Control of Pacemaker Rate by Impedance-based Respiratory Minute Ventilation*

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Several studies have shown that the capability for exercise can be increased in patients with pacemakers by means of adjusting the rate. Respiration is one of the parameters considered for rate control. The aim of our study was to determine how respiratory parameters such as ventilation, tidal volume, and respiratory rate are capable of controlling the pacemaker rate, especially when measured indirectly by means of impedance plethysmography. We examined four volunteers and eight patients with implanted cardiac pacemakers using bicycle ergometry at increasing work loads. We recorded heart rate, uptake of oxygen, and ventilation directly (by pneumotachygraphy) and indirectly (by chest wall impedance plethysmography). A good correlation of directly to indirectly measured ventilation ($r = 0.8657$) was found. Our study suggests that respiratory minute volume is more appropriate for rate control of physiologic pacemakers than tidal volume or respiratory rate alone. Measurement by means of impedance plethysmography is sufficiently precise to be used for this purpose. Further studies must be conducted as to the optimum realization within an implantable device.

Since expectations with regard to cardiac pacing have changed considerably in recent years, hemodynamic aspects of pacing have become more and more important. Some recently published reports have shown that especially with physical exercise an increase in heart rate has a more pronounced effect on the capability for exercise and on hemodynamics than atrioventricular synchrony. Since the majority of patients with pacemakers have no or only an inadequate increase in heart rate with exercise, there is a need for reliable parameters to control the rate of physiologic pacemaker systems. These parameters should be linked as directly as possible to the metabolic state of the body. The current metabolic situation is well represented by the oxygen uptake of the body ($V_{O_2}$).

The uptake of oxygen is performed by the lungs; its transport is effected by the circulatory system. In the absence of severe or even with moderate pulmonary disease, the limiting factor of exercise tolerance is the transport capacity for oxygen (ie, cardiac output) and not the uptake of oxygen by the lungs. This applies not only to healthy people but also to patients with pacemakers who have a limited increase in heart rate under conditions of exercise. Since there is a well-known individual correlation of work load, oxygen uptake, and heart rate within submaximal levels of exercise, the aim of our study was to determine the extent to which respiratory rate, tidal volume (TV), and respiratory minute volume correlate with the parameters mentioned previously when measured not only directly, but also indirectly by means of impedance plethysmography. Another aim was to detect the extent to which different parameters are capable of controlling the pacemaker rate.

**Materials and Methods**

We studied four healthy volunteers and eight elderly patients with cardiac pacemakers (Table 1). All participants had given their voluntary consent to the testing prior to the study after being informed about its nature, goals, and possible risks. There was no history of pulmonary disease in either group. In four of the patients, a physiologic pacemaker system (DDD or VDD) was implanted as therapy for a complete atrioventricular block, three of the patients had a DDD system for binodal disease, and one patient had received

<table>
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<th>Group and Subject, Sex, Age (yr)</th>
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<td>12,M,42</td>
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*AV, Atrioventricular.
his DDD pacemaker as therapy for the sick sinus syndrome.

Exercise tests were performed with increasing work loads on a bicycle ergometer (35 to 250 W), each work load being performed over a period of five minutes in order to achieve a steady state of circulatory and respiratory parameters. The increase in work load was adapted to the individual's physical exercise capacity by steps of 25 or 50 W. Exercise tests in patients with pacemakers were performed at a standard DDD/VDD setting. Heart rate was continuously monitored on an electrocardiographic monitor (Hellige) and was recorded together with the respiratory parameters simultaneously on a three-channel strip-chart recorder (Gould).

Respiratory parameters were measured in two different modes. First, respiratory parameters were measured by means of pneumotachygraphy. Along with the respiratory rate, TV, and respiratory minute volume, the oxygen content and carbon dioxide content of the expired air were also determined (Ergo-Oxyscreen; Jaeger). Final data processing and presentation of the results were done on a computer (Apple). Secondly, respiratory parameters were determined by measuring the thoracic impedance (impedance plethysmography). A high-frequency alternating current (100 kHz; 10 mV) was applied to two common cutaneous electrocardiographic electrodes that were placed on the fifth intercostal space at the right and left lateral portions of the chest wall. Ventilation was calculated according to the changes in impedance following respiration, as basically described already.74 Calculations of indirectly measured ventilation were made with the help of a computer program especially developed for our purposes.

The analog data of pneumotachygraphy and impedance plethysmography were recorded simultaneously together with the electrocardiogram on the previously mentioned strip-chart recorder. The recording of the respiratory values had been calibrated prior to the trials according to conditions of body temperature and pressure, saturated. Statistical analysis was done with the help of a calculator (Hewlett-Packard 33E) using standard statistical methods.

**RESULTS**

**Direct Respiratory Measurements**

(Electrocardiography)

Figure 1 shows the respiratory rate, respiratory minute volume, and heart rate with an increasing work load of 100, 200, and 250 W in a well-trained healthy male volunteer (42 years of age). Respiratory minute volume and heart rate feature a rapid increase at the onset of 100 and 200 W of work load, and both maintain a plateau with continuing exercise at these levels. At 250 W, respiratory minute volume achieves no steady state, reflecting the onset of respiratory compensation for the metabolic acidosis of exercise. In contrast to the mainly parallel slope of respiratory minute volume and heart rate, the respiratory rate shows somewhat different behavior. The increase in respiratory rate at 100 and 200 W is less pronounced compared to the increase in heart rate and respiratory minute volume. Only with the high work load of 250 W is there a clear increase in respiratory rate.

In order to analyze this better, we looked at the respective relation of TV, respiratory rate, respiratory minute ventilation, and oxygen uptake to heart rate under the previously mentioned conditions of exercise.

![Figure 1](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21565/)

**Figure 1.** Respiratory rate (RR), respiratory minute ventilation (RMV) and heart rate (HR) in 42-year-old volunteer during bicycle ergometry at 100, 200, and 250 W. After end of exercise, heart rate and ventilation return to their initial values, while respiratory rate remains elevated.
Each point of the plots represents the average of the respective value over a period of 30 seconds. One can see that at the beginning of exercise, even with only a small increase in heart rate, TV shows a rapid increase from about 0.5 L to about 2 L, whereas TV with heart rates above 120 beats per minute remains fairly constant at 2.5 L (Fig 2B). Respiratory rate shows the opposite behavior (Fig 2A). At the beginning of exercise, the increase in heart rate is followed by a small increase in respiratory rate, while with higher exercise loads a further increase in respiratory minute volume is predominantly covered by an increase of respiratory rate. After exercise the respiratory rate remains at a relatively high level of 24 breathing cycles per minute (Fig 2A, values shown in circle) compared to the decrease of respiratory minute volume and also to heart rate. As expected, respiratory minute volume (Fig 2C) and oxygen uptake (Fig 2D) both have a more linear relation to heart rate.

A response similar to that described previously was observed in a 44-year-old patient who had received a DDD pacemaker for a complete atrioventricular block. For the testing shown in Figure 3, the patient's pacemaker was temporarily programmed to the VVI mode at a rate of 70 beats per minute. Bicycle ergometry was performed at 50 and 100 W. Because of the patient's atrioventricular block, the intrinsic heart rate shows only a slight increase to 85 beats per minute at 100 W. Despite this inappropriate increase in heart rate, respiratory minute volume displays an adequate increase according to the increased oxygen uptake with work. As known from Figure 1, the respiratory rate remains at a somewhat elevated level after exercise in this case as well, while heart rate and respiratory minute volume trend faster towards resting conditions. One can see that both in volunteers and in patients with pacemakers, the respiratory rate after exercise is at the same increased level as it is at the first stage of exercise, but respiratory minute volume differs considerably between exercise and the resting condition after exercise.

Tables 2 and 3 summarize the results of respiratory measurements and heart rate with increasing work loads in all volunteers (Table 2) and patients (Table 3).
Control of Pacemaker Rate (Alt et al)
FIGURE 4. Part of simultaneous strip-chart recording of ventilation by means of pneumotachygraphy (top channel), impedance plethysmography (middle channel), and heart rate (bottom channel) in healthy volunteer with bicycle ergometry at 50, 100, and 150 W. With higher work loads, ventilatory impedance signal additionally features changes in impedance caused by increased cardiac output.

FIGURE 5. Plot of all directly measured data on ventilation vs indirectly gained values. RMV, Respiratory minute ventilation.
**Indirect Respiratory Measurements (Impedance Plethysmography)**

Figure 4 shows an original registration of directly measured respiratory parameters, indirectly measured respiratory parameters, and heart rate at rest at 100 and 150 W in a healthy 26-year-old volunteer. The correlation of respiratory minute volume between directly measured and indirectly calculated values was 0.8687 in this individual case. We analyzed and compared the values obtained with direct and indirect measurement of respiration under resting and exercise conditions. We found that respiratory rate, TV, and respiratory minute volume could be determined by means of indirect impedance plethysmography sufficiently well compared to directly measured data. The data of directly measured minute ventilation and the indirectly determined respiratory minute volume for all volunteers and patients are displayed in Figure 5.

**DISCUSSION**

In conformity with the literature,\(^\text{10,11}\) we also found a good correlation between work load, oxygen uptake, and respiratory minute volume not only in healthy persons, but also in patients with pacemakers. Since healthy persons show a good correlation of the previously mentioned parameters to heart rate, it seems possible to control the pacemaker's rate in patients who have an inadequate rate increase with exercise by means of respiratory minute volume.

Our data favor respiratory minute volume over the other ventilatory parameters such as respiratory rate or TV, since the initial increase in ventilation with exercise (depending on the respiratory type) is established more by an increase in TV than by an increase in respiratory rate, while with higher work loads an increase of minute ventilation is effected more by an increase in respiratory rate. Furthermore, the ratio of respiratory rate to heart rate prior to and after exercise can differ as well. Especially after strenuous exercise the respiratory rate might tend to stay at a somewhat increased level, despite a normal decrease in heart rate, ventilation, and oxygen uptake. In order to mimic a more truly physiologic rate response in a respiration-dependent cardiac pacemaker, it seems better to control the heart rate by minute ventilation than by respiratory rate alone, as has been suggested in the past.\(^\text{12}\)

It has been reported\(^\text{13}\) that the individual ratio of TV to respiratory rate depends on factors such as the individual's exercise capability, sex, age, and concomitant pulmonary disorders.\(^\text{5,6}\) A person who is relatively fit generally tends to cover his respiratory minute volume by a greater TV at a lower respiratory rate, whereas an older and less well-trained individual effects ventilation more by an increase in respiratory rates. In our study the relatively low increase in respiratory rate of only 11 breathing cycles per minute (from 19/min to 30/min) with a work load of 100 W might be partly caused by the unfamiliar situation of breathing through a mouthpiece and the tube of the ventilation check, which may have resulted in a falsely elevated respiratory rate at rest. This should also be considered when analyzing and weighing the results of respiratory rate in volunteers as well as in patients with pacemakers.

The use of respiratory minute volume to control the rate of physiologic pacemakers allows the heart rate to be adjusted to metabolic needs independently of individual variations of respiratory rate and TV. Since indirect measurement of respiration correlates sufficiently with directly determined ventilation in patients with pacemakers as well, the adjustment of the pacing rate according to respiratory minute volume determined by means of impedance seems to be practicable. Data processing with the help of a microprocessor-controlled pacemaker could calculate respiratory minute volume from measurements of impedance. Further investigations must be conducted as to the optimum way and site of measurement when incorporated into an implantable pacemaker system.

**REFERENCES**

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