External Cardiac Pacing Using Low Impedance Electrodes Suitable for Defibrillation: A Comparative Blinded Study

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Objectives. The objective of this study was to determine whether the threshold for successful cardiac pacing is affected by electrode impedance and whether this procedure can be successfully carried out through low impedance electrodes that are also suitable for defibrillation.

Background. Reintroduced in the early 1980s, external cardiac pacing utilizes large externally placed electrodes with a high impedance, in conjunction with a stimulator capable of producing an impulse of 20 to 40 ms in duration. On the basis of empirical observation, high impedance electrodes (>500 Ω) are believed to be optimal for external cardiac pacing. Such electrodes are unsuitable for defibrillation, a technique that is most successful when impedance is low. In view of the absence of controlled data to support this recommendation, as well as the desirability of using one set of electrodes for both pacing and defibrillation, we undertook the following study.

Methods. Thirty-two normal subjects underwent a total of 110 attempts at external cardiac pacing with either (or both) high or low impedance electrodes in combination with one or two commercially available external cardiac pacemakers. Each subject underwent pacing at least twice in a randomized double-blind fashion to determine the pacing threshold and level of discomfort.

Results. Individual subjects had a wide range of pacing thresholds but did not experience any greater discomfort with one pacemaker-electrode combination than with any other. Similarly, no pacemaker-electrode combination was superior to another in terms of pacing thresholds. The mean pacing threshold was 72.5 ± 6 mA for the 40-ms impulse/high impedance electrode combination, 78.7 ± 6 mA for the 40-ms impulse/low impedance electrode, 73.8 ± 7 mA for the 20-ms impulse/high impedance electrode and 77.5 ± 7 mA for the 20-ms impulse/low impedance electrode (p = NS for all comparisons).

Conclusions. Contrary to previous belief, a high impedance electrode offers no advantage for external pacing in terms of either pacing threshold or discomfort level during pacing. This study demonstrates that it is feasible to perform external pacing through an electrode that is also suitable for defibrillation and suggests that a single external pacing-defibrillation electrode is all that is needed to perform these two procedures.

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The specific characteristics considered to be responsible for a reduction in pacing threshold and the resultant improvement in patient tolerance include the use of external electrodes with a large surface area and an increase in pacing pulse width from the original 2 ms (1) to 20 to 40 ms (6). The earliest published results (4) with a modern prototype external pacemaker used sponges moistened with tap water as electrodes. These electrodes had a high impedance and it was suggested, on the basis of empirical observation, that a high impedance was a critical factor for reducing discomfort arising from skin stimulation and possibly for minimizing pacing thresholds (6). Consequently, commercially available pacing electrodes were developed with an impedance >500 Ω.

In contrast to external pacing, studies have demonstrated that low electrode impedance and a low electrode-skin resistance to energy flow reduces the energy requirements for defibrillation (7–9). Thus, in contrast to electrodes used for external pacing, those manufactured for defibrillation are of low impedance (<10 Ω). This difference in impedance between external pacing electrodes and defibrillation electrodes makes it necessary to use two separate electrode pairs in cases where both defibrillation and external pacing are required.

Supportive data for the recommendation that external

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pacing is best performed using high impedance electrodes are sparse, and the development of a combined defibrillation-pacing electrode has considerable advantages because periods of bradycardia may follow elective cardioversion or may occur during cardiopulmonary resuscitation. It was the purpose of this study to determine whether external pacing could be successfully performed using low impedance electrodes with characteristics suitable for both pacing and defibrillation. To compare pacing thresholds and discomfort levels attained at threshold with this type of electrode with those obtained with standard high impedance electrodes, both pacing threshold and level of discomfort were compared directly in the same subject. Two commonly used commercially available external pacing devices were compared, each in combination with high and low impedance electrodes. Because these devices use different pacing waveforms, the comparison allowed additional information to be gathered to determine whether differences in waveform have any clinically significant effects.

Table 1. Characteristics of Standard (high impedance) and Pacing-Defibrillation (low impedance) Electrodes

<table>
<thead>
<tr>
<th></th>
<th>High Impedance</th>
<th>Low Impedance</th>
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<tr>
<td></td>
<td>ZMI (device A) Electrodes</td>
<td></td>
</tr>
<tr>
<td>Impedance (Ω)</td>
<td>1,000</td>
<td>19/2*</td>
</tr>
<tr>
<td>Area (cm²)</td>
<td>Anterior 78</td>
<td>Anterior 78</td>
</tr>
<tr>
<td></td>
<td>Posterior 115</td>
<td>Posterior 115</td>
</tr>
<tr>
<td>Construction</td>
<td>Wet gel in foam over tin conductor</td>
<td>Wet gel in foam over tin conductor</td>
</tr>
<tr>
<td></td>
<td>Physio-Control (device B) Electrodes</td>
<td></td>
</tr>
<tr>
<td>Impedance (Ω)</td>
<td>540</td>
<td>19/2*</td>
</tr>
<tr>
<td>Area (cm²)</td>
<td>82 × 2</td>
<td>82 × 2</td>
</tr>
<tr>
<td>Construction</td>
<td>Dry multilayer laminate conductor</td>
<td>Polymeric-based adhesive gel over tin conductor</td>
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*At defibrillation level currents, electrode impedance is less than pacing currents.
Subjects were asked to assess the discomfort level at pacing threshold on a scale of 0 to 4, where 0 = no discomfort, 1 = minimal discomfort, "+" = mildly uncomfortable (perceived ability to continue pacing for 1 to 5 min), 3 = very uncomfortable (perceived ability to continue pacing for up to 1 min) and 4 = intolerable (discomfort requiring immediate discontinuation). In addition, subjects in pacing groups 3 and 4 were asked to assess their discomfort level at a standardized stimulation current of 50 mA. This permitted an assessment of any differences in discomfort related to characteristics of either the pacing stimulus or the electrodes by eliminating the confounding factor of different stimulus intensities.

Data analysis. Stimulation current produced by device A can be increased by 1-mA increments, whereas that produced by device B can be increased only in 5-mA increments. Thus, for data analysis, individual pacing thresholds using device A were rounded up to the next 5-mA increment to allow better comparison.

Pacing thresholds in each pacing group were compared using two-way repeated analysis of variance. Results are expressed as mean value ± SEM. The sample size was determined to provide 90% power to detect a clinically meaningful difference in pacing thresholds, defined as ±30 mA, between groups.

Results

Group 1. Device B (20-ms pacing impulse) with both high and low impedance electrodes. Fifteen subjects underwent external pacing using the LIFEPAK 10 device in combination with both high and low impedance electrodes. For each of the 15 subjects tolerated external pacing with the high impedance (540 Ω) electrode, and all 15 tolerated pacing to threshold with the low impedance electrode. The mean pacing threshold using the high impedance electrode was 75.4 ± 6 mA (range 45 to 130). For the low impedance electrode, the threshold was 77 ± 6 mA (range 58 to 135). These differences are not significant (Table 2).

Discomfort. Although the subjects were asked to score discomfort level as a number between 0 and 4, they tended to respond with the use of fractions (for example, 3.5 instead of 3 or 4). For the high impedance electrodes, seven subjects ranked the level of discomfort as >3 (very uncomfortable or intolerable), five subjects as >2<3 (moderately uncomfortable or intolerable), and three subjects as 0<2 (mildly uncomfortable or tolerable).

Table 2. Mean (±SEM) Threshold for Each Pacemaker-Electrode Combination

<table>
<thead>
<tr>
<th>Electrode Combination</th>
<th>Combined Groups</th>
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<tbody>
<tr>
<td>Device A: high impedance electrode</td>
<td>78.9 ± 7</td>
</tr>
<tr>
<td>Device B: low impedance electrode</td>
<td>80.7 ± 7</td>
</tr>
<tr>
<td>Device C: high impedance electrode</td>
<td>75.4 ± 6</td>
</tr>
<tr>
<td>Device D: low impedance electrode</td>
<td>77.0 ± 6</td>
</tr>
</tbody>
</table>

*Group 1; †group 2; ‡group 3; §group 4. Values are in mA. p = NS for any intergroup comparison. See Methods for definition of groups.
able) and three subjects as ≤2 (well tolerated). Similar discomfort levels were reported for the low impedance electrodes (six subjects >3, six subjects >2<3 and three subjects as ≤2).

Group 2. Device A (40-ms pacing impulse) with both high and low impedance electrodes. In group 2, the two ZMI electrode pairs were compared in 15 subjects. One subject was unable to tolerate external pacing with either electrode, even at very low stimulus intensity, because of extreme anxiety and he was therefore excluded from further analysis. Of the remaining 14 subjects, 12 were able to tolerate stimulation to the point of pacing threshold with either or both electrode pairs. The mean pacing threshold did not differ significantly between the two electrode pairs: it was 78.9 ± 7 mA (range 54 to 110) for the high impedance electrode and 80.7 ± 5 mA (range 48 to 110) for the low impedance electrode. Assessment of discomfort level again demonstrated no difference between the two combinations, with six subjects ranking discomfort level as >3, five subjects as >2<3 and three subjects as ≤2 in each electrode group.

Group 3. Comparison of low impedance electrodes. In this group, the two low impedance electrodes were compared, both of which were 19 Ω at pacing level currents. Thirteen subjects, aged 25 to 47 years, participated in this segment.

All subjects could be paced with these electrodes. The mean pacing threshold for the ZMI low impedance electrode was 76.5 ± 6 mA (range 46 to 115). This was not significantly different from that obtained with the Physio-Control low impedance electrodes (78.1 ± 7 mA, range 40 to 130). Comparison of the discomfort level at pacing threshold again did not show any significant difference.

Group 4. Comparison of high impedance electrodes.

Twelve subjects underwent pacing comparing the two brands of high impedance electrodes. In this group, stimulation with the 540 Ω pacing electrode resulted in a mean pacing threshold of 71.7 ± 8 mA (range 30 to 130) and the 1,000 Ω electrode had a threshold of 65 ± 5 mA (range 45 to 105). This difference was not statistically significant (p = 0.15). There was no difference in the ranking of discomfort at pacing threshold between either of the two combinations.

Relation between stimulation current and discomfort level.

To evaluate any subtle differences in sensation between the two device electrode combinations and to determine whether stimulation current was related to discomfort level, additional information was sought in groups 3 and 4, regarding the subjective discomfort level at a standardized stimulus of 50 mA. This was determined whether or not pacing had occurred. The pacing stimulus of 50 mA was easily tolerated by the majority of subjects. Of the 50 pacing attempts (26 in group 3 and 24 in group 4), 35 (70%) were ranked as causing only mild discomfort (level of ≤2) when the pacing stimulus was 50 mA. There was no difference between either subgroup in the proportion of subjects experiencing mild discomfort at 50 mA. Examination of the pacing threshold for groups 1 to 4 revealed that 12 (38.7%) of 31 subjects had a pacing threshold ≤55 mA, of whom 8 had a threshold ≤50 mA.

Discussion

Effect of 20- or 40-ms pacing stimulus on pacing threshold.

As early as 1952, Zoll (1) determined by trial and error that a constant current stimulus appeared to produce the lowest pacing threshold. The earliest external pacemakers utilized a 2-ms stimulus duration, but Zoll et al. (6) later demonstrated that increasing pulse width could further decrease threshold. A 40-ms stimulus was chosen on the basis of the construction of strength-duration curves (10), but review of these curves (10,11) suggests that above 20 ms, the benefit of increasing current duration on the pacing threshold is minimal.

The two devices used in the present study had pacing waveforms that differed in both shape and duration. The ZMI device delivers a constant current, 40-ms, stimulus compared with the 20-ms, partially truncated, stimulus delivered by the Physio-Control pacemaker (Fig. 1). In light of the difference in pulse duration and configuration produced by the two devices, we sought to determine whether a difference existed in either pacing threshold or level of discomfort during stimulation. Both devices caused an equal amount of discomfort at threshold and at a fixed current of 50 mA, suggesting that the difference in pacing impulse characteristics is of no clinical significance. This finding is supported by data from Geddes et al. (12). Utilizing a theoretic model that considered external pacing as a two-compartment model (overlying tissue and cardiac muscle), these investigators calculated strength-duration curves for both pacing and pain fiber stimulation. Assuming a membrane time constant of excitability of 0.5 ms for pain fibers and of 2 ms for cardiac tissue, they concluded that no benefit would be accrued in terms of reducing skin stimulation at pacing threshold once the pacing stimulus duration was >10 ms. The value of 10 ms determined by Geddes et al. (12) is based on theoretic considerations, but our data are based on clinical observations and confirm that there is no benefit in increasing the pacing impulse duration, at least >20 ms.

Effect of electrode impedance.

The concept that high electrode impedance results in a decrease in discomfort has not been systematically documented, although this belief has been propagated in published reviews (13). In the present study, comparison of high and low impedance electrodes revealed no significant difference in subjective discomfort ratings with any two electrodes either at pacing threshold or at a standard 50-mA output, despite wide differences in impedance.

Thus, on the basis of these data it may be stated that contrary to previously held beliefs, electrode impedance plays no obvious role in modifying the discomfort level during brief pacing attempts in normal subjects. This has considerable importance in clinical practice because it opens
up the possibility of utilizing a single electrode for both pacing and defibrillation.

Limitations of the study. This study was performed on normal subjects for brief periods only. Although there is no reason to believe that prolonged pacing with low impedance electrodes would differ in terms of discomfort caused by skeletal muscle stimulation from pacing with high impedance electrodes, the effect on the skin under the electrodes is unclear. Erythematous skin is common after pacing with high impedance electrodes (4,14), but postpacing discomfort is usually mild and rapidly resolves. It remains to be determined whether long-term pacing with a low impedance electrode will have any adverse effect on the skin, although no greater degree of erythema was noted after our brief pacing attempts.

Conclusions. Combined pacing-defibrillation electrodes may be useful in cardiac arrest if defibrillation is followed by prolonged bradycardia or bradycardia-mediated ventricular arrhythmias (4,5). Similarly, occasional patients have profound bradycardia after elective cardioversion from supraventricular arrhythmias. In such cases, external pacing has been shown to be helpful (15), and the availability of a single electrode pair through which both cardioversion and pacing can be performed would eliminate any delays in applying separate pacing electrodes. The present study suggests that combined defibrillation-pacing electrodes are feasible and do not differ from high impedance electrodes in their ability to pace. An additional observation in this study was the finding that at a pacemaker output of 50 mA, the majority of subjects found external stimulation easily tolerable. The factors determining pacing threshold in normal subjects remain unclear, but do not appear to be related to body surface area or chest diameter because thresholds are similar in adults and children (16). Approximately 25% of our subjects had a pacing threshold of ≤50 mA during at least one pacing attempt, and a 50-mA external stimulation was well tolerated in the majority of subjects whether or not this produced pacing. However, at levels of stimulation required to pace most subjects, the discomfort was considerable. Although the degree of discomfort produced by external pacing in patients requiring the technique because of sudden symptomatic bradycardia is less important than the need to support the circulation, the development of a less uncomfortable stimulus would make external pacing more acceptable. Our data suggest not only that external pacing is feasible through defibrillation electrodes, but also that future research in external pacing should concentrate on methods to define features affecting the pacing threshold in individual subjects and to seek ways to reduce pacing threshold to ≤50 mA.

References