Optimal Maximum Tracking Rate of Dual-Chamber Pacemakers Required by Children and Young Adults for a Maximal Cardiorespiratory Performance

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MATHONY, U., ET AL.: Optimal Maximum Tracking Rate of Dual-Chamber Pacemakers Required by Children and Young Adults for a Maximal Cardiorespiratory Performance. Introduction: Children and young adults require a higher maximum tracking rate (MTR) for physical activity. The objective of the present study was to observe whether higher MTR of 170 or 190 beats per minute (bpm) have a positive impact on the maximal cardiorespiratory capacity of children and young adults in comparison with a lower MTR of 140 bpm.

Methods: Fifteen patients with atrioventricular block and normal sinus-node chronotropic function (age 7–24 years) with DDD- (14) or VDD-pacemakers (PM) (1) were enrolled. First, the MTR was adjusted to 140 bpm for 6 weeks and elevated in a second step to 170 or 190 bpm. At the end of each period two cardiopulmonary exercise tests, a 24-hour ECG and a PM test were performed.

Results: All patients increased their maximal heart rate (139.0 ± 1.0 vs 177.0 ± 10.0 bpm, P < 0.001), peak cardiorespiratory capacity (2.4 ± 0.6 vs 2.8 ± 0.7 W/kg, P < 0.001), peak oxygen uptake (28.3 ± 7.0 vs 35.7 ± 9.5 mL/kg/min, P < 0.005), and oxygen uptake (23.7 ± 7.4 vs 29.3 ± 8.4 mL/kg/min, P < 0.02) at the anaerobic threshold. There were no evident heart rhythm disturbances with elevated MTR. Patients with a Wenckebach behavior of the PM had an attenuated increase of maximal cardiorespiratory performance.

Conclusion: Children and young adults with DDD-/VDD-PM benefit from an elevated MTR by an increased cardiorespiratory capacity, without having more heart rhythm disturbances. A Wenckebach behavior of the PM should be avoided. (PACE 2005; 28:378–383)

dual-chamber pacemakers, exercise testing, children, oxygen uptake, optimal pacemaker programming

Introduction

The implantation of pacemakers for children and young adults is an established procedure. In 1999 approximately 1% of all pacemaker implantations in Germany were performed in children and adolescents up to an age of 20 years. Implantation of pacemakers in these patients is difficult because the pacemaker system is designed to be ideal for adults, and there are few data for the optimal adjustment of pacemaker parameters in this young age group. Since dual-chamber pacemakers have beneficial effects on hemodynamics they are considered as the most appropriate systems of antibradycardic stimulation, especially in children and adults. However, there are no data concerning the optimum programming of the upper maximum tracking rate (MTR) limit of DDD-pacemakers for a maximum of cardiorespiratory performance in this group.

This study tested the hypothesis that an elevation of the MTR limit from 140 to 170 or 190 beats per minute (bpm) (depending on the system implanted) may increase the cardiorespiratory capacity in children and young adults. It also tested the evidence of increased propensity to heart rhythm disturbances or pacemaker induced tachycardias with the higher tracking rates.

Methods

This study was approved by the local ethics committee of the Martin-Luther-University Halle-Wittenberg and all patients as well as their parents gave their written informed consent.

Fifteen patients (age 7–28 years, mean age 16.9 years) were enrolled with a third degree (n = 14) or second degree (n = 1) atrioventricular block and recent DDD- (14×) or VDD- (1×) pacemaker stimulation (Table I).

The evaluated pacemaker systems were Thera and Kappa (Medtronic, Duesseldorf, Germany) and Clarity (Vitatron, Dieren, The Netherlands).
The etiology of atrioventricular block was congenital (n = 11, diagnosis during the first few years of life, without initial symptoms of heart failure), surgical (n = 2, both with an optimal surgical result), and acquired (n = 2, diagnosis after initial normal ECG and with acute symptoms). All patients were in NYHA class I and showed in their clinical and echocardiographic investigation a normal cardiac function without valvular stenosis or insufficiency greater than mild. Normal sinus-node function with an increase of the P-wave frequency higher than 150 bpm during exercise was shown by exercise test and 24-hour ECG. None of the patients was taking medication during the study time.

The study protocol is illustrated in Figure 1. Firstly, the MTR limit was adjusted to 140 bpm and after 6 weeks for adaptation we performed two cardiorespiratory exercise tests. Additionally, a 24-hour ECG was applied and a pacemaker test performed. Secondly, the MTR was elevated to 170 bpm (Thera, Kappa) or 190 bpm (Clarity). After 6 weeks the patients were reassessed.

The aim of the study was the assessment of the cardiorespiratory capacity. The two cardiorespiratory exercise tests on two consecutive days were performed to minimize the fluctuations of the assessed parameters. A constantly increasing workload protocol was used according to Wassermann et al.8 The following parameters were assessed during the test: maximum heart rate, oxygen uptake, peak workload, and oxygen uptake at the anaerobic threshold and workload at the anaerobic threshold. The individual predicted peak oxygen uptake for healthy children and adults was calculated.8 All data were assessed as 60-seconds-means but when the test was interrupted at the peak workload at least as 30-seconds-means.

ECG recorders (Oxford, Wiesbaden, Germany) with a sampling rate of ~2000 Hz were used for the

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### Table I.
Demographic Data and Ventricular Premature Beats (VPB) at Two Time Points

<table>
<thead>
<tr>
<th>Number</th>
<th>Age at Study</th>
<th>Age at 1st Implantation</th>
<th>Age at Diagnosis</th>
<th>PM-Indication (AVB-Degree)</th>
<th>PM</th>
<th>WB (140 bpm)</th>
<th>VPB</th>
<th>VPB (170/190 bpm)</th>
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<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>11</td>
<td>2</td>
<td>AVB III (congenital)</td>
<td>DDD</td>
<td>n</td>
<td>7.7</td>
<td>2.8</td>
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<tr>
<td>2</td>
<td>12</td>
<td>7</td>
<td>7</td>
<td>VSD, AVB III (surgical)</td>
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<td>18</td>
<td>18</td>
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<td>DDD</td>
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<td>DDD</td>
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</tr>
<tr>
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<td>15</td>
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<td>1</td>
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<td>8</td>
<td>AVB III (congenital)</td>
<td>DDD</td>
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<td>14</td>
<td>13</td>
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<td>DDD</td>
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<td>4.0</td>
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</tr>
<tr>
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<td>16</td>
<td>12</td>
<td>0</td>
<td>AVB III (congenital)</td>
<td>DDD</td>
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<td>18</td>
<td>18</td>
<td>AVB III (acquired)</td>
<td>VDD</td>
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<td>DDD</td>
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<td>NA</td>
</tr>
<tr>
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<td>15</td>
<td>0</td>
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<td>AVB III (congenital)</td>
<td>DDD</td>
<td>y</td>
<td>21.0</td>
<td>4.9</td>
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</table>

Mean ± SD 16.9 ± 4.8 10.3 ± 5.5 4.1 ± 5.3 637.4 ± 2121.4 157.0 ± 458.3 *(P = 0.14)*

Age in years; WB = Wenckebach behavior at maximum tracking rate of 170/190 bpm; NA = not assessed; TOF = tetralogy of Fallot; VSD = ventricular septal defect; VPB = number of VPB/24 hour.

*The mean ± SD was calculated only for those values for which exists data for both time points.

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**Figure 1.** Design of the study. First step: programming a maximum tracking rate of 140 bpm. In the interim of 6 weeks the patients adapted to this adjustment. After 6 weeks two exercise tests were conducted, a pacemaker test and a 24-hour ECG. Second step: switch of the maximum tracking rate to 170/190 bpm for 6 weeks. After the adaptation phase two exercise tests, a pacemaker test and a 24-hour ECG were repeated.
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Figure 2. Maximal increase of the heart rate during the exercise test in the single patient and mean ± standard deviation with a maximum tracking rate of 140 (left bar) or 170/190 bpm (right bar, P < 0.001).

The recording of the 24-hour ECG. The recordings were analyzed by a standard software package (Oxford, Wiesbaden, Germany) and standard Holter analysis techniques for labeling beats and artifacts. Only recordings with ≥20 hours of usable data were included in the analysis.

A Wenckebach behavior of the pacemaker was considered when the P-wave rate exceeded the MTR or when the P-waves were registered within the refractory periods of the pacemaker. The pacemaker tests were performed using the standard equipment of the aforementioned companies.

The data were evaluated using the software SPSS (version 11.0, SAS, Chicago, IL, USA). Numerical data are given as means ± SD except when indicated otherwise. The Kolmogorov-Smirnov-test was used to test for normal distribution, and, if required, data were log-transformed. The Student's t-test or Wilcoxon-test for repeated measures were used for comparison of baseline with values under therapy. Pearson's correlation analysis and simple linear regression models were performed. P values <0.05 were considered significant.

Results

Cardiorespiratory Performance

The switch to higher maximal tracking rates yielded a significant increase of the maximum heart rate at maximum workload (Table I, Fig. 2). The maximum workload was also augmented (+17%) and peak oxygen uptake was elevated (+26%, Table II, Fig. 3). Eleven versus four patients reached their predicted peak oxygen uptake. The workload at the anaerobic threshold (+21%) increased as well as oxygen uptake (+24%) (Table II).

There was also a positive correlation between maximum heart rate and peak oxygen uptake at maximum workload (r² = 0.28, P = 0.002) as a sign of hemodynamic improvement.

A Wenckebach behavior of all pacemakers of patients was registered with a MTR of both 140 bpm (n = 15) and 170 bpm (n = 6). Wenckebach was seen only once when programmed at a MTR of 190 bpm (n = 9). The onset of this behavior was clearly recognized by the patients and described as very unpleasant. In addition, Wenckebach behavior had an impact on maximum heart rate and peak oxygen uptake (Fig. 4). There was both a flattened increase as well as a blunted peak heart rate and maximum oxygen uptake in comparison to the group without Wenckebach behavior (Fig. 4).

No signs of myocardial ischemia were detected with the elevated MTR.

Heart Rhythm Disturbances

In three cases, a junctional escape rhythm and ventricular premature beats occurred during the Wenckebach behavior at programmed MTR of 140 or 170 bpm. There were no pacemaker-mediated tachycardias detected.

In the 24-hour ECG—there were no signs of pacing failures recorded and the number of ventricular premature beats was not different at both time points (Table I). Neither the 24-hour ECGs nor the pacemaker tests yielded any signs for an increase in pacemaker-mediated tachycardias using the higher maximal MTR.

Altogether, the results of 53 exercise tests and 30 24-hour ECG could be analyzed. Seven exercise tests were excluded on account of technically inadequate recordings.

Discussion

This study shows that a high MTR is a prominent factor for the cardiorespiratory performance in children and young adults with atrioventricular block and DDD- and VDD-pacemaker stimulation without heart failure.

Elevating the MTR increases peak oxygen uptake and maximal workload and is safe in terms of heart rhythm disturbances. A Wenckebach behavior of the pacemaker blunted the increase of cardiorespiratory performance under programmed higher MTR and should therefore be avoided in the observed cohort of patients.

Children and adolescents require higher heart rates for an optimal exercise performance than adults. Although Kruse et al.7 have clearly shown the positive hemodynamic effects of a synchronized atioventricular versus a ventricular inhibited stimulation in adults and also Karpawich et al.6 were able to prove these results for children and adolescents, there are nearly no data concerning a potential increase in cardiorespiratory performance by programming an high MTR. The results

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The Parameters Maximal Heart Rate, Maximum Workload, Peak Oxygen Uptake, and Workload as Well as Oxygen Uptake at the Anaerobic Threshold Were Compared at a Maximum Tracking Rate of 140 bpm and After Switching to 170/190 bpm

<table>
<thead>
<tr>
<th>N</th>
<th>MTR</th>
<th>HR(_{max}) (1/min)</th>
<th>P(_{max}) (W/kg)</th>
<th>VO(_{2\text{max}}) (mL/kg/min)</th>
<th>P(_{AT}) (W/kg)</th>
<th>VO(_{2\text{AT}}) (mL/kg/min)</th>
<th>Pred. VO(_{2\text{max}}) (Patients)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>140</td>
<td>138.8 ± 1.4</td>
<td>2.4 ± 0.6</td>
<td>28.3 ± 7.0</td>
<td>1.9 ± 0.4</td>
<td>23.7 ± 7.4</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>170/190</td>
<td>177.7 ± 10.4*</td>
<td>2.8 ± 0.7*</td>
<td>35.7 ± 9.5†</td>
<td>2.2 ± 0.6‡</td>
<td>29.3 ± 8.4‡</td>
<td>11</td>
</tr>
</tbody>
</table>

*P < 0.001, †P = 0.003, ‡P = 0.015.

MTR = maximum tracking rate; HR\(_{max}\) = maximal heart rate; P\(_{max}\) = maximum workload; VO\(_{2\text{max}}\) = peak oxygen uptake; P\(_{AT}\) = workload at the anaerobic threshold; VO\(_{2\text{AT}}\) = oxygen uptake at the anaerobic threshold; Pred. VO\(_{2\text{max}}\) = number of patients with VO\(_{2\text{max}}\) within the predicted VO\(_{2\text{max}}\) (95% confidence interval).

Newer pacemakers have additional features such as improved sensing, adaptive refractory periods; intervention algorithms for pacemaker-mediated tachycardias and recent mode-switch options and thus make MTRs of up to 190 bpm feasible.\(^1\)\(^,\)\(^2\)\(^,\)\(^1\)\(^1\)\(^−\)\(^1\)\(^9\) The present study indicates that the use of these high MTRs contributes to an increase in cardiorespiratory performance in children and young adults.

**Cardiorespiratory Capacity**

In the present study, the peak oxygen uptake of a maximal cycle ergometry was assessed as an indicator of the cardiorespiratory capacity. This procedure is well established for pacemaker patients and was used in several studies for the evaluation of the cardiorespiratory fitness of children.
and adolescents with implanted pacemakers (e.g., after the introduction of the rate-response pacemaker systems AAIR and VVIR\textsuperscript{11–13,15–19}).

In the present study, all patients increased their maximal heart rate after switching to 170 or 190 bpm. This was the precondition to prove that the observed children and young adults really benefited from this procedure. A significant increase was found in the achieved maximal workload (+17\%) and of peak oxygen uptake (+26\%). The latter parameter reflects the level of cardiorespiratory fitness and depends especially on the maximum cardiac output, the arterial oxygen content, the regional distribution of the cardiac output to the working muscle and their ability to extract oxygen.\textsuperscript{8,23} With the higher MTR most of the patients reached the peak oxygen uptake of healthy persons.\textsuperscript{8,23} A correlation was found between peak oxygen uptake and maximum heart rate during the exercise tests. Thus, a direct link between the increased cardiorespiratory capacity and the hemodynamic improvement of the patients with the high MTR can be assumed.

The anaerobic threshold reflects that level of oxygen uptake which to exceed requires an additional method of energy supply (initiation of anaerobic glycolysis). It is marked by a sequential lactate acidosis.\textsuperscript{8} Under the higher MTRs our patients increased their workload (+21\%) as well as the oxygen uptake (+24\%) at the anaerobic threshold. These promising results can be interpreted as follows: higher maximal tracking rates elicit hemodynamic improvements. Thus, the critical arterial oxygen content, exceeding which initiates the supplementation of the aerobic production of ATP by the anaerobic glycolysis, is shifted to higher workloads. These presented results are in keeping with studies of Cabrera et al.\textsuperscript{11} Hanisch et al.\textsuperscript{13} and Ragonese et al.\textsuperscript{17} who found an increase in both maximum workload and peak oxygen uptake at the anaerobic threshold and an elevated anaerobic threshold in children using rate-response sensors. This study differed in that it used DDD- or VDD-pacemakers and a higher MTR limit.

**Wenckebach Behavior of the Pacemaker During the Exercise Test**

These results clearly show that patients without the Wenckebach symptoms had a significantly higher heart rate at maximal workload and a more increased oxygen uptake compared to those with a Wenckebach behavior (Fig. 4, Table I). Patients with a Wenckebach behavior remained with their maximal workload or peak oxygen uptake at baseline. Hence, the occurrence of this symptom seems to have a significant impact on the cardiorespiratory performance of the enrolled patients. Therefore, it could be proposed that the optimum MTR exceeds the maximal atrial rate achieved in the exercise test (for our cohort 177.7 ± 10.4/min). For an optimal programming of the pacemaker the individual heart rate of a patient has to be assessed e.g., in a exercise test.

A MTR of 140 or 170 but not of 190 bpm was accompanied by the occurrence of junctional and ventricular arrhythmias at nearly maximal workload. Thus, the Wenckebach behavior is presumably a factor facilitating such heart rhythm abnormalities. A MTR of 190 bpm seems to prevail over the lower rates on account of the lack of these disturbances.

**Heart Rhythm Disturbances**

Higher maximal tracking rates may have the potential risk to harm the patients by the induction of heart rhythm disturbances. There have been no signs of an increased number of heart rhythm abnormalities with the higher MTR in the analyzed 24-hour ECGs and the pacemaker tests (Table I). The cited studies\textsuperscript{11,13,17} do not discuss this issue, and therefore, they are not comparable to these observations. Altogether, larger prospective trials should focus on the occurrence of heart rhythm disturbances in young pacemaker patients to elucidate whether high tracking rates are safe.

**Summary**

The technical progress in pacemakers makes today a MTR of 190 bpm possible for pacemaker patients. This study of children and young adults with DDD- and VDD-pacemakers due to atrioventricular block and with normal cardiac function describes the benefit in cardiorespiratory performance of adjusting the MTR to 170/190 bpm. No additional heart rhythm abnormalities were found under these higher tracking rates. The occurrence of a Wenckebach behavior under maximal workload seems to attenuate the increase in the cardiorespiratory capacity in the observed cohort of patients.

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**References**


