A n implantable cardioverter defibrillator (ICD) has become an important treatment modality in patients at risk of sudden cardiac death. However, patients with an ICD are also at risk of receiving inappropriate shocks, possibly affecting mortality, quality of life, and overall ICD longevity.

Methods and Results—Patients with a new atrial lead placement as part of a cardiac resynchronization therapy and defibrillator implant and a history of paroxysmal or persistent AF were eligible. If proper atrial lead position was confirmed, AVNS software was uploaded to the cardiac resynchronization therapy device, tested, and optimized. AVNS was delivered via a right atrial pacing lead positioned in the posterior right atrium. Software allowed initiation of high frequency bursts triggered on rapidly conducted AF. Importantly, the efficacy was evaluated during spontaneous AF episodes between 1 and 6 months after implant. Forty-four patients were enrolled in 4 centers. Successful atrial lead placement occurred in 74%. Median implant time of the AVNS lead was 37 minutes. In 26 (81%) patients, manual AVNS tests increased the ventricular interval by >25%. Between 1 and 6 months, automatic AVNS activations occurred in 4 patients with rapidly conducted AF, and in 3 patients, AVNS slowed the ventricular rate out of the implantable cardioverter defibrillator shock zone. No adverse events were associated with the AVNS software.

Conclusions—The present study demonstrated the feasibility of implementation of AVNS in a cardiac resynchronization therapy and defibrillator system. AVNS increased ventricular interval >25% in 81% of patients. AVNS did not influence the safety profile of the cardiac resynchronization therapy and defibrillator system.

Clinical Trial Registration—ClinicalTrials.gov; Unique Identifier: NCT01095952.

Key Words: atrial fibrillation ▪ shock ▪ vagal stimulation
WHAT IS KNOWN

- Atioventricular nodal-stimulation (AVNS) is effective in reducing ventricular rate chronically in animals.
- AVNS is effective in reducing ventricular rate acutely in humans.
- AVNS can be done using a standard atrial pacing lead.
- Lead characteristics remain stable over months when a lead is positioned where AVNS can be accomplished.

WHAT THE STUDY ADDS

- AVNS can be performed automatically in a chronic setting using a standard active fixation atrial lead and AVNS software uploaded to a cardiac resynchronization therapy–implantable cardioverter defibrillator.
- AVNS probably reduces inappropriate shocks.
- The effectiveness of acute AVNS is quantified.

by the Medical Ethics Committees of participating hospitals and the Competent Authorities of the relevant countries. All adverse events, technical observations, and deaths were reviewed by an independent Adverse Event Advisory Committee.

In- and Exclusion Criteria

Patients with a documented history of paroxysmal or persistent AF were eligible for this study if they had an indication for the following:

- Cardiac resynchronization therapy and defibrillator (CRT-D) implant
- Upgrade to CRT-D from a single-chamber device
- Upgrade or revision to CRT-D with an atrial lead positioned septally at the AVNS site or a dislodged atrial lead

Exclusion criteria were permanent AF; patients who were not on anticoagulant therapy; advanced atrioventricular block; patients who had previously undergone atrioventricular or the parasympathetic nerve(s); age <18 years; patients who had previously undergone valvular surgery, which potentially re-

AVNS Software Design

An investigational AVNS algorithm (AVNSₐ) was developed to deliver AVNS (ie, selective high frequency stimulation of parasympathetic nerves to the atrioventricular node) in a burst pattern during the ventricular refractory period (50 Hz, pulses 8, pulse width 1.5 ms, burst duration 160 ms) for 30 seconds via the posteroseptally positioned atrial lead. AVNS software could be uploaded to the Medtronic Consulta™ biventricular ICDs only. High frequency stimulation was performed during the refractory period of the ventricles to prevent induction of ventricular arrhythmias in case of atrial lead dislocation and movement of this lead into the right ventricle. AVNSₐ was designed to initiate when AT/AF is detected in combination with manual activation during the in-hospital tests or in combination with detection of 7 subsequent rapid ventricular intervals (<360 ms) during the follow-up period. AVNSₐ was terminated if the therapy was ineffective (defined as <150 ms reduction in median VV (ventricular) interval checked at 5 ventricular intervals after AVNS was started), or if a single short VV interval (<360 ms) was detected after this point, or if the programmed duration of AVNS therapy of 30 seconds had passed. Ventricular tachycardia (VT) and ventricular fibrillation (VF) limits were set to 360 and 300 ms, respectively.

Atrial Lead Implant Procedure

Atrioventricular nodal conduction is modulated by the parasympathetic nervous system through nerve fibers residing in an epicardial plexus located in the posterior right atrium. These nerve fibers extend through the interatrial septum at the coronary sinus ostium or the pos-

In-hospital tests. The primary end-point was the proportion of pa-

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the desired confidence interval width) of 15%, it was estimated that at least 37 patients would be needed to reach the primary end-point.

Considering early experiences in selective His bundle pacing without appropriate implant tools, an implant success rate of 67% was reported.\textsuperscript{16} We assumed that a similar result would be acceptable as first implant experiences in the AVNS study. It was estimated that \approx 55 patients needed to be enrolled to obtain the required 37 patients for the primary end-point. Slower than expected enrollments as a result of reimbursement difficulties resulted in an evaluation of the initial sample size calculations during the study. The proportion of patients meeting the primary end-point was found to be higher than expected. Therefore, a new sample size calculation was performed, assuming 78% of those with a successful lead placed would fulfill the end-point and using a confidence interval of 95% and a precision (ie, half of the desired confidence interval width) of 15%. The 32 successfully implanted patients appeared to be acceptable to meet the precision requirement of the primary objective.

Secondary objectives were to evaluate (1) the performance of AVNS\textsubscript{A} in shock reduction during the follow-up period, (2) safety of AVNS\textsubscript{A} and (3) to assess symptoms related to interventions of AVNS\textsubscript{A} both during acute tests and follow-up.

Statistical Analyses
The statistical analysis for this feasibility study was based on a per-protocol approach to assess the effect in those patients who were able to receive the therapy. Continuous variables were expressed as mean with standard deviation in case of normal distribution or median with interquartile ranges of the 25th and 75th percentile (IQR) when variables were not normally distributed. Chi-square tests were used to compare categorical data. Continuous data were compared with a paired t test or repeated measures analysis of variance for >2 group comparisons. P values <0.05 were considered statistically significant. All statistical analyses were performed using SAS software version 9.3 (SAS Institute).

Results
Patient Population
Forty-four patients were enrolled between January 2011 and June 2013. Baseline characteristics are displayed in Table 1. In 1 patient, the atrial lead placement was not attempted. Thirty-seven patients had a new device implantation, 5 underwent an upgrade to CRT-D with a new atrial lead placement, and 1 patient already had a septally positioned right atrial lead. Atrial lead placement was successful in 32 (74%) patients. In 6 cases, a site with a negative dromotrop effect could not be found, and in 3 cases, the ventricular R wave influenced accurate atrial sensing. In one case, the atrial lead dislodged and could not be replaced because of a VT storm, and in one case, the atrial pacing threshold was too high. Median implant time for the atrial lead was 37 minutes (IQR, 17–84), with a median number of (re)positioning of 3 (IQR, 1–7).

Directly after the implant procedure, the median atrial pacing threshold determined at 1 ms was 0.9 V (IQR 1–2), and median P wave amplitude was 1.6 mV (IQR 1–3), median Far Field R wave was 0 mV (IQR 0–1), and median pacing impedance was 494 Ω (IQR 456–627).

AVNS\textsubscript{A} Test Directly After Implant
Directly after the implant procedure, AVNS\textsubscript{A} efficacy tests were performed manually in 11 patients, who were already in AF, and in 21 patients in whom AF was induced by burst pacing. A typical example of the effects of AVNS\textsubscript{A} on the ventricular interval during AF is illustrated in Figure 1.

Table 1. Patient Demographics

<table>
<thead>
<tr>
<th>Patient Characteristics</th>
<th>Total (N=44)</th>
<th>Successful Patients (N=32)</th>
<th>Unsuccessful Patients (N=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender, (N, %)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>38 (86.4%)</td>
<td>27 (84.4%)</td>
<td>11 (91.7%)</td>
</tr>
<tr>
<td>Female</td>
<td>6 (13.6%)</td>
<td>5 (15.6%)</td>
<td>1 (8.3%)</td>
</tr>
<tr>
<td>Age, y</td>
<td>69±8</td>
<td>68±8</td>
<td>71±7</td>
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<tr>
<td>Height, cm</td>
<td>172±10</td>
<td>171±9</td>
<td>174±10</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>81±14</td>
<td>79±15</td>
<td>86±12</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>27.1±3.7</td>
<td>26.9±3.8</td>
<td>27.8±3.3</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>28.5±5.5</td>
<td>28.6±5.4</td>
<td>28.0±6.1</td>
</tr>
<tr>
<td>NYHA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class I</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Class II</td>
<td>3 (6.8%)</td>
<td>1 (3.1%)</td>
<td>2 (16.7%)</td>
</tr>
<tr>
<td>Class III</td>
<td>39 (88.6%)</td>
<td>30 (93.8%)</td>
<td>9 (75.0%)</td>
</tr>
<tr>
<td>Class IV</td>
<td>1 (2.3%)</td>
<td>1 (3.1%)</td>
<td>0 (0.0%)</td>
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<tr>
<td>Not available</td>
<td>1 (2.3%)</td>
<td>0 (0.0%)</td>
<td>1 (8.3%)</td>
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<tr>
<td>Primary heart failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ischemic cardiomyopathy</td>
<td>23 (52.3%)</td>
<td>16 (50.0%)</td>
<td>7 (58.3%)</td>
</tr>
<tr>
<td>Idiopathic dilated</td>
<td>16 (36.4%)</td>
<td>12 (37.5%)</td>
<td>4 (33.3%)</td>
</tr>
<tr>
<td>Hypertensive</td>
<td>1 (2.3%)</td>
<td>1 (3.1%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Valvular</td>
<td>1 (2.3%)</td>
<td>1 (3.1%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Other</td>
<td>3 (6.8%)</td>
<td>2 (6.3%)</td>
<td>1 (8.3%)</td>
</tr>
<tr>
<td>Symptoms experienced in the last year</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chest pain</td>
<td>6 (13.6%)</td>
<td>5 (15.6%)</td>
<td>1 (8.3%)</td>
</tr>
<tr>
<td>Dizziness</td>
<td>9 (20.5%)</td>
<td>7 (21.9%)</td>
<td>2 (16.7%)</td>
</tr>
<tr>
<td>Dyspnea</td>
<td>36 (81.8%)</td>
<td>25 (78.1%)</td>
<td>11 (91.7%)</td>
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<tr>
<td>Edema</td>
<td>10 (22.7%)</td>
<td>10 (31.3%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Exercise</td>
<td>11 (25.0%)</td>
<td>10 (31.3%)</td>
<td>1 (8.3%)</td>
</tr>
<tr>
<td>Fatigue</td>
<td>7 (15.9%)</td>
<td>5 (15.6%)</td>
<td>2 (16.7%)</td>
</tr>
<tr>
<td>Nausea/vomiting</td>
<td>2 (4.5%)</td>
<td>2 (6.3%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Palpitations</td>
<td>9 (20.5%)</td>
<td>5 (15.6%)</td>
<td>4 (33.3%)</td>
</tr>
<tr>
<td>Orthopnea</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Cardiovascular history</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>20 (45.5%)</td>
<td>13 (40.6%)</td>
<td>7 (58.3%)</td>
</tr>
<tr>
<td>Prior myocardial infarction</td>
<td>17 (38.6%)</td>
<td>12 (37.5%)</td>
<td>5 (41.7%)</td>
</tr>
</tbody>
</table>

BMI indicates body mass index; LVEF, left ventricular ejection fraction; and NYHA, New York Heart Association.

Manual AVNS\textsubscript{A} was always effective (>150 ms increase in median VV interval at 5 VV intervals after it started) and was therefore never terminated because of inefficacy. In 26 patients (81%), AVNS\textsubscript{A} performed at 8 V increased the ventricular interval by \geq 25%. Baseline ventricular interval was 670±220 ms, which was significantly increased during AVNS at 8 V to 930±310 ms (P<0.001), corresponding to an average increase
in ventricular interval of 40%±29%. In 12 patients, AVNS was tested at 2 V, 4 V, and 8 V, with a significant dose-dependent difference in terms of ventricular interval increase (% increase at 8 V, 57±34; 4 V, 31±21; and 2 V, 27±20; P<0.001).

No patients experienced palpitations, shortness of breath, dizziness, or phrenic nerve stimulation during the AVNS ia test at maximal output. Five out of 32 patients reported chest, arm, or jaw discomfort during the AVNS ia test, but only at 8 V output.

**Follow-Up**

Automatic AVNS activations occurred in 4 patients because of AT/AF with a ventricular interval <360 ms. In 5 AVNS activations in 3 patients, AVNS was associated with an increase in ventricular interval out of the ventricular tachycardia/ventricular fibrillation (VT/VF) zone, as displayed in Figure 2. These patients did not receive an inappropriate ICD shock during the AF episode. The patient in whom automatic AVNS at 8 V was not effective had an increase of VV interval of 7% during the in-hospital test at 8 V and did not receive an inappropriate ICD shock during the AF episode.

Ten patients developed 30 VF episodes, which were terminated by an ICD shock in 22 cases. AVNS was activated in one of these episodes because the VF episode coincided with an AT/AF episode (Figure 3). After 5 ventricular beats, the AVNS was automatically deactivated and did not delay the treatment with an appropriate ICD shock.

There were no differences found in the atrial pacing threshold (P=0.89), P-wave amplitude (when in sinus rhythm; P=0.54), far-field R-wave amplitude (P=0.63), and pacing impedance (P=0.24) at 1, 3, or 6 months when compared with implant. During follow-up, we did not observe ventricular capture because of AVNS ia. Seven patients were lost to follow-up.

**Safety**

All safety issues related to the atrial lead placement or its procedure are displayed in Table 2. Of note, there were no adverse events related to the AVNS ia software.

In 2 patients, an atrial lead dislodgement was diagnosed 1 and 24 days after implant, respectively. These leads were repositioned in the right atrial appendage. In the same patients, 2 left ventricular lead dislodgements were reported.
In this feasibility study, high frequency stimulation of the right inferior ganglionated plexus with AVNS was successfully implemented using a conventional CRT-D system in 32 patients. Directly after the implant procedure, AVNS increased ventricular intervals by >25% in 81% of these patients. AVNS did not influence the safety profile of the CRT-D implant and was not associated with adverse events. AVNS activations during follow-up increased the ventricular interval during AF. AVNS may be an important tool in reducing inappropriate shocks in patients with paroxysmal AF and an ICD.

**Shock Prevention**

Significant improvements have been made to reduce inappropriate shocks in the last few years, ranging from 21% during a 3 year German registry to 3% to 6% in 1.4 years in a recent study.\(^2\),\(^3\),\(^7\),\(^34\) Furthermore, a reduction of ICD shocks was achieved by using higher VT/VF detection thresholds, longer

**Discussion**

In this feasibility study, high frequency stimulation of the right inferior ganglionated plexus with AVNS was successfully implemented using a conventional CRT-D system in 32 patients. Directly after the implant procedure, AVNS increased ventricular intervals by >25% in 81% of these patients. AVNS did not influence the safety profile of the CRT-D implant and was not associated with adverse events. AVNS activations during follow-up increased the ventricular interval during AF.
VT/VF detection durations, use of supra ventricular tachycardia discriminators, and use of antitachycardiac pacing. By using data from previous studies combining wavelet, T-wave discrimination, lead noise discrimination, lead integrity alert, and improved recognition of rhythm termination during charging, it seems to be possible to reduce the occurrence of inappropriate shocks within 1 year to 1.8%. The majority (55%) of the inappropriate shocks were because of rapidly conducted AT/AF. The present study shows that AVNS is effective in increasing the ventricular interval during paroxysmal AF and may possibly reduce the inappropriate shock rate even more.

**Safety**

Implantation of the atrial lead was unsuccessful in 11 patients. Potentially, the angle of the atrial lead was too steep in relation to the myocardial wall compromising lead implant time and success rate. Furthermore, implant time of the atrial lead seems to be increased compared with normal atrial lead placement. A supportive sheath with an improved curve and stiffness can be designed, allowing easier navigation of the atrial lead and increasing implant success rate, while reducing procedure time. In addition, atrial lead dislodgement rate in the present study (6%) seems to be in line with the 5% dislodgement rate reported in a previous study on septally positioned atrial leads compared with a 2% dislodgement rate for atrial leads positioned in the right atrial appendage. Of note, atrial lead impedance, pacing threshold, impedance, and far-field R-wave oversensing were within normal ranges and remained stable during follow-up.

The AVNS software was not associated with adverse events, neither during the implant procedure nor during the follow-up period. During the implant procedure, the ICD system was tested extensively to exclude ventricular capture because this may induce VT/VF episodes because of rapid pacing. We did not observe any VT/VF episodes related to AVNS. Importantly, AVNS does not prolong time to ICD shock in case of VT/VF, as is demonstrated in Figure 3. However, future studies with larger patient populations are necessary to provide sufficient statistical power for the safety aspects of AVNS.

**Future Studies**

AVNS may be useful to prevent inappropriate shocks in patients with rapidly conducted paroxysmal AT/AF, as illustrated by the 3 patients, who did not receive an inappropriate ICD shock because of the application of AVNS. However, studies with a larger population size are necessary to provide more extensive clinical evidence. It should be noted though that chronic AF patients will be more readily treated by atrioventricular node ablation. Furthermore, lead placement and the AVNS software appeared to be safe in this feasibility study, but more studies are necessary to confirm these observations, potentially using leads with adapted stiffness, curvatures, screws, and implant tools.

**Conclusions**

The present study demonstrated the feasibility of implementation of AVNS in a CRT-D system. During the implant procedure, AVNS increased ventricular interval >25% in 81% of patients. AVNS did not influence the safety profile of the CRT-D system. AVNS may be an important tool in reducing inappropriate ICD shocks in patients with a short ventricular interval during AF.

**Acknowledgments**

We thank the teams within the hospitals, the (technical) support people, and the software development team for their contribution.

**Disclosures**

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**References**


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