Cellular Mechanisms of Depressed Atrial Contractility in Patients With Chronic Atrial Fibrillation

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Background—After cardioversion of atrial fibrillation (AF), the contractile function of the atria is temporarily impaired. Although this has significant clinical implications, the underlying cellular mechanisms are poorly understood.

Methods and Results—Forty-nine consecutive patients submitted for mitral valve surgery were investigated. Twenty-three were in persistent AF ($\geq 3$ months); the others were in sinus rhythm. Before extracorporeal circulation, the right atrial appendage was excised. $\beta$-Adrenoceptors were quantified by radioligand binding, and $G$ proteins were quantified by Western blot analysis. The isometric contractile response to $Ca^{2+}$, isoproterenol, Bay K8644, and the postrest potentiation of contractile force were investigated in thin atrial trabeculae, which were also examined histologically. The contractile force of the atrial preparations obtained from AF patients was 75% less than that in preparations from patients in sinus rhythm. Also, the positive inotropic effect of isoproterenol was impaired, and Bay K8644 failed to increase atrial contractile force. In contrast, the response to extracellular $Ca^{2+}$ was maintained, and the postrest potentiation was preserved. $\beta$-Adrenoceptor density and $G$-protein expression were unchanged. Histological examination revealed 14% more myolysis in the atria of AF patients.

Conclusions—After prolonged AF, atrial contractility was reduced by 75%. The impairment of $\beta$-adrenergic modulation of contractile force cannot be explained by downregulation of $\beta$-adrenoceptors or changes in $G$ proteins. Dysfunction of the sarcoplasmic reticulum does not occur after prolonged AF. Failure of Bay K8644 to restore contractility suggests that the $L$-type $Ca^{2+}$ channel is responsible for the contractile dysfunction. The restoration of contractile force by high extracellular $Ca^{2+}$ shows that the contractile apparatus itself is nearly completely preserved after prolonged AF.

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Key Words: arrhythmia $\bullet$ contractility $\bullet$ receptors, adrenergic, beta $\bullet$ remodeling $\bullet$ signal transduction.

Contractile dysfunction of the atria after cardioversion of atrial fibrillation (AF) is an important clinical issue. Echocardiographic studies have shown that the transmitial blood flow during atrial contraction is markedly reduced after restoration of sinus rhythm (SR). The degree of atrial contractility and the time required for restoration of normal atrial transport function depend on the duration of AF. This temporary loss of atrial contractile function may lead to thromboembolic events even when atrial thrombi are not present at the time of cardioversion.

The cellular mechanisms responsible for AF-induced contractile dysfunction are still poorly understood. First, it has been thought that the electric energy applied during DC cardioversion caused “atrial stunning.” However, later studies have shown that contraction of the atria was also impaired after pharmacological and spontaneous cardioversion. Sustained AF has been shown to cause alterations in atrial cellular ultrastructure. Myolysis and fragmentation of the sarcoplasmic reticulum might explain the contractile dysfunction in remodeled atria. Prolonged rapid atrial rhythms have also been shown to cause a pronounced reduction in the $L$-type $Ca^{2+}$ current. This offers an alternative explanation for the loss of contractile force in the course of prolonged AF. Tachycardia-induced changes of intracellular $Ca^{2+}$ handling have been studied by Sun et al in canine atrial cardiomyocytes. They found that both contractility and intracellular $Ca^{2+}$ transients were markedly reduced.

In the present study, we investigated the cellular mechanisms of postfibrillatory atrial contractile dysfunction in humans. In atrial trabeculae isolated from patients with and without AF, the $\beta$-adrenergic response, the positive inotropic effect of $Ca^{2+}$ and Bay K8644, and the postrest potentiation were evaluated. In addition, the most important proteins involved in the $\beta$-adrenergic signal transduction pathway were biochemically determined.

Methods

Patients

Right atrial appendages were obtained from 49 patients undergoing mitral valve surgery (Table 1). Twenty-three patients were in chronic AF (3 months); the others were in SR. Despite a tendency for a
lower cardiac index and a higher wedge pressure in AF patients, hemodynamics did not differ significantly between the 2 groups. AF patients more often received Ca2+ antagonists and digitalis for control of their ventricular rate. The patients did not receive drugs at least 12 hours before surgery. All patients gave written informed consent, and the study was approved by an institutional review committee.

**Contractility Studies**

Immediately after surgical excision, right atrial appendages were placed into Tyrodé’s solution (pH 7.4, gassed with 5% CO2/95% O2). Thin myocardial muscle bundles were prepared in parallel with the muscle fiber direction under stereomicroscopic control. The length of the bundles ranged between 3 and 6 mm, and the diameters were 0.45 ± 0.03 mm (n = 55) in SR patients and 0.43 ± 0.03 mm (n = 51) in AF patients (P = NS). They were connected to isometric force transducers with silk threads and placed in an organ bath filled with prewarmed (37°C) bathing solution. After an equilibration period of 30 minutes, the muscles were stretched to a resting tension of 1.0 mN. External field stimulation was performed with rectangular pulses (5 ms, 5% to 10% above threshold) at a frequency of 1 Hz. Resting tension was increased in 0.2-mN steps until the muscle length providing maximal active force generation was reached (Lmax, which was 5.1 ± 0.2 mm in SR patients and 5.2 ± 0.2 mm in AF patients; P = NS). The resting tension at Lmax was not different in the 2 groups (1.80 ± 0.04 mN [n = 55] in SR patients and 1.74 ± 0.06 mN [n = 51] in AF patients, P = NS). The muscles were allowed to equilibrate for 30 minutes. All muscles showing a decline of force of contraction (FC) of >5% during this period were excluded from the study. In 20 preparations obtained from 16 patients in SR and in 19 preparations from 13 AF patients, first a cumulative dose–response curve of isoproterenol was determined. After isoproterenol was washed out and baseline FC was restored, the positive inotropic effect of Ca2+ was studied for comparison. Another subgroup of preparations (19 bundles prepared from 16 SR patients and 16 bundles prepared from 12 AF patients) was first exposed to 10.8 mmol/L extracellular Ca2+ followed by washout. Thereafter, Bay K8644 was cumulatively added to the organ bath. K8644 was cumulatively added to the organ bath.

**Histological Examination**

At the end of the experiments, the bundles were examined histologically. To compare the atrial morphology with less diseased hearts, right atrial specimens were obtained from 19 patients undergoing coronary artery bypass graft surgery (10 in SR, 9 in AF). All preparations were fixed in 3% glutaraldehyde in 90 mmol/L KH2PO4 for 48 hours. After postfixation with OsO4, the specimens were dehydrated by a graded ethanol series and embedded in epoxy resin. The sections (2 μm) were stained with periodic acid Schiff (PAS) and toluidine blue. Morphometric quantification was carried out in transverse sections of each bundle by using a grid of 500 intersections as described previously.8 At each intersection, the cellular and extracellular structures were classified as follows: (1) sarcomeres, (2) nuclei, (3) other intracellular structures of cardiomyocytes (mostly glycogen), (4) extracellular matrix, including fibroblasts and other nonmyocytes, and (5) vessels, including perivascular cells. The content of each structure was expressed as the percentage of all 500 measuring points. The transmural cell diameter of 50 cardiomyocytes (shortest axis) was measured with a digital imaging system (Sony CCD camera equipped with NIH image software).

**Western Blot Analysis**

To quantify G proteins, electrophoresis of homogenate aliquots containing 80 μg protein per lane was carried out with the use of 10% polyacrylamide gels.13 After they were tank-blotted, the nitrocellulose membranes were exposed to primary antibody (antiserum AS/7 [inhibitory G protein] or RM/1 [stimulatory G-protein], NEN Life Sciences). After they were labeled with 125I-protein A, the nitrocellulose membranes were cut, and single band signals were quantified in a γ-counter.

**Statistical Analysis**

Data are expressed as mean ± SEM. For EC50 values, 95% CIs are given. Statistical significance was determined with the unpaired Student t test or by 1-way ANOVA for comparison of multiple groups. Significance of differences in medication or sex were calculated by χ2 test. A value P < 0.05 was considered to be statistically significant.

**Results**

**Light Microscopy**

Representative examples of longitudinal and transverse sections of atrial muscle preparations are shown in Figure 1. In SR and AF patients, marked myolytic alterations and pronounced interstitial fibrosis were present. However, the degree of myolysis was more pronounced in chronically fibrillating atria. Also, the cell size was larger in AF patients, with the average transverse cell diameter being 11.2 ± 0.4 μm in SR patients and 17.3 ± 0.6 μm in AF patients (+55%, P < 0.01).

In all bundles, the sarcomere content was 14% lower in AF patients compared with SR patients (Figure 1, Table 2). The amount of noncontractile material (mostly glycogen) was nearly 2 times higher in AF patients. The extracellular matrix constituted =40% of the extracellular matrix is consistent with changes described as the result of mitral valve or rheumatic heart disease.15,16 In the additional group of patients with coronary heart disease, the amount extracellular
matrix was less (Table 2). However, the differences between coronary artery disease patients in SR compared with those in AF were similar to the observations in patients with mitral valve disease.

**Contractility**

Single contractions at baseline conditions (37°C, 1 Hz, and 2.5 mmol/L Ca$^{2+}$) of all muscle preparations are superimposed in Figure 2. In trabeculae isolated from patients in SR, the strength (FC) was 11.5 mN/mm$^2$ (n=55, range 4.1 to 21.9 mN/mm$^2$). In contrast, in muscle bundles of AF patients, FC was only 3.1 mN/mm$^2$ (n=51, range 0.9 to 7.4 mN/mm$^2$, P<0.01). Thus, in the atrial myocardium of AF patients, baseline contractility was reduced by ≈75%. Increasing the extracellular Ca$^{2+}$ concentration increased FC in SR and AF patients (Figure 3). However, the relative increase was more pronounced in the AF group. As a result, at Ca$^{2+}$ concentrations ≥7.4 mmol/L, FC was no longer significantly lower than in the SR group (but still slightly below the force in the SR group). Thus, high extracellular Ca$^{2+}$ concentrations nearly overcame the contractile dysfunction in muscle preparations of AF patients. In 31 bundles of 19 SR patients and 30 bundles of 15 AF patients, maximal FC ($F_{max}$) was directly compared with the differences in sarcomere content. In AF patients, the reduction in sarcomere content (−14%) was similar to the slight decrease in $F_{max}$ (−15%), although the
latter only nearly reached the level of statistical significance (P = 0.069). The correlation coefficient between sarcomere content and F_max was 0.89 (P < 0.001).

The β-adrenoceptor agonist isoproterenol exerted a pronounced positive inotropic effect in the SR and AF groups (Figure 4A). However, in AF patients, the concentration-response curve was shifted downward and to the right. FC at the maximal isoproterenol concentration (10^{-6} mol/L) was lower in the AF group (18.3 ± 1.8 versus 30.0 ± 1.3 mN/mm², P < 0.01). In the SR group, the half-maximal positive inotropic effect of isoproterenol was reached at 2.6 (1.8 to 4.4) nmol/L, and the response curve was shifted downward and to the right. FC at 10^{-5} mol/L was 4.7 ± 1.1 mN/mm² compared with 28.0 ± 2.6 mN/mm² at 10.8 mmol/L Ca²⁺ (P < 0.01). Treatment with Ca²⁺ antagonists did not change the response to Bay K8644 in the AF patients. In the treated patients, FC at 10^{-5} mol/L Bay K8644 was 4.7 ± 1.3 mN/mm² (n = 7) versus 4.2 ± 1.3 mN/mm² (n = 5) in the patients who were not treated with Ca²⁺ antagonists (P = NS). Digitalis did also not affect the response to Bay K8644.

### Loss of Effect of Bay K8644

The positive inotropic effect of Bay K8644 is shown in Figure 5. In the SR group, the Ca²⁺ channel agonist exerted a pronounced positive inotropic effect. At 10^{-5} mol/L Bay K8644, FC was comparable to FC at 10.8 mmol/L extracellular Ca²⁺. In contrast, the response to Bay K8644 was abolished in the AF group, although these muscle preparations did respond to an increase in extracellular Ca²⁺ concentration. At the highest concentration of Bay K8644 (10^{-4} mol/L), FC was 4.5 ± 1.1 mN/mm² compared with 28.0 ± 2.6 mN/mm² at 10.8 mmol/L Ca²⁺ (P < 0.01). Treatment with Ca²⁺ antagonists did not change the response to Bay K8644 in the AF patients. In the treated patients, FC at 10^{-5} mol/L Bay K8644 was 4.7 ± 1.3 mN/mm² (n = 7) versus 4.2 ± 1.3 mN/mm² (n = 5) in the patients who were not treated with Ca²⁺ antagonists (P = NS). Digitalis did also not affect the response to Bay K8644.

### Preserved Postrest Potentiation of FC

Figure 6 shows representative experiments on the postrest potentiation of FC (rest interval 10 seconds). FC of the first postrest twitch was markedly increased in the SR and the AF patients. Compared with the force amplitude at steady-state conditions, the postrest FC was equally enhanced in both patient groups (4.1 ± 1.0 mN/mm² [SR, n = 16] versus 3.9 ± 1.1 mN/mm² [AF, n = 16], P = NS).

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**Table 2. Relative Tissue Composition of Right Atrial Muscle Bundles**

<table>
<thead>
<tr>
<th>Muscle preparations/patients, n/h</th>
<th>SR</th>
<th>AF</th>
<th>SR</th>
<th>AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiomyocytes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarcomeres</td>
<td>50.4 ± 2.0</td>
<td>43.5 ± 2.0 *</td>
<td>60.7 ± 2.9 †</td>
<td>52.7 ± 1.4 †</td>
</tr>
<tr>
<td>Intracellular noncontractile material</td>
<td>6.8 ± 0.3</td>
<td>11.7 ± 0.3 *</td>
<td>8.1 ± 0.8</td>
<td>13.0 ± 0.8 *</td>
</tr>
<tr>
<td>Nuclei</td>
<td>1.2 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>1.4 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>Extracellular space</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extracellular matrix including fibroblasts</td>
<td>38.7 ± 2.0</td>
<td>41.1 ± 1.9</td>
<td>26.7 ± 2.6 †</td>
<td>29.7 ± 1.4 †</td>
</tr>
<tr>
<td>Vessels including perivascular cells</td>
<td>2.9 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>3.1 ± 0.4</td>
<td>3.1 ± 0.2</td>
</tr>
</tbody>
</table>

Values are mean ± SEM (percentage of total tissue volume).

*P < 0.05 for AF vs SR; †P < 0.05 for coronary artery disease vs mitral valve disease.

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**Figure 2.** Superimposed force recordings of atrial muscle preparations from 25 SR patients (55 preparations) and from 22 AF patients (51 preparations) recorded under isometric conditions (37°C, 1 Hz).
Discussion

The present study provides the first insight into the cellular mechanisms of the postfibrillatory atrial contractile dysfunction in humans. It demonstrates that the contractility of atrial muscle bundles isolated from AF patients is reduced by $\approx 75\%$. The data confirm previous observations in a dog model of tachycardia-induced atrial contractile dysfunction in which the systolic shortening of atrial cardiomyocytes was found to be reduced to a similar extent.\textsuperscript{12} The present study demonstrates that AF-induced myolysis is only of limited importance as a cause of atrial contractile dysfunction. Instead, downregulation and/or altered function of the L-type Ca\textsuperscript{2+} channels seems to underlie AF-induced atrial dysfunction.
Myolysis and AF-Induced Loss of Atrial Contractility

In patients with chronic AF, recovery of atrial contractile function after cardioversion may require several weeks or months. Restoration of the cellular (ultra)structure might explain such a long recovery of contractile function. Indeed, the present study shows that myolysis and replacement of sarcomeres by glycogen was more pronounced in the trabeculae of AF patients. The same alterations have previously been reported in the goat model of AF, and it has been concluded that the loss of sarcomeres might contribute to the delayed recovery of atrial function after conversion to SR. However, in the latter study, a direct relation between structural changes and the contractile function of the atrial myocardium was not investigated. In the present study, the loss of sarcomeres was compared with the maximal achievable FC in the same muscle preparations to evaluate the contribution of structural remodeling to the AF-induced atrial contractile dysfunction. At high extracellular Ca\textsuperscript{2+} concentrations, atrial FC was only slightly reduced in the AF group (15%). This moderate reduction in maximal FC corresponded to a similar reduction in sarcomere content (14%). There was a strong correlation between the maximal FC and the sarcomere content of the individual muscle preparations. Therefore, AF-induced myolysis can only partly explain the pronounced reduction of contractility in remodeled atria. The main mechanism of postcardioversion atrial contractile dysfunction is a disturbed activation rather than a loss of atrial myofilaments.

β-Adrenergic Signaling

An important mechanism controlling myocardial force in atrial and ventricular myocardium is the β-adrenergic signal transduction pathway. Our data demonstrate that in atrial myocardium of AF patients, the positive inotropic effect of isoproterenol was markedly reduced. Although the impaired β-adrenergic response cannot explain the reduced atrial contractility in vitro, it might contribute to the atrial contractile dysfunction in vivo by blunting the positive inotropic response to the physiological variations in sympathetic tone.

In human failing ventricular myocardium and in a canine model of pacing-induced heart failure, desensitization toward catecholamines has been shown to be due to a reduced density of the β-adrenoceptors and an upregulation of the inhibitory G protein. In contrast, in the present study, atrial β-adrenoceptor density and G-protein levels were not altered in AF patients. This indicates that the atrial contractile dysfunction after the cessation of AF is due to mechanisms different from the ventricular cardiomyopathy in heart failure or experimental tachycardia-induced cardiomyopathy on the ventricular level.

Role of the L-Type Ca\textsuperscript{2+} Channel

Because the positive inotropic effect of catecholamines is mainly due to activation of the L-type Ca\textsuperscript{2+} channel, we tested the hypothesis that alterations of the Ca\textsuperscript{2+} channels were responsible for the diminished isoproterenol effect. A reduction in Ca\textsuperscript{2+} current has been shown to be the most important ionic mechanism of AF-induced electrical remodeling. Several studies have demonstrated a downregulation of L-type Ca\textsuperscript{2+} channel subunits in AF. In our present study, the L-type Ca\textsuperscript{2+} channel agonist Bay K8644 failed to increase atrial FC in AF patients. Potential explanations include changes in the number and/or function of the L-type Ca\textsuperscript{2+} channels. Downregulation of channel subunits is expected to reduce the positive inotropic effect of the Ca\textsuperscript{2+} channel agonist and might have caused the lack of response to Bay K8644. Altered function of the channel due to changes of the phosphorylation state is a second possibility to explain the loss of effect of Bay K8644. In failing ventricular myocardium, the spatial relationship between the L-type Ca\textsuperscript{2+} channel and the Ca\textsuperscript{2+}-release channel of the sarcoplasmic reticulum is disturbed. This would provide a third explanation for the absence of the Bay K8644 effect. The latter possibility would also explain why the positive inotropic effect of Bay K8644 is abolished in atrial myocardium of AF patients, whereas Bay K8644 could partly overcome the decrease of the Ca\textsuperscript{2+} inward current in the atrial cells of dogs undergoing rapid atrial pacing.
The blunted response to Bay K8644 not only emphasizes that a change in the function and/or number of the L-type Ca\(^{2+}\) channels is the key to understanding post-AF atrial contractile dysfunction, it also explains why the positive inotropic effect of isoproterenol was reduced in AF patients, although β-adrenergic receptor density and G-protein levels were unaltered. Isoproterenol increases FC by increasing the Ca\(^{2+}\) inward current and by enhancing the Ca\(^{2+}\) reuptake by the Ca\(^{2+}\)-ATPase of the sarcoplasmic reticulum (SERCA). As a result of both effects, the Ca\(^{2+}\) load of the sarcoplasmic reticulum is increased. In atrial myocardium of AF patients, the inotropic effect of isoproterenol was reduced, which can be explained by the above-mentioned changes of the L-type Ca\(^{2+}\) channel. Interestingly, isoproterenol still elicits some positive inotropic effect in the atrial myocardium of AF patients. This remaining stimulatory effect is most likely due to stimulation of the Ca\(^{2+}\) reuptake into the sarcoplasmic reticulum by SERCA, which would be consistent with our hypothesis that the function of the sarcoplasmic reticulum is preserved in the atrial myocardium of AF patients (see below). In contrast, Bay K8644, acting purely on the L-type Ca\(^{2+}\) channel, lacks this alternative positive inotropic mechanism and becomes ineffective in the atrial myocardium of AF patients.

No Dysfunction of the Sarcoplasmic Reticulum

As reported in human failing ventricular myocardium and in experimental tachycardia-induced heart failure, a dysfunction of the sarcoplasmic reticulum might also contribute to the reduced atrial contractility after the cessation of AF. Postrest potentiation of contractile force critically depends on the ability of the sarcoplasmic reticulum to store and release Ca\(^{2+}\) and reflects the functional capacity of the sarcoplasmic reticulum. In atrial myocardium of AF patients, the postrest potentiation was fully preserved, indicating that in fibrillating atria, FC is not limited by the capacity of the sarcoplasmic reticulum to release and take up Ca\(^{2+}\) again. This observation is in accordance with the finding of Sun et al, who reported that the postrest potentiation was still present in atrial cardiomyocytes from dogs with tachycardia-induced atrial contractile dysfunction.

Limitations of the Study

Although the present study has demonstrated that in atrial muscle bundles from AF patients, contractility is reduced by 75%, a causative relationship between AF and the atrial contractile dysfunction has not been studied. We cannot exclude the possibility that a common underlying factor causes both the atrial contractile dysfunction and AF. However, the L-type Ca\(^{2+}\) current is the main determinant of contractile force and becomes downregulated by AF. Therefore, it is reasonable to assume that electrical remodeling goes hand in hand with the atrial contractile dysfunction. This hypothesis is supported by the study of Sun et al, who showed that in dogs undergoing rapid atrial pacing, the decrease in atrial contractility follows a time course similar to the shortening of the action potential duration and the decrease of the Ca\(^{2+}\) inward current.

In all patients, the atria showed histological changes that were probably due to the underlying structural heart disease. Although the structural differences in atria from patients in AF and SR were similar to the changes found in the goat model of AF (resembling the situation in lone AF), extrapolation to AF in less diseased hearts should be performed with great caution. Further studies on atrial preparations from patients with lone AF would certainly be worthwhile.

A further limitation concerns the heterogeneity of our study population. Digitalis and Ca\(^{2+}\) antagonists were more frequently taken by the AF patients, and some patients from our study population were on β-blockers. The subgroup analysis revealed that drug treatment did not change contractile force and the response to positive inotropes in the atrial muscle preparations. Thus, although we cannot exclude the possibility that differences in medication might have influenced the contractile behavior of the muscle preparations, the marked differences in atrial contractility between SR and AF patients could not be explained by differences in drug therapy.

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References

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