Having felt a faint discomfort that felt like a beating, I turned to my right while my heart sank into the pit of my stomach. This is not what I had expected. It was not the way it was supposed to be. It was more than just a faint feeling; it was a feeling of impending doom.

I was not sure what was happening, but I knew that it was serious. For a moment, I thought about running away, but then I realized that I couldn't do that. I had to face this, whatever it was. I took a deep breath and tried to calm myself down. I knew that I had to stay calm, that I had to think clearly.

I tried to focus on my breathing, to slow it down and make it deeper. I tried to think about something else, anything else, to take my mind off of this. But it was hard. The feeling was so strong, so overwhelming.

I closed my eyes and tried to imagine myself somewhere else, anywhere else, but I couldn't. The feeling was too strong, too real. I opened my eyes again, and the feeling was still there, still the same.

I looked around me, and I saw that everything was normal. The room was still, the furniture still in place, the light still on. But the feeling was not normal. It was not something I could ignore.

I knew that I had to act. I knew that I had to find out what was happening. I knew that I had to do something.

I stood up, and I took a few steps forward. I knew that I was going to make the right decision. I knew that I was going to do what needed to be done.
not in patients with ejection fraction >30%. Disturbed diastolic filling is regarded by some authors as an earlier and more sensitive sign of ischaemic damage to the myocardium than systolic changes. An early sign of evolving left ventricular dysfunction could indicate when a defibrillation threshold test should be discontinued for further optimization of the patient. The aim of this study was to use transoesophageal echocardiography to evaluate the impact of repeated episodes of ventricular fibrillation and defibrillation on systolic function and diastolic filling of the left ventricle in patients receiving a transvenous ICD system.

Material and methods

Patients

Between January and December 1992, 12 patients (seven males) in sinus rhythm, aged 18–75 years (mean 52 years) had an ICD implanted because of malignant ventricular arrhythmias and were included in the study.

Implantation technique

After an overnight fast and approximately 1 h prior to anaesthesia, the patients were premedicated with morphine (0.05–0.1 mg. kg⁻¹) and scopolamine (2–4 μg. kg⁻¹). Anaesthesia was induced with thiopental sodium (3–5 mg. kg⁻¹). Neuromuscular blockade was achieved with vecuronium (0.1 g. kg⁻¹).

A monoplane transoesophageal echo-Doppler probe, 5/4 MHz (Vingmed Sound AS, Horten, Norway) was inserted after the induction of anaesthesia but before endotracheal intubation. Anaesthesia was maintained with isoflurane in oxygen/nitrous oxide. External defibrillation patches were placed on the chest to enable delivery of rescue shocks. In all 12 patients, endocardial leads (Medtronic Inc. Minneapolis, MN or Cardiac Pacemakers Inc. St Paul, MN, U.S.A.) were introduced through either the left cephalic or subclavian vein combined with a subcutaneous patch electrode placed in the left axillar region. The endocardial leads were positioned with one large coil electrode in the right ventricular apex and one thinner one in the junction of the superior vena cava and the right atrium. The electrodes were positioned under fluoroscopic guidance. Once the electrodes were in the appropriate anatomical positions, they were connected to the test equipment and the pacing threshold, impedance, slew rate and the R wave amplitude were estimated. When these values satisfied the implantation criteria, ventricular fibrillation was induced with alternating current via the ventricular lead. The implantation criteria were three successful episodes of ventricular fibrillation terminated with a maximal energy requirement of 20 joules. After testing the electrodes, they were connected to the defibrillator and a final test of 34 joules with the ICD in the abdominal pouch was performed.
Methods

Left ventricular systolic function was evaluated with the transoesophageal echo probe placed in the ventricular fundus region to depict the left ventricle in a short axis view at the midpapillary level. The fractional area was defined as the end-diastolic area minus the end-systolic area divided by the end-diastolic area. It was calculated as the mean of three beats immediately prior to the induction of ventricular fibrillation, in 30 consecutive beats after defibrillation, and as a mean of three beats 60 and 90 s after defibrillation. During ventricular fibrillation, the left ventricular area was estimated at 2 s intervals until the heart was defibrillated. During all episodes, ECG and blood pressure variables were monitored and recorded continuously. The blood pressure was measured invasively. Left ventricular diastolic filling was evaluated with the echo probe pulled back in the oesophagus and with the pulsed Doppler signal recorded at the tip of the mitral valve leaflets, from which the filling components of the left ventricle were estimated. This was made after induction of anaesthesia, immediately before the first induction of ventricular fibrillation, and then 90 s after each episode of ventricular fibrillation and defibrillation. The maximal velocities and the velocity time integrals in the passive (E-velocity) and atrial (A-velocity) filling phases, were estimated. The two peak velocities and the velocity time integrals (VTI) were compared to obtain the E/A ratio and VTI E/VTI A ratio231. In eight of the 12 patients, pulmonary venous blood flow velocities were measured immediately prior to and 90 s after the last episode of ventricular fibrillation and defibrillation to ensure preload stability. One hour, 4 h and 1 week after the procedure, the patients were re-evaluated by means of transthoracic echocardiography using the same protocol. Anaesthesia was then reversed.

Data analysis

All echo-Doppler analyses were made from a stopped-frame videotaped recording by the same investigator to minimize inter-observer variation. Whenever possible, each value was calculated as the mean of three consecutive beats. End-diastolic frames were taken at the start of the R wave and end-systole was defined by the smallest chamber diameter in association with the T wave. In approximately the first ten beats after defibrillation, the end-diastolic area was defined as the largest cross-sectional area without guidance from the ECG, which became blocked by the defibrillation. The E/A ratio values were normalized to allow inter-individual comparison and facilitate data presentation and analysis. The first value was set at 1 and the remainder as percent changes in relation to the initial value. A second investigator, blinded with regard to patient identity and episode number, double-checked ten randomly chosen observations to allow estimation of the inter-observer variation.

Statistical methods

The data, presented as means ± standard error of the mean, were analysed by analysis of variance for repeated measures. Repeating factors were episodes with five levels and time with different levels. When the overall F-ratio in analysis of variance was significant at the 5% level, contrasts (trends) between the repeated measures were calculated24. Between-group comparisons were made using Fisher’s exact test. Inter-observer variation was calculated with a paired T-test according to Dahlberg25. Statistical significance was defined as a P value <0.05.

Ethics

This study was approved by the Ethics Committee of the Karolinska Hospital and the patients gave their informed consent to participate.

Results

The patients underwent 4 to 18 (mean 6.5) episodes of ventricular fibrillation and defibrillation during the implantation procedure, which lasted between 70 and 235 min (mean 150 min). Ventricular fibrillation was induced and terminated after 17 ± 1 s. No complication associated with the transoesophageal echocardiography occurred during the study. The method error for single E/A ratio determinations was 0.02, estimated from duplicates of two independent observers.

Haemodynamic variables

The systolic blood pressure decreased from 111 ± 3 mmHg to 65 ± 2 mmHg immediately after defibrillation and returned to pre-fibrillation values within 5 to 90 s (mean 19 s). Systolic blood pressure declined from 113 ± 5 mmHg to 108 ± 6 mmHg (ns) and diastolic blood pressure from 66 ± 2 mmHg to 60 ± 2 mmHg (ns) after five episodes of ventricular fibrillation and defibrillation. The heart rate did not change significantly during the same period.

Fibrillating function

During ventricular fibrillation the left ventricular cross sectional area decreased from 24 ± 1 cm² immediately after induction of ventricular fibrillation to 20 ± 2 cm² before defibrillation (ns) (Fig. 1). This phenomenon was seen in all patients. After defibrillation the heart started with a dilatation, although not significant, in all registered episodes.

Systolic function

Left ventricular systolic function, assessed as the fractional area change, was not significantly affected by
ventricular fibrillation and defibrillation except for the two first heart beats after defibrillation (Fig. 2). During these two beats, the mean fractional area increased from 0.2 ± 0.01 to 0.4 ± 0.02 and 0.3 ± 0.02, respectively (P<0.001). There was no accumulated effect on fractional area change after four to five episodes of ventricular fibrillation and defibrillation. The fractional area change was 0.2 ± 0.02 before the first episode of fibrillation and defibrillation and 0.2 ± 0.02 15 s after the last episode (ns). The end-systolic area did not change.
Figure 4 Normalized E/A ratio in 12 patients receiving an implantable cardioverter-defibrillator. Five episodes were recorded in nine patients and in four episodes in three. Mean ± SEM. ** = P<0.01.

significantly except for the two first beats after defibrillation when the end-systolic area decreased from a pre-fibrillation value of 22 ± 1 cm² to 17 ± 1 cm² and 19 ± 1 cm² respectively (P<0.05) (Fig. 1). This was returned to normal at the third heart beat and no accumulated effect was seen. The end-diastolic area did not change significantly during the procedure.

**Diastolic filling**

The E/A ratio decreased from 2.6 ± 0.5 before to 1.6 ± 0.4 (P<0.01) after repeated episodes of ventricular fibrillation and defibrillation (Fig. 3). This was caused by a combined decrease in E-velocity and an increase in A-velocity. The VTI E/VTI A ratio decreased from 3.2 ± 0.4 to 1.4 ± 0.3 (P<0.01). The mean normalized E/A ratio for the whole group decreased from 1 to 0.6 ± 0.1 (P<0.01) after five episodes of ventricular fibrillation and defibrillation. One hour postoperatively, the mean normalized E/A ratio had returned to the pre-operative level. Three of the 12 patients had not regained their pre-operative normalized E/A ratio even at the pre-discharge echocardiographic examination one week postoperatively. The mean normalized E/A ratio for this small subgroup was 0.7 ± 0.01 compared to 1.3 ± 0.2 (P<0.05) for the other nine patients (Fig. 4). The aetiology for these patients was dilated cardiomyopathy with normal coronary angiography. Of the remaining nine patients, eight had ischaemic heart disease and one a long QT syndrome as the underlying cardiac disorder. The pulmonary venous blood flow velocities during systole and diastole including the reversed flow during atrial contraction did not change significantly during the procedure.

**Discussion**

This study confirms that repeated defibrillation threshold tests during ICD implantation does not cause a deterioration of left ventricular systolic function, which is in accordance with other studies. However, the effect on diastolic filling assessed with transoesophageal Doppler echocardiography was an evolving decrease in the E/A and the VTI E/VTI A ratios, which could be an early sign of myocardial depression. This effect was usually reversible within 1 h, but in a few patients with dilated cardiomyopathy, it persisted for at least one week. In contrast, there was no difference in left ventricular systolic function between the two groups.

**Haemodynamic effects of ventricular fibrillation**

Little information is available on the physiological changes occurring during ventricular fibrillation and defibrillation. In animal experiments, Pansegrau et al.
studied the haemodynamic response to ventricular fibrillation using invasive techniques. Two different types of response, a cholinergic and an adrenergic one were observed 1 to 10 min after direct-current conversion. The cholinergic component included sinus bradycardia, sinus arrest, and atrioventricular block. The adrenergic component was characterized by an increase in arterial pressure, cardiac output, and ventricular stroke work. These responses were primarily related to ventricular fibrillation rather than to the direct-current conversion shocks which, when delivered without preceding fibrillation, caused a more transient and less pronounced response than after fibrillation. In addition, the responses observed seemed to be more pronounced when fibrillation was prolonged. Secondly, in animals depleted of endogenous catecholamines by administration of reserpine, only one out of six survived the procedure, indicating that the adrenergic component might be essential for conversion.

Assessment of left ventricular function

In this study transoesophageal echocardiography was used to evaluate left ventricular function. This technique has the advantage that the isolated left ventricle can be assessed by continuous beat-to-beat evaluation of cardiac volume. In order to study systolic function, we used changes in the fractional area, as described by Feigenbaum. Diastolic filling was assessed using transoesophageal echocardiography where the filling components of the left ventricle were registered at the tip of the mitral valve leaflets. The accuracy of this method has been validated against both invasive and non-invasive methods. As both methods are dependent on loading conditions we tried to maintain stable haemodynamic conditions with the aid of close invasive monitoring of blood pressure and assessment of pulmonary venous blood flow and end-diastolic dimensions. Both systolic blood pressure and pulmonary venous blood flow as well as the end-diastolic area remained unchanged. With these parameters stable, we consider the loading conditions to be reasonably well controlled. In accordance with our experiments, Keyle et al., who also studied 12 patients during transvenous ICD implantation (and one patient during thoracotomy procedure), found no change in pulmonary capillary wedge pressure and a minor (although statistically significant) increase in systemic vascular resistance only in the group of patients with an ejection fraction <30%.

Systolic function

Depression of left ventricular systolic function could increase the defibrillation threshold during the implantation of an ICD, leading to extensive threshold testing with further reduction of an already pre-operatively depressed left ventricular performance, thus establishing a vicious circle. In a recent report, Sgarabossa et al. described difficulties in establishing an acceptable defibrillation threshold in patients undergoing multiple inductions, which supports this theory. Four earlier studies have assessed systolic function in conjunction with ventricular fibrillation and defibrillation during the implantation of an ICD. Hachenberg et al. studied ten patients undergoing ICD implantation with epicardial patch electrodes. Left ventricular function was evaluated by invasive monitoring after an average of 9 ± 3 episodes of fibrillation. The authors found a significant decrease in the cardiac index (16%) and a significant increase in left ventricular diastolic filling pressure and pulmonary vascular resistance. Postoperative inotropic support had to be prescribed for 40% of the patients. Part of the changes seen could have been caused by the more traumatic implantation technique. Secondly, the average number of fibrillation episodes was high in comparison with the recent study, which might further contribute to the observed deterioration of left ventricular function. In an animal model using invasive monitoring, Cole et al. investigated the effect of three and six episodes of ventricular fibrillation and external defibrillation. They found a depression of cardiac output after three inductions, with further deterioration after six inductions. This effect was ascribed mainly to a reflex vasoconstriction as the change in cardiac output was associated with an increase in systemic vascular resistance without any real change in preload recruitable stroke work or the end-systolic pressure-dimension relationship. Keyl et al. studied 13 patients undergoing transvenous ICD implantation by invasive haemodynamic monitoring and a thermodilution technique. They found that patients who preoperatively had a left ventricular ejection fraction below 30% showed a decrease in cardiac index and an increase in systemic vascular resistance after an average of 5 (2–7) direct-current counter shocks. No change was seen, however, after three shocks. In patients with an ejection fraction above 30%, no effect on systolic function was observed. These data seem to agree quite well with those of Hachenberger and imply that a limited number of fibrillation/defibrillation episodes do no harm to left ventricular systolic function, but that an increased number of episodes may have a depressing effect. We did not observe any changes in systolic function, although eight out of 12 patients tested had an ejection fraction below 30%. One explanation for the changes seen in Keyl's studies could be the simultaneous increase in systemic vascular resistance, implying that changes in ejection fraction were due rather to an increase in resistance caused by adrenergic response than to a decrease in contractility. In the clinical situation with biphasic shocks, more than three inductions during intra-operative testing are becoming more unusual. In summary, we have found no clear evidence that a limited number of episodes (3–5) of ventricular fibrillation and defibrillation during ICD implantation depresses left ventricular systolic function.
Diastolic filling

There are few data available on the effects of ventricular fibrillation and defibrillation on diastolic filling. Stoddard et al.\textsuperscript{[13]} reported improved diastolic filling in patients undergoing a single induction performed as a prehospital discharge test when evaluated by trans-thoracic echocardiography. They suggested that their findings indicated improved diastolic relaxation secondary to a release of catecholamines in conformity with the observations by Pansegrau et al.\textsuperscript{[12]}. As there were no changes in arterial blood pressure and left ventricular end-diastolic dimensions after defibrillation, the authors considered the external load to be virtually unchanged. In contrast to Stoddard’s study, we observed a deterioration of the E/A ratio which could be an indication of impaired diastolic filling function. In all patients except those with dilated cardiomyopathy, the E/A ratio had returned to normal 1 h after the last shock. There are several reasons why our findings cannot be directly compared with the findings of Stoddard et al.\textsuperscript{[13]}. In their study, 10 out of 12 patients had epicardial patch electrodes, whereas in the present study all patients had transvenous electrodes. The importance of previous thoracotomy, pericardiodytomy and stiff epicardial patch electrodes for the diastolic filling is not clear. Secondly, only one shock was delivered in Stoddard’s study compared to 4 to 5 in our work. Thirdly, our patients underwent general anaesthesia during implantation, but no mention is made of what type of anaesthesia, if any, the patients in Stoddard’s study underwent. Also, the patients in Stoddard’s study were investigated immediately after defibrillation while the patients in our study were investigated 90 s after defibrillation. In the immediate post-defibrillation period both the systolic and the diastolic variables were unstable in our study with decreased end-diastolic area, enlarged end-diastolic area and increased fractional area change, which was why we waited 90 s before making the measurements of diastolic function. After 90 s haemodynamic and echocardiographic conditions were stable and the neurohumoral response to the trauma ought to have been reasonably stable. Deterioration in diastolic filling is usually regarded as an early sign of left ventricular dysfunction\textsuperscript{[11–13]}. The observation that depressed diastolic filling occurs after 4 to 5 episodes of ventricular fibrillation suggests that it precedes the occurrence of a depressed systolic function.

Limitations

Our data are derived from a limited number of patients. Theoretically, the lack of difference with respect to systolic function could therefore be due to a type II error. This seems most unlikely, however, as the mean values showed no trends toward deterioration of systolic function. An interesting finding is the significant deterioration of diastolic filling. Prolonged diastolic filling dysfunction in three patients was observed and needs to be confirmed. One practical problem using the transoesophageal technique for repeated validation of left ventricular function is that the echo probe has to be repositioned between measurements, which increases the risk that the measurements will not be done in the same spot. This problem was minimized, however, since most of the estimates were made as relationships between two areas or velocities. The use of the E/A ratio as an indicator of diastolic filling is controversial, since several factors, myocardial as well as extracardiac, might affect the E/A ratio. A limitation with our study is the lack of invasive data supporting the presumption that left atrial and ventricular pressures were unaffected by the combined arrhythmic and electrical trauma. Loading conditions, heart rate, atrial contractility, and not the least left atrial and ventricular pressures are all known to influence the E/A ratio, making the interpretation of this non-invasive observation uncertain. However, the unchanged end-diastolic area and pulmonary venous blood flow velocities indicate relatively stable loading conditions. The unchanged pulmonary venous flow velocities might also imply that the left atrial pressure was unaffected by the procedure. These assumptions are in accordance with a study by Kempf et al.\textsuperscript{[27]}, in which no effect of endocardially delivered counter-shocks was seen on pulmonary artery wedge pressure. Another factor of importance is the contractility of the left atrium. However, if left atrial contractility had been affected by the arrhythmia and the rather moderate electrical trauma caused by the DC-counter-shocks an effect would probably also have been seen in the left atrium. Left ventricular systolic function was not affected in our study. Another limitation with our study is that the patients were anaesthetised during the implantation procedure and awake during the postoperative investigations, which in addition, were made with transthoracic echocardiography. The effect of anaesthesia on diastolic filling is not completely understood, but could affect the filling variables with a decline in E/A ratio and the results have to be interpreted with some caution. However, the use of two different echocardiographic methods would probably not affect the results as most investigations were made as ratios between two areas or velocities.

Clinical implications

Data from the present study and previously published work suggest that repeated episodes of ventricular fibrillation and defibrillation can depress myocardial function. The degree of deterioration seems to be dependent on the underlying heart disorder and the number of episodes. Signs of diastolic filling dysfunction seem to appear in an additive fashion already after a limited number (≤3) of shocks, whereas, according to the literature, signs of systolic dysfunction seem to appear only after multiple\textsuperscript{[11–13]} shocks. Failure to establish an adequate defibrillation threshold after a limited number of inductions should result in optimization of the patient
before further attempts are made. The fact that a more prolonged diastolic filling dysfunction was observed in patients with dilated cardiomyopathy indicates that important differences in myocardial metabolism may exist. Further studies on the effects on cardiac metabolism in conjunction with defibrillation are required to confirm this hypothesis. Transoesophageal echocardiographic monitoring is a valuable noninvasive tool for monitoring changes in left ventricular function. In this study, the method was not associated with complications and can be recommended for routine use.

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