Rate control of physiologic pacemakers by central venous blood temperature

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ABSTRACT Heart rate and central venous blood temperature (CVT) were measured in 31 people with different exercise capacities by means of a thermistor integrated into a lead that was placed in the right ventricle. Bicycle ergometric and treadmill stress tests with increasing workloads were performed. The maximum increase in CVT with ergometric exercise was found to be 1.3°C at 250 W in healthy young volunteers and 1.0°C at 125 W in cardiac patients. Despite a relatively greater increase in CVT in the elderly patients compared with the volunteers, the correlation between the increase in CVT and that in heart rate at the end of each exercise stage was found to be very high (r = .9693 in volunteers and r = .9864 in cardiac patients), independent of physical fitness. Even with everyday activities such as walking there was a marked increase in CVT. Due to its close relationship to human metabolism, CVT represents a good parameter for physiologic control of pacing rate.

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INDICATIONS for pacemaker therapy have been steadily expanding in recent years. More and more pacemakers are now implanted, not only for the purpose of prolonging life, but also with the aim of optimizing the quality of the patient’s daily life. Therefore, one of the basic requirements of pacing is that it adapt cardiac output in relationship to metabolic needs. Although pacemakers capable of adjusting heart rate according to changes in atrial rate were suggested more than 20 years ago, presently more than 70% of patients receiving so-called physiologic pacemaker systems have no or only inadequate adjustment of heart rate with exercise. Since an increase in cardiac output with exercise is determined mostly by an increase in heart rate, the current forms of physiologic pacing will provide major benefits with respect to exercise performance only in patients with regular sinus function and an exercise-induced rate increase. In patients with little or no acceleration of heart rate, physiologic pacing will be more beneficial with respect to restoration of normal resting hemodynamics1–2 than improvement of exercise performance. Therefore, the need for physiologic input signals to drive pacing rate is evident. Some parameters like oxygen saturation,3 QT interval,4 respiratory rate,5,6 activity sensing,7 and temperature8–10 have been suggested in the past.

While body temperature with exercise has been studied in dogs8,9 and in man extensively as rectal and esophageal temperatures,11–13 little is known about the behavior of intracardiac temperature in people with different exercise capacities. We therefore studied intracardiac temperature at different workloads in volunteers with fair-to-excellent exercise capacities and in elderly patients with cardiac pacemakers. The aim of our study was to determine what parameters would influence changes in body temperature with exercise and to observe their relationship to heart rate. We studied how the absolute or relative metabolic rate would determine the increase in temperature and to what extent the slope of temperature incline was dependent on individual parameters.

Patients and methods

Fourteen healthy volunteers (23 to 44 years old) and 17 elderly patients with cardiac pacemakers (47 to 82 years old) were studied. Five of the volunteers and seven of the patients were women. All of the subjects were informed as to the nature, purpose, and possible risks involved in the study before giving their voluntary consent to participate.

A custom-made No. 5F polyurethane isolated lead with a thermistor integrated into the lead 5 cm behind the top of the electrode (figure 1) was inserted in each subject by the Seldinger technique through an antecubital vein and passed under fluoroscopic control to the apex of the right ventricle. Temperature was recorded on a portable digital-memory device with 28 kbyte of capacity able to record heart rate, central venous blood temperature, and respiratory rate every 5 or 10 sec. Real-time and
marker events were recorded continuously. Accuracy of temperature measurement was within 1/100 of a degree centigrade. Temperature was registered in steps of 1/100 of a degree centigrade. The catheter and thermistors were calibrated to measure absolute temperatures. Deviations were found to be less than 0.1°C absolute temperature within different leads. Due to the low mass of the thermistor and the thin layer of insulation, temperature response was found to be very fast (less than 1 sec). Except for the development of one local thrombophlebitis, all tests in this study were performed without complications.

Lead position was confirmed by fluoroscopy at the beginning and end of the study. An Edwards cardiac output computer was used as an additional check on temperature. Data were processed with an Apple computer with the capability for graphic and alphanumeric presentation. All events during the test were recorded on paper as well as registered on the digital memory device.

Exercise tests were performed on a bicycle ergometer, with workload increasing according to individual’s fitness in increments of 25 to 50 W every 4 min. Pedaling was done at 50 to 60 revolutions per minute. Treadmill tests were performed with increasing speed and grade with the goal of achievement, as nearly as possible, of the individual’s maximum aerobic capacity. Between different exercise tests there was an average rest period of at least 20 min to allow blood temperature and heart rate to return to resting levels.

Correlation coefficients and regressions were calculated by means of the statistical program incorporated within a HP33C calculator.

Results

Figure 2 shows heart rate and central venous blood temperature (CVT) of a healthy 28-year-old male volunteer. The graph represents data collected over a period of 30 min. A bicycle test was performed at workloads starting at 50 W and increasing up to 250 W. While heart rate increased rapidly at the beginning of exercise, temperature declined slightly during the first minute of exercise, but then increased from 37.0°C to

![FIGURE 1. No. 5F polyurethane insulated bipolar lead with the thermistor mounted 5 cm behind the tip.](image_url)

![FIGURE 2. Effects of bicycle ergometric exercise in a 28-year-old male volunteer. HF = heart rate; T = central venous blood temperature.](image_url)
38.3°C. Heart rate plateaued at initial workloads. Temperature also showed a tendency toward an increase that was related to the higher metabolic rate of each workload. After exercise, there was a rapid decline in both CVT and heart rate.

In an 82-year-old patient with a pacemaker and complete atrioventricular block, we found, as in the young healthy subject, that blood temperature increased markedly (from 36.9°C to 37.6°C) with exercise at 50 and 75 W (corresponding to 3 and 4 METS). This patient performed the exercise protocol with his pacemaker in the VVI mode at 70 beats/min (figure 3). Fifteen minutes after the end of the trial, we programmed the pacemaker back to the VDD mode, resulting in an increase in heart rate by 15 beats/min. This represents a metabolic need for a higher heart rate. In response to the higher heart rate and circulation, temperature then decreased somewhat more rapidly.

Figures 4 and 5 summarize the heart rate and temperature increases with increasing workloads on the bicycle ergometer in 14 healthy volunteers (figure 4) and 17 cardiac patients (figure 5). The highest workload reached by the volunteers was 250 W, and that reached by the patients was 125 W. While the absolute increase in temperature in volunteers was 1.3°C at 250 W, we noted an increase of nearly 1°C in patients at their maximum exercise level of 125 W, even though this represents only half of the workload performed by volunteers. From the comparison of the increases in temperature in volunteers and patients at identical absolute working levels, it becomes evident that the increase in temperature is markedly higher in cardiac patients.
patients than in volunteers. On the other hand, the rate increase at comparable exercise loads was also higher in patients than in the better trained volunteer group—a finding that was expected based on exercise physiology. The correlation between the increase in heart rate and the increase in temperature seen at the fourth minute of each exercise stage was therefore very high (r = .9693 in volunteers and r = .9864 in patients), independent of the absolute workload. These statistical calculations were done by means of the determination of the difference between the instantaneous heart rate and temperature at the end of each 4 min exercise stage and the respective basic data at rest. For each individual we found the increases in heart rate and temperature at a certain external workload to be determined by the relative part of the oxygen uptake at this workload compared with the individual's maximum possible oxygen uptake. This means that someone who is well trained will experience less of an increase in heart rate and temperature at a given workload compared with someone less fit. This holds true not only when comparing subjects with different exercise capacities, but also for within-subject comparisons of effects of the same level of exercise under different hemodynamic conditions.

Our special interest was to determine to what extent heart rate and cardiac output as a function of heart rate would influence the degree of increase in temperature.

The first trial was in a healthy 28-year-old female subject. After completing the exercise protocol, as shown in figure 6, we repeated the same protocol after intravenous administration of 20 mg metoprolol (figure 7), which limited the increase in heart rate to a maximum of 130/min, despite the fact that the same workload was attained. The period of rest between these two trials was long enough to allow comparable baseline conditions (figures 6 and 7).

Subsequent to this study of walking on the treadmill with increasing speed and grade was performed at different pacemaker settings in a 58-year-old patient with a pacemaker and complete atrioventricular block. A programmable DDD pacemaker had been implanted 2 years previously. With pacing in the VDD mode rate increased to 150 beats/min, while temperature rose by 0.7° C by the end of the first trial (figure 8). We then programmed the pacemaker to the VVI mode with a rate of 70 beats/min. With exercise the patients intrinsic heart rate rose to 95 beats/min, but his temperature rose by more than 1° C (figure 9). With the patient at rest after the end of exercise, we reprogrammed the

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**FIGURE 6.** Heart rate (HF) and temperature (T) in a 28-year-old female volunteer during ergometric exercise before β-blockade.
pacemaker to the VDD mode once again, and heart rate rose from 70 to 115 beats/min.

Discussion

Each external workload represents a certain rate of oxygen uptake and metabolic cost. Since the ratio of mechanical energy to heat production in hormonally healthy people is independent of individual factors, 22 ± 4% of the total metabolic energy is used for mechanical work and 78 ± 4% is turned into heat. Therefore, heat production at identical workloads is the same in well-trained and unfit persons. However, there is a relatively greater increase in temperature in cardiac patients because impaired cardiac output restricts ability to dissipate heat by increasing skin circulation. Body temperature rises until heat dissipation equals the rate of heat production. This new plateau depends on the maximum aerobic capacity, as demonstrated by our results not only with different subjects, but also within the same individual. Since the data presented in figures 6 to 9 were obtained in only one volunteer and one patient, care must be taken in generalizing these observations to others. However, our results in a larger group of patients with pacemakers during repetitive exercise tests performed during two different modes of stimulation (VVI and VDD) showed a significant difference in temperature rise at identical workloads, as described above. These results have been described in detail.*

This principle of a negative feedback of heart rate and temperature represents an important feature in a temperature-driven pacemaker system. Harmful positive feedback (which is conceivable with a respiratory rate–driven pacemaker under conditions of pulmonary congestion) is impossible with a temperature-controlled pacemaker.

In contrast to another report, we found that even with activities like walking there was a clear increase in CVT. This might be due to the position of our thermistor. In the previous study the thermistor was situated in the high right atrium, while we placed it at the right ventricle to achieve a good mixture of blood of various temperatures. During an additional treadmill test we also measured temperature at the high right atrium and found a marked delay between the onset of exercise and the increase in temperature. Since with leg work heat will be transported with blood that

comes from the lower limbs, it is conceivable that it will take some time until the blood that comes from the relatively cooler upper limbs will show an increase in temperature.

Our results further demonstrate that the increase in temperature is not as slow as assumed by others.\textsuperscript{16, 17} Due to its close relationship to human metabolism we believe that temperature represents a good parameter for physiologic control of pacing rate for medium and higher working levels. Since only respiratory minute volume and central venous oxygen saturation\textsuperscript{1} show such a direct relationship to metabolism and their measurement on a stable long-term basis seems to be more difficult, central venous blood temperature represents a truly physiologic parameter for control of pacing. Compared with QT interval\textsuperscript{4, 16} and activity,\textsuperscript{7} which have only a rather random relationship to oxygen uptake and metabolism, temperature has a higher specificity.

Based on our results, we developed a special algorithm to cover different hemodynamic and metabolic situations, such as exercise, rest, and fever. An increase in temperature per se has an accelerating effect of about 10 beats per degree centigrade on spontaneous

heart rate of isolated surviving human fetal hearts.\textsuperscript{18} Similar results were obtained after temperature changes that were applied to the human heart after autonomous blockade.\textsuperscript{19} The effect of temperature per se is also known from animal experiments with denervated hearts\textsuperscript{20} and from observations during cardiac surgery with cold cardioplegia.\textsuperscript{21}

Besides this direct influence of temperature on the endogenous heart rate, fever has been shown to result in increased peripheral circulation and metabolism, which contribute to an increase in heart rate averaging 15 to 25 beats per degree centigrade temperature increase.

To ensure adequate function of a pacemaker with exercise and during fever, we designed a special algorithm that used two different characteristic lines.\textsuperscript{22} The first one, the baseline, has a slope of about 15 beats per degree centigrade, corresponds to absolute temperature values, and follows changes in temperature that occur more slowly, such as circadian temperature variations\textsuperscript{23} and changes that occur with fever. The second one, the exercise line, disposes of a slope of about 80 beats per degree centigrade, which allows adjustment to physical exercise using relative changes in tempera-
ture. The differentiation between the lines is made by the change in temperature over time. Simulation tests with the use of the temperature data described here and stress tests with an external device using this algorithm (Intermedics Nova MR) have been performed with good results, providing an adequate heart rate under different metabolic conditions.

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