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TECHNICAL NOTE

Respiratory variation of the ballistocardiogram during increased respiratory load and voluntary central apnoea

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Respiratory variation of the ballistocardiogram during increased respiratory load and voluntary central apnoea. O. Polo, M. Tafti, M. Hämäläinen, K. Vaahtoranta, J. Alihanka.

ABSTRACT: Heavy snoring is associated with increased respiratory variation of the ballistocardiogram (BCG). The cause for this association is not known. Although the BCG is a sensitive method to measure myocardial performance, the validity of the signal as a marker of snoring-related haemodynamic changes has not been tested

The aim of this study was to investigate whether ballistocardiographic respiratory variation (BRV) correlates with intrathoracic pressure variation (IPV). The BRV and the IPV were measured in five healthy, normal-weight, awake adults during normal breathing, during breath-holding with constant intrathoracic pressure, and during breathing against increased respiratory resistance (high IPV). The BCG was recorded with the static charge-sensitive bed (SCSB) and the intrathoracic pressure with an oesophageal balloon.

The mean BRV was significantly lower during central apnoea than during free breathing (8.2 *versus* 29.4% $p<0.0001$). When breathing against increased respiratory load, the BRV increased in a linear manner as function of the IPV ($r=0.68$, $p<0.01$). There was significant interindividual variation in the response.

We conclude that changes in the BRV reflect changes in the IPV. Further studies are needed to evaluate whether the BCG could be used as a noninvasive alternative to the oesophageal balloon in monitoring changes of respiratory resistance during heavy snoring.

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The ballistocardiogram (BCG) reflects the mechanical activity of the heart [1]. Displacement of large blood volumes from the heart into the aorta produces vibrations in the body that can be recorded with sensitive movement detectors such as the static charge-sensitive bed (SCSB) [2].

Normal breathing induces slight respiratory variation to the systolic BCG wave amplitude [3]. Sleep recordings with the SCSB have shown that the ballistocardiographic respiratory variation (BRV) increases during heavy snoring [4] and decreases during episodes of central apnoea [5]. According to preliminary observations in heavy snorers, there is a close association between the BRV and increases in the intrathoracic pressure variation [6]. This suggests that the BRV could be used to detect episodes of partial upper airway obstruction during sleep. A noninvasive method for assessing changes in respiratory resistance would be of interest in view of the high prevalence of habitual snoring [7] and for studying the claimed association between snoring and cardiovascular disease [8, 9].

Although the BRV has previously been shown to increase during resistance breathing [10], there are no studies evaluating the relationship between the BRV and the intrathoracic pressure. We designed an experimental protocol where BRV changes were monitored during increased intrathoracic pressure variation (IPV) and voluntary central apnoea.

Subjects and methods

The BRV was studied in five healthy male volunteers who were not habitual snorers (mean age 29.6 yrs, range 22–33 yrs, mean body mass index (BMI) 21.3 $kg \cdot m^{-2}$, range 19.6–23.0 $kg \cdot m^{-2}$). Each subject gave his informed consent to the study, which was approved by the joint Ethical Committee of the University and the University Hospital of Turku.

The study was performed during the daytime, while all subjects were awake, lying supine on a static charge-sensitive bed (SCSB). Each experiment was started with 5–10 min of free breathing, during which time the baseline BRV was measured. An oesophageal balloon was inserted and an airtight silicone rubber mask covering both mouth and nose was fixed. The mask incorporated separate lines for inspiration and expiration with low resistance valves controlling the breathing route. The inspiratory line was connected to an occluder, the calibre of which was remotely controlled.

To obtain the desired levels of negative intrathoracic pressure during inspiration, sustained inspiratory resistive loading was produced by slowly reducing the calibre of the occluder until a response was observed in the IPV. The subjects were requested not to change their breathing pattern. The respiratory rate was continuously monitored and the subjects were informed if the respiratory rate showed a tendency to fall as a response to loading [11]. The loadings were applied for 30–120 s and the BRV measured when the IPV stabilized to a steady-state level. During the recovery periods, the subjects continued to breathe through the mask without load increment in the occluder.

By changing the aperture of the occluder, steady-state levels of IPV ranging from 5–42 cmH_2O were obtained. The BRV readings obtained during separate episodes of breathing at given IPV levels were pooled for each subject. The mean frequency of the BRV samples per one IPV steady-state level was 20.4 (range 2–77).

When this part of the experiment was concluded, the subjects, still fitted with the oesophageal balloon and the mask, simulated 6–13 cycles of Cheyne-Stokes respiration with periodic episodes of central apnoea with open glottis.

stored in an IBM PC-AT compatible microcomputer and analysed with the BR11® software, which is designed for analysis of the SCSB signals. The BRV was measured by the computer at 6 s intervals by storing the amplitudes of the maximal systolic BCG deflections during four consecutive 1.5 s periods and returning the value of:

$$\frac{\text{highest maximum - smallest maximum}}{\text{highest maximum}} \times 100\%$$

This algorithm is based on the presumption that every 6 s interval would contain at least one complete respiratory cycle and that during each of the four consecutive 1.5 s periods at least one heart beat would be encountered.

Static charge-sensitive bed

The static charge-sensitive bed (SCSB, Bio-Matt®, Biorec, Turku-Finland) is a recent method for recording the BCG [2, 12, 13]. The SCSB consists of a 2 cm thick movement sensoring device which is placed under a normal foam plastic mattress (fig. 1). Except during gross body movements, the SCSB allows the BCG to be monitored continuously; no cables or electrodes need to be attached to the subject. By using analogue frequency filters the respiratory movements and snoring vibrations are also recorded.

The BCG is a record of the small body movements caused by the mechanical activity of the heart. Left venticular contraction and rapid acceleration of blood

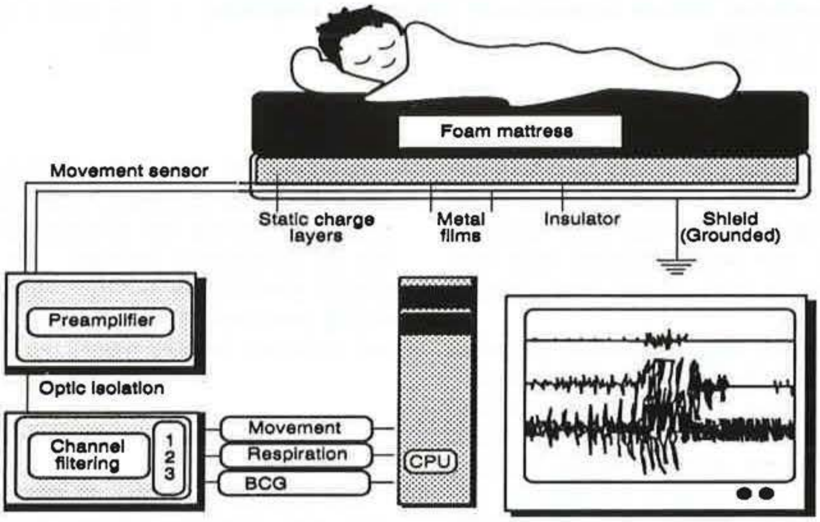

Fig. 1. – Set-up for a static charge-sensitive bed (SCSB) recording. The body movements, respiratory movements and ballistocardiogram (BCG) are derived from the original amplified signal through frequency filtration. The ballistocardiographic respiratory variation is analysed on-line by a personal computer. CPU: central processing unit.

The oesophageal pressure (Poes), three channel SCSB (BCG, respiratory movements, and gross body movements) and the electrocardiogram (ECG) were recorded on a polygraph (Grass model 79 C) with a paper speed of 1.5 $mm \cdot s^{-1}$. The signals from the oesophageal balloon and the SCSB were also input and

in the ascending aorta produce a swift footward movement, which is followed by a headward movement caused by acceleration of blood in the descending and abdominal aorta [1]. During free breathing the systolic wave amplitudes are higher during inspiration than during expiration [14].

The SCSB is well adapted for sleep studies. The validity of the SCSB in detecting obstructive sleep apnoea has been demonstrated previously [15–21]. Substantial clinical experience has accumulated evidence that even partial upper airway obstruction during heavy snoring is detected with the SCSB [4–6, 22].

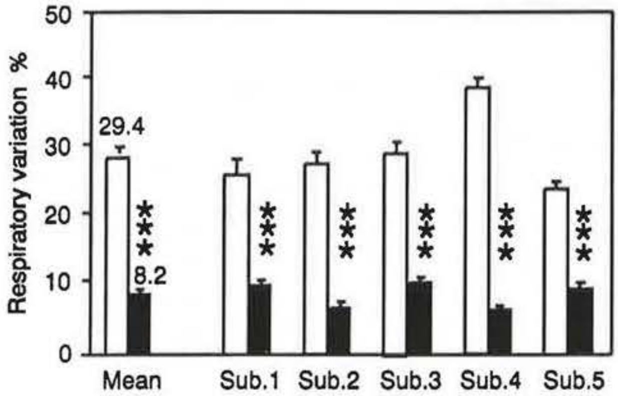

Fig. 2. – The difference between the ballistocardiographic respiratory variation (BRV) during free breathing (□) and during central apnoea (■) was highly significant (***: p<0.001) in each individual subject. In subject no. 4 the BRV during free breathing was higher than that observed in any other subject (p<0.001).

Statistical analyses

One way analysis of variance and Bonferroni's multiple comparison procedure were used to study the differences in the BRV between the individual subjects during free breathing. The linear correlation coefficient between the IPV and the BRV % was calculated. Student's paired t-test was used to assess the difference of the BRV during free breathing and central apnoea. The statistical analyses were made with the BMDP statistical software library for microcomputers [23].

Results

BRV during free breathing

The systolic BCG wave amplitude was highest during inspiration and lowest during expiration. The mean BRV during free breathing was 29.4±0.8% (fig. 2). The BRV was higher (39.2%) in subject no. 4 than in any other subject (range 23.7–29.0, p<0.001).

The effect of increased IPV

When the IPV rose during inspiratory loading, the BRV increased with the appearance of spiky systolic waves synchronized with respiration (fig. 3).

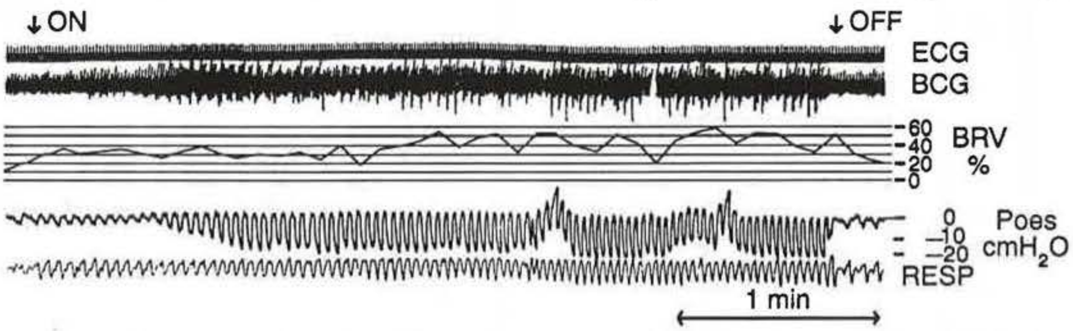

Fig. 3. – Ballistocardiographic respiratory variation (BRV) during inspiratory resistive loading (ON: onset of loading; OFF: loading released). During highly increased intraathoracic pressure variations (IPV) the spiking BCG is a typical finding. The BRV percentages calculated by the computer are presented together with the corresponding polygraphic recording. ECG: electrocardiogram; BCG: ballistocardiogram; Poes: oesophageal pressure; RESP: respiratory movements; IPV: intrathoracic.

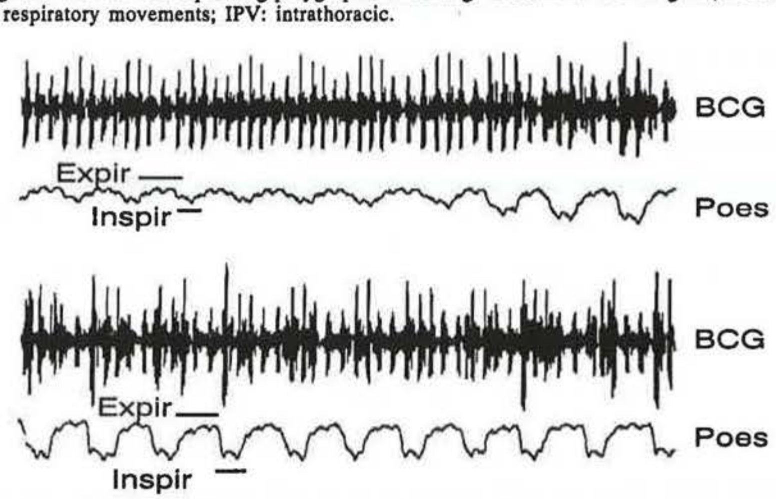

Fig. 4. – The BR11-software output of the ballistocardiogram (BCG) and the oesophageal pressure (Poes) showing the gradual increase of the ballistocardiographic respiratory variation and the timing of the high amplitude BCG spikes in relation to the respiratory cycle. The systolic wave amplitude is higher during inspiration (Inspir) than expiration (Expir).

The highest systolic wave amplitude occurred usually immediately after the onset of inspiration (fig. 4). After the release of loading the BRV soon returned to the resting level (fig. 3).

There was a linear relationship between the intrathoracic pressure and the BRV (r=0.68, $p<0.01$) (fig. 5). The individual correlations were significant in four out of five subjects. The correlation was not significant in subject no. 4, in whom the BRV was exceptionally high already during free breathing. The individual regression lines differed significantly among the subjects ($p<0.0001$).

BRV during central apnoea

The BRV decreased significantly during voluntary central apnoea (fig. 6). The mean BRV reading during central apnoea was 8.2±0.4%, which was lower than that observed during free breathing (29.4±0.8%, $p<0.0001$) (fig. 2). The difference was also highly significant ($p<0.001$) in all individual subjects.

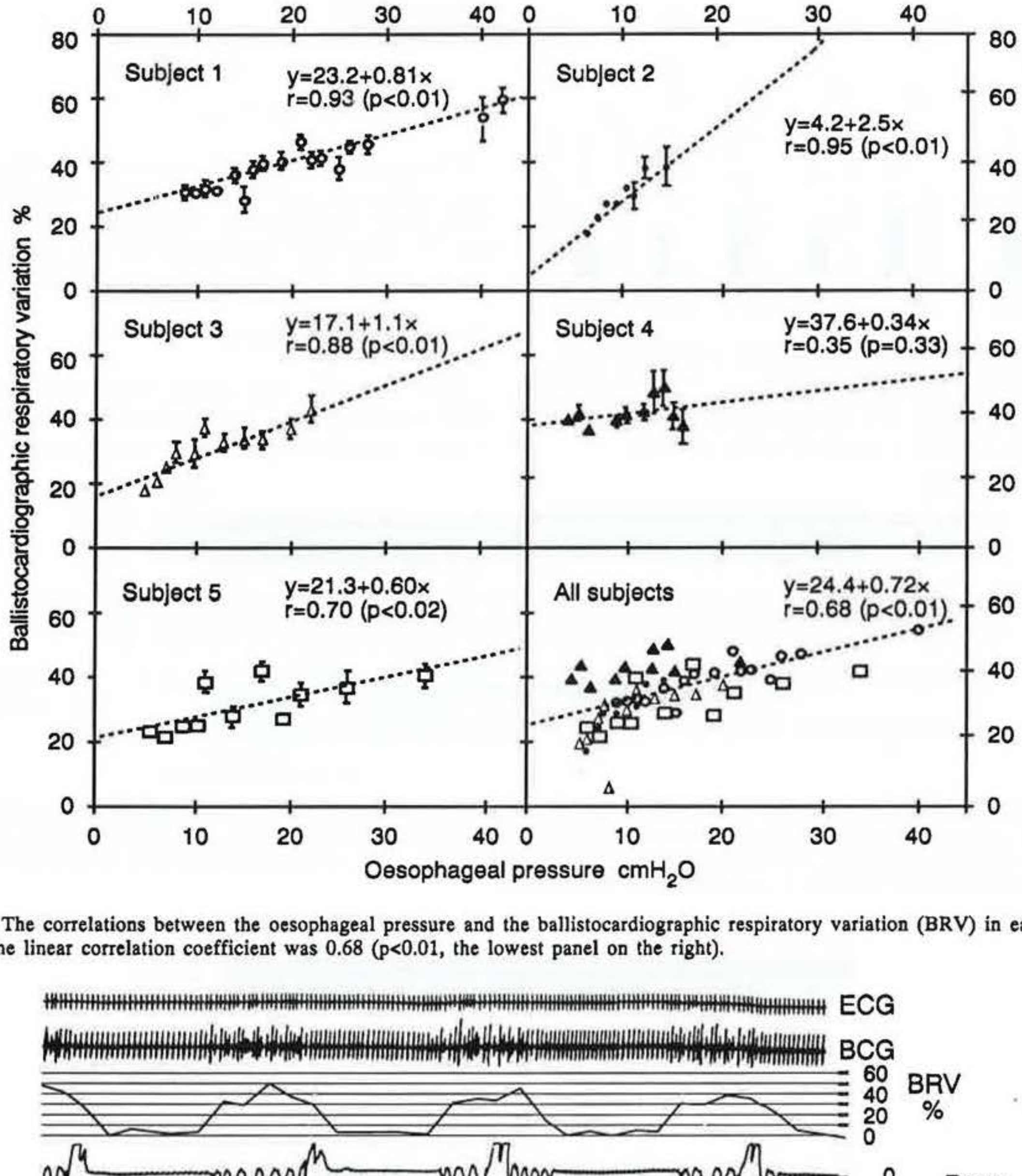

Fig. 5. – The correlations between the oesophageal pressure and the ballistocardiographic respiratory variation (BRV) in each individual subject. The linear correlation coefficient was 0.68 ($p<0.01$, the lowest panel on the right).

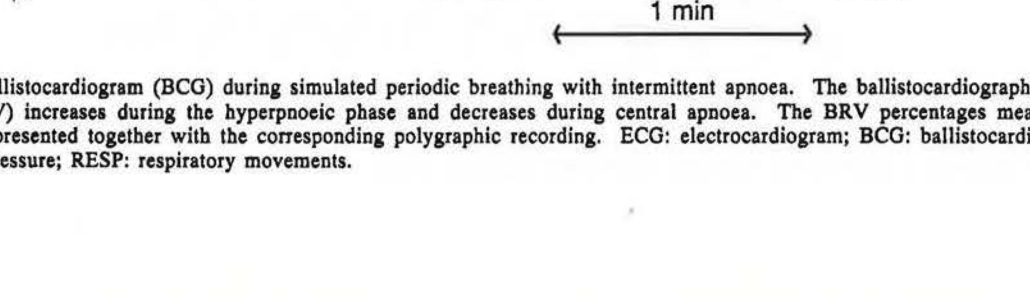

Fig. 6. – Ballistocardiogram (BCG) during simulated periodic breathing with intermittent apnoea. The ballistocardiographic respiratory variation (BRV) increases during the hyperpnoeic phase and decreases during central apnoea. The BRV percentages measured by the computer are presented together with the corresponding polygraphic recording. ECG: electrocardiogram; BCG: ballistocardiogram; Poes: oesophageal pressure; RESP: respiratory movements.

Discussion

Our experiment provides evidence that the BRV is related to the intrathoracic pressure. The BRV was lowest during central apnoea and increased in a linear manner as a function of the intrathoracic pressure. The linearity of the BRV response within one subject suggests that temporal changes in the IPV within a given subject could be reliably monitored with the BCG. However, there was significant interindividual variation in the response. Cardiorespiratory factors, such as heart rate, the position of the heart [3], effects of the autonomic nervous system on the myocardium, the compliancy of the lung tissue, as well as anatomical factors, such as body mass and shape of the thorax, explain part of the variation. The influence of these factors should be tested in a larger population. The marked interindividual variation excludes the possibility of deriving the absolute IPV levels from the BRV without individual calibration. When using the heart, the "physiological intrathoracic balloon", as a pressure sensor, it is understandable that the output depends on the physical properties of each "balloon".

Prolonged periods of elevated IPV provoked in some awake subjects a feeling of discomfort or anxiety. Therefore, continuous steady-state levels with intrathoracic suction pressures <-25 cmH_2O were obtained in only two subjects. These values should be viewed against the suction pressures (<-50 cmH_2O [24]) in some heavy snorers during sleep. This suggests that the arousal threshold is markedly increased in heavy snorers and that the respiratory muscles may become hypertrophic as a result of habitual heavy snoring [25].

In one of the five subjects (subject no. 4) there was no significant correlation between the BRV and the intrathoracic pressure. This was probably due to the fact that his BRV was exceptionally high already during free breathing. Increased BRV during free breathing is associated with coronary artery disease, hypertension, postsympathectomy or pulmonary emphysema [3]. This subject was, however, in good physical health, but the highest steady-state IPV level obtained by loading was only 17 cmH_2O. A significant correlation might have been obtained if higher IPV levels could also have been tested.

Decreased BRV was a constant and clearly distiguishable finding during central apnoea. Although "flattening" of the systolic BCG wave amplitude seems to be specific enough to allow detection of central apnoea, the interruption of respiratory movements should be confirmed by using the respiratory movement channel.

The mechanism of the BRV during normal breathing is not fully understood, although at least two factors are involved. Firstly, breathing changes the position of the heart with respect to the long axis of the body: with inspiration the heart becomes more vertical and produces a more pronounced footward component of the cardiac recoil [3]. Secondly, the negative intrathoracic pressure increases the venous return and the right ventricular filling. Although this leads to partial compression of the left ventricle and slightly decreased left-sided filling [26], the total ventricular volume increases [27], resulting in reinforcement of the systolic recoil. During periods of increase respiratory load with ample intrathoracic pressure swings, other factors may also be involved.

The enthusiasm for ballistocardiography subsided in the late 1950s and many physicians today are not familiar with the technique. Now there are, however, at least two important circumstances that prompt a re-evaluation of the method. Firstly, the static charge-sensitive bed (SCSB) is a new, non-invasive method that allows long-term monitoring of the BCG in the subject's own bed. Secondly, partial upper airway obstruction and increased intrathoracic pressure variation during sleep has recently been shown to have clinical importance [28, 29]. Heavy snoring has been identified as a risk factor for ischaemic heart disease, hypertension [8], and cerebral infarction [9]. Heavy snoring [7, 30] and its important sequel, the obstructive sleep apnoea syndrome are frequent within the population, and have motivated the development of better diagnostic facilities. Only early recognition of increased upper airway resistance allows prevention of the complications of snoring, and prevention is more efficacious than treatment of an already developed syndrome [29].

There was a linear correlation between the BRV and the intrathoracic pressure in healthy adults. This observation warrants further studies on patients with increased respiratory load during sleep (heavy snoring or nocturnal asthma). If similar correlations are obtained in older and obese subjects in various body positions, the BRV could become a noninvasive alternative to the direct measurement of intrathoracic pressure by the oesophageal balloon, which is too demanding as a routine procedure in all subjects suspected of having increased respiratory resistance during sleep.

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