this age group it is probably the only suitable device for recordings during the night.

The main purpose of the present study was to test the patient acceptability and the failure rate of 24 hour recording with this portable device. Only a limited validation of the system and no individual calibration were performed. The accuracy of these measurements remains uncertain, and further trials using children are required. Any validation procedure carried out at only one point in time, however, will not necessarily reflect the conditions prevailing over 24 hours in children of this age group. In the present study acceptance was worse and the failure rate higher than those reported in studies in adults⁴ or in children that had been performed only during the day.⁵ Acceptance as well as failure rates were comparable, however, with results reported in adults who were studied during a full 24 hour period.¹¹ Patient acceptance was better and the failure rate lower in girls, who manually operated the monitor less frequently. More pronounced physical activity and a greater interest in the apparatus in boys might account for this difference.

The children reported here maintained a circadian pattern of blood pressure and heart rate, which corresponded with the sleep-wakefulness cycle. This cycle could be analysed by a cosine function, as previously advocated by Halberg.¹⁰ A slightly better approximation could be achieved using a Fourier analysis, which better reflects the plateau of blood pressure and heart rate that occurs from the late morning to the early evening hours. In older healthy subjects or patients with essential hypertension blood pressure and heart rate showed a comparable circadian rhythm.^{2 3 11} In adults the circadian rhythm of blood pressure parallels that of heart rate and plasma concentrations of noradrenaline, suggesting that changes in sympathetic tone control the diurnal changes in blood pressure.¹¹ Plasma noradrenaline concentrations were not assessed in our

group of children; we found, however, that as in adults the changes in heart rate correlated significantly with those in blood pressure. The circadian pattern in blood pressure might, therefore, be strongly influenced by the sympathetic nervous system in children as well as in adults.¹² Blood pressure increases before waking up; and this has led to the assumption that a true inherent rhythm in blood pressure might exist, though with the influence of sleep and activity superimposed.¹⁰

Blood pressure was higher in boys than in girls and correlated positively with the age, body weight, and height of the volunteers, confirming data from casual blood pressure readings.^{13 14} As girls were studied when not at school and boys on a school day one might assume that stress related to the school activity increased the sympathetic tone and consequently the blood pressure in boys. The absolute values of heart rate, an index of sympathetic nervous tone;^{11 12} the variability of heart rate, as judged by its standard deviation or coefficient of variation; the 24 hour course of heart rate, and the relation between heart rate and blood pressure were comparable in both sexes thereby arguing against such an explanation. The heart rate pattern was also independent of age, body weight, and height; sympathetic mechanisms do not fully explain the influence of age, body weight, and height on blood pressure. Differences in the composition of the body water compartments might be a more likely explanation for the influence of sex, age, and height on blood pressure.¹⁵ The time of starting the 24 hour recording significantly influenced the course of heart rate in boys but not in girls. This difference is probably related to the setting in which the investigation was begun—namely, familial home environment for the girls and a hospital outpatient clinic after the examination of pubertal status for the boys. In the present study no correlation was found between body mass index and blood pressure. This finding does not question the well recognised link between overweight and high blood pressure: all our subjects were lean with a body mass index of less than 30 kg/m².^{16 17}

As in adults the most obvious uses of this newly available technique in children may be the evaluation of borderline hypertension and the efficacy of antihypertensive drug regimens.¹ Another use might be research in essential hypertension, a common condition in adults that probably starts early in life and is influenced by familial factors. Now that the great diurnal variability of blood pressure is beginning to be appreciated it is somewhat surprising that isolated clinic, office, or home measurements have been such good predictors for the risk associated with a high blood pressure. Some recent investiga-

tions suggest, however, that hypertensive target organ damage, including left ventricular hypertrophy or retinopathy, correlates better with 24 hour blood pressure measurements and especially with measurements taken during work than with those taken outside work.¹ Left ventricular hypertrophy has been observed not only in adolescents with borderline essential hypertension but also in the offspring of hypertensive families. As the degree of heart hypertrophy correlates only weakly with isolated blood pressure measurements an interplay of more factors than the simple increased blood pressure load has been suggested to explain the myocardial response to hypertension. In this context ambulatory 24 hour monitoring of blood pressure in normotensive children of hypertensive families might uncover new determinants of heart hypertrophy.¹⁸ It has been shown, by invasive methods, that patients with established or borderline essential hypertension, as well as young normotensive adults with a positive family history for essential hypertension, often present a changed pressor response to sympathetic stimulation.¹⁹ The ambulatory recording technique for blood pressure, as used in this study, might become a useful non-invasive tool for further investigation of the relation between blood pressure and the sympathetic nervous system in children as well as in adults. In contrast with other clinical variables like body weight, height, and blood lipids, casual measurements of blood pressure rarely follow individual centiles over time.¹³⁻¹⁶ This finding might be explained at least in part by the great diurnal and individual variability of the blood pressure that occurs naturally. Multiple measurements of blood pressure over one day might possibly lead to more conclusive results and detect children at risk of becoming hypertensive adults. In this context ambulatory 24 hour monitoring of blood pressure in children has already been advocated.¹⁷⁻²⁰

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