The effects of daily exercise on susceptibility to sudden cardiac death

GEORGE E. BILLMAN, PH.D., PETER J. SCHWARTZ, M.D., AND H. LOWELL STONE, PH.D.

ABSTRACT The purpose of this study was to investigate the effects of daily exercise on susceptibility to sudden cardiac death. A 2 min coronary occlusion was initiated during the last minute of an exercise stress test and continued for 1 min after cessation of exercise in chronically instrumented dogs with a healed anterior wall myocardial infarction. Thirteen dogs developed ventricular fibrillation (VF; susceptible), while five did not (resistant). Before the exercise plus ischemia test, the baroreflex was evaluated with a bolus injection of phenylephrine (10 μg/kg). The changes in heart rate caused by a 30 mm Hg increase in systolic arterial pressure as well as the slopes of either heart rate or RR interval plotted against systolic arterial pressure were significantly lower in dogs that developed VR (resistant, −49.6 ± 7.8; susceptible, −15.3 ± 6.4 beats/min; p < .001). Four resistant and eight susceptible animals were then placed on a 6 week daily exercise program, while eight susceptible dogs had an equal period of rest. At the end of the 6 week period the exercise plus ischemia test was repeated; no susceptible animal that performed daily exercise developed VF, and all but one of the rested animals did. Daily exercise improved baroreflex control of heart rate in the susceptible group but not in the resistant group. Rest did not alter baroreflex function (change in heart rate after 30 mm Hg increase in systolic arterial pressure: after 6 weeks of exercise, resistant −43.3 ± 18.9 beats/min, susceptible −60.8 ± 16.6 beats/min; after 6 weeks of rest, susceptible 27.4 ± 11.0 beats/min). We conclude that daily exercise prevents VF induced by acute myocardial ischemia in a subgroup of dogs that were previously identified as susceptible to sudden cardiac death. Exercise also altered the autonomic control of the heart, possibly decreasing sympathetic and/or increasing parasympathetic tone. Thus if these data can be extrapolated to the clinical setting, daily repetitive exercise may provide a means of preventing sudden cardiac death, particularly among high-risk patients.

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CARDIAC ELECTRICAL instability has been identified as one of the primary factors responsible for sudden cardiac death.1 Electrical stability of the heart has been found to be reduced by an elevation of sympathetic efferent activity2,3 and to be increased by a major increase in vagal efferent activity.4 These results are largely independent of direct effects on heart rate and blood pressure.5,6 Accordingly, interventions that reduce cardiac sympathetic activity, particularly β-adrenergic blockade, have been shown to reduce cardiovascular mortality in patients.7 Results of experimental studies have shown that animals with strong vagal reflexes have a reduced incidence of fibrillation during acute myocardial ischemia.8 Together, this evidence strongly suggests that modification of the autonomic nervous system could improve electrical stability of the heart and reduce the incidence of sudden cardiac death.

Physiologically, endurance exercise training has been shown to alter the autonomic nervous system, resulting in an apparent increase in parasympathetic efferent activity and a decrease in sympathetic efferent activity. Specifically, heart rate at submaximal workload was found to be reduced in dogs subjected to exercise protocols for 8 to 10 weeks.8-11 The contractile response of the myocardium was also reduced.3 Measurements of both acetylcholine content12 and the quantity of cholineacetyl transferase13 obtained from hearts of trained rats were increased when compared with those of untrained rats. These data suggest that exercise training enhanced cardiac parasympathetic activity. In human beings exercise training has resulted in similar hemodynamic changes.14 These changes in autonomic neural activity could be beneficial in patients at high risk for sudden death. The
available clinical evidence, however, is both meager and inconclusive. A reduction in the incidence of sudden death among postinfarction patients participating in a multifactorial intervention program that included exercise has been reported from Finland. However, other studies have failed to report significant protection with exercise, in spite of a favorable trend in some of them. In most of these studies the exercise intensity may have been insufficient for cardiovascular conditioning.

Recently, we developed an animal preparation in which ventricular fibrillation (VF) could be consistently induced by a combination of acute myocardial ischemia and exercise in dogs with a healed myocardial infarction. In these animals the degree of reduction of heart rate that followed a phenylephrine-induced increase in blood pressure accurately identified those dogs that survived or that died during the exercise plus ischemia test. We further demonstrated that the greater the reduction in heart rate for a given increase in blood pressure, the lower the risk for VF.

Using this preparation, we designed this study to investigate whether or not daily exercise would alter the propensity toward life-threatening arrhythmias, particularly in those dogs with a healed myocardial infarction identified to be at a higher risk of sudden death.

Methods

Surgical preparation. Twenty-six mongrel dogs (13 male and 13 female) weighing 16.5 to 27 kg were chronically instrumented for measurement of left circumflex coronary blood flow and electrocardiogram.

The animals were given thiopental sodium (Pentothal; Abbott Laboratories 20 mg/kg iv) as a preanesthetic, and the surgical plane of anesthesia was maintained by the inhalation of a halothane, nitrous oxide, and oxygen mixture. By aseptic procedures, a left thoracotomy was performed in the fourth intercostal space. The left circumflex coronary artery was dissected from the surrounding epicardial fat, and both an 8 mHz continuous-wave Doppler flow transducer and a pneumatic occluder were placed around this vessel (proximal to the marginal branch of the left circumflex artery). Insulated silver-coated copper wires were sutured to the epicardial surfaces of the left and right ventricles and were later used to record a ventricular electrogram.

An experimental myocardial infarction was then produced. A modified two-stage occlusion was performed on the left anterior descending coronary artery approximately one-third the distance from its origin. The vessel was partially occluded for 20 min and then tied off. In addition, two to three branches from the left anterior descending coronary artery were ligated proximal to the occlusion site.

The leads to the cardiovascular instrumentation were tunneled under the skin to exit on the back of the animal's neck. Pentazocine lactate (Talwin Winthrop Laboratories, 30 mg im) was given approximately every 9 hr for the first 24 hr to control postoperative pain.

The animals were placed in an intensive care setting and antiarrhythmic therapy was administered as previously described. This therapy was not completely successful; eight dogs died within the first 72 hr, presumably because of VF. Thus only 18 of the original 26 dogs survived to be studied. The principles for the care and treatment of experimental animals as suggested by the American Physiological Society were followed at all times during this study.

Autonomic reflex and sudden death testing. Testing began after a 3 to 4 week surgical recovery period. The techniques for testing autonomic reflex and sudden death used in this study have been described in detail elsewhere and shall be only briefly summarized below.

Cardiac autonomic neural function was assessed by activation of the baroreceptor reflex. The animals were given bolus injection of phenylephrine HCl (Neo-Synephrine; Winthrop Laboratories 10 μg/kg) to raise systolic arterial pressure 30 to 50 mm Hg. RR interval (and heart rate) were plotted against the preceding systolic arterial pressure and the slope was determined by least-squares fit linear regression (an index of baroreceptor reflex sensitivity). The heart rate change for a 30 mm Hg increase in arterial blood pressure was determined.

On the following day, the susceptibility to VF was assessed by the combination of acute myocardial ischemia and exercise. In brief, the animals ran on a motor-driven treadmill for 17 min while workload increased every 3 min (4.8 kph, 0% grade during the first 3 min period and 6.4 kph, 16% grade during the last 3 min period). During the last minute of the exercise test, the left circumflex coronary artery was occluded, the treadmill was then suddenly stopped, and the occlusion was maintained for an additional minute. The occlusion therefore lasted a total of 2 min. Large steel plates were placed across the animal's chest so that electrical defibrillation could be performed with a minimal delay. Electrocardiogram and heart rate were monitored throughout the exercise test. Coronary flow was monitored only to verify the effectiveness of occlusion.

The procedures for autonomic reflex testing allowed for the identification of animals particularly vulnerable to the development of VF. The animals with small reductions in heart rate after an increase in arterial pressure invariably experienced VF (most often, ventricular flutter, which rapidly proceeded to VF if countermeasures were not taken) during the exercise plus ischemia test (susceptible). In contrast, those animals that exhibited a large reduction in heart rate for the same pressure increase did not have VF (resistant). On the basis of the results of the test described above, the animals were assigned to the various groups.

Daily exercise protocol. A total of 18 animals were studied (five resistant and 13 susceptible to VF) and assigned to the groups described below.

Five resistant and five susceptible animals were placed on a 6 week daily exercise program. Eight susceptible animals received an equal (6 weeks) period of rest in their cages and served as time controls for the exercising group. At the end of the rest period, four animals from this group entered the daily exercise program. Of the 18 dogs entering the study, five resistant and nine susceptible animals were given daily exercise for a 6 week period while eight susceptible animals were given an equal period of rest. During the 6 weeks of daily exercise two animals died (one resistant and one susceptible) and the data from these two animals were not included in the subsequent analysis.

The exercise program has also been described in detail elsewhere. In brief, the program consisted of running on a motor-driven treadmill 5 days per week. On alternate days the major portion of each period consisted of either sprint or endurance running. The duration of each exercise period increased weekly; during the first week each session lasted a total of 35 min, while during the sixth week the period had increased to 60 min. Baroreceptor reflex testing was repeated every 2 weeks.
death testing was repeated at the completion of the 6 week rest and exercise periods for all animals. In the four dogs that first received rest and were then subjected to daily exercise, the exercise plus ischemia test was repeated both at the end of the rest period and again after completion of the daily exercise program.

**Data analysis.** All data were recorded on a Beckman type R612 recorder. The slopes of the lines obtained by plotting either heart rate or RR interval vs systolic pressure were determined by least-squares fit linear regression and treated as a response variable. All data were analyzed by analysis of variance (ANOVA) for repeated measures. When the F ratio value was found not to exceed the critical value (p < .01), Newman Keul's multiple range test was used to compare means.21 The hypothesis that daily exercise could protect against sudden cardiac death was tested (null hypothesis: daily exercise did not reduce the susceptibility to VF). In addition, the hypothesis that daily exercise altered the autonomic reflex control of the heart, as assessed by the baroreceptor reflex activation, was also tested (null hypothesis: daily exercise did not alter the autonomic reflex control of the heart).

Control heart rate and systolic arterial pressure were obtained by averaging over the last 5 beats immediately preceding the drug infusion (baroreceptor reflex testing). The changes in heart rate produced by a 30 mm Hg increase in systolic arterial pressure were also calculated. The myocardial infarct size was determined by the nitro blue tetrazolium enzymatic staining technique22 and is reported as percentage of the left ventricle involved. These data were compared as described above.

**Results**

**Susceptibility to VF before exercise.** The 18 dogs that survived myocardial infarction could be divided into two groups on the basis of their responses to the exercise plus ischemia test. Thirteen dogs (72%) developed VF and were considered to be susceptible to sudden death. Five dogs (28%) did not have life-threatening arrhythmias and were therefore considered to be resistant to VF. Heart rate either decreased or did not change during ischemia in the resistant animals. In contrast, heart rate invariably increased more during exercise plus ischemia in the susceptible dogs.

The resistant and susceptible dogs could be further classified on the basis of the cardiac responses to baroreceptor activation. The regression analysis for two dogs, one resistant and one susceptible to VF, are presented in figure 1. Both the slopes obtained by plotting either RR interval or heart rate vs systolic pressure (table 1) were significantly smaller in the susceptible group (RR slope F ¼ 1.45.26, p < .001, heart rate slope F ¼ 22.05, p < .001).

In a similar manner, the average heart rate reduction associated with a 30 mm Hg increase in arterial pressure was significantly reduced in the susceptible dogs (table 1; F ¼ 93.71, p < .001). The prephenylephrine (control) heart rate and systolic arterial pressure were similar in both groups (table 1). The extent of myocardial infarction did not differ significantly between groups (table 1).

The animals were divided into groups to be studied with the daily exercise program described above. Five resistant and five susceptible dogs were placed on a 6 week daily exercise program, while eight susceptible dogs were placed in a cage for an equivalent period of time. At the end of the rest period, four susceptible animals from this group also entered the daily exercise program. The

**TABLE 1**

<table>
<thead>
<tr>
<th>Baroreceptor reflex slope, heart rate, and arterial pressure before exercise (mean ± SD)</th>
<th>Resistant (n = 5)</th>
<th>Susceptible (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR slope (msec/mm Hg)</td>
<td>17.9 ± 2.2</td>
<td>5.0 ± 1.3A</td>
</tr>
<tr>
<td>HR slope (beats/mm Hg)</td>
<td>−1.27 ± 0.21</td>
<td>−0.58 ± 0.03A</td>
</tr>
<tr>
<td>ΔHR 30 mm Hg (beats/min)</td>
<td>−49.6 ± 7.8</td>
<td>−15.3 ± 6.4A</td>
</tr>
<tr>
<td>Prephenylephrine HR (beats/min)</td>
<td>85.8 ± 26.3</td>
<td>98.8 ± 26.6(NS)</td>
</tr>
<tr>
<td>Prephenylephrine APsys (mm Hg)</td>
<td>136.0 ± 11.4</td>
<td>130.2 ± 16.8(NS)</td>
</tr>
<tr>
<td>Infarct size (% left ventricle)</td>
<td>17.4 ± 9.1</td>
<td>21.4 ± 8.9(NS)</td>
</tr>
</tbody>
</table>

APsys = systolic arterial pressure; HR = heart rate; ΔHR 30 mm Hg = change in heart rate produced by 30 mm Hg increase in APsys.

Data from all animals before exercise.

*A p < .001.*
effects of exercise on the susceptibility to sudden death are described below.

Susceptibility to VF after exercise. At the end of the 6 week rest or exercise period, the exercise plus ischemia test was repeated on all the animals. It is important to note that one susceptible and one resistant animal died before completion of the exercise program. The cause of death was not established but signs suggestive of congestive heart failure were present. Thus five resistant and nine susceptible animals began the exercise program while four resistant and eight susceptible animals completed it. The data from these two animals were not included in the study.

The ischemia plus exercise test failed to elicit VF or cardiac arrhythmias in the animals that completed 6 weeks of exercise. This observation was true for both the resistant and more importantly the susceptible animals. In contrast, the exercise plus ischemia test resulted in VF in all but one of the susceptible animals rested for 6 weeks.

After completion of the exercise program, two susceptible animals were then given 6 weeks of rest. When the exercise plus ischemia test was repeated at the end of the rest period, one animal had VF while the other developed numerous premature ventricular contractions, including short runs of ventricular tachycardia. The exercise plus ischemia records for the former animal before exercise, after 6 weeks of exercise, and after 6 weeks of rest are displayed in figure 2.

The effects of the autonomic nervous system on the heart were assessed by baroreceptor reflex testing every 2 weeks throughout the study. Exercise did not affect either the heart rate or the RR interval baroreflex slopes for the resistant animals (table 2, figure 3). In contrast, exercise significantly increased both the heart rate and RR slopes in the susceptible dogs by the second week of the program (table 2, figure 3) (heart rate slope F $\frac{3}{21} = 13.71, p < .001$; RR interval slope F $\frac{3}{21} = 14.91, p < .001$). The slopes in fact improved from the susceptible to the resistant range. This is graphically represented in figure 3. The shaded area represents the area bounded by the lower limit of the 99% confidence interval of the preexercise mean for the resistant animals (upper line) and the upper limit of the 99% confidence interval of the susceptible animals (lower line).

Rest, serving as a time control, did not significantly affect the baroreflex slope (table 2, figure 3). One

![FIGURE 2](image-url) Actual recordings of the exercise plus ischemia test from one susceptible animal before daily exercise (control), at the end of 6 weeks of daily exercise, and after 6 weeks of rest that followed the exercise period. The animal developed VF before daily exercise but not after completion of the exercise program. This protection was reversed by 6 weeks of rest.
TABLE 2
Effects of daily repetitive exercise on the baroreflex (mean ± SD)*

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>2 wk</th>
<th>4 wk</th>
<th>6 wk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistant + exercise (n = 4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR slope (msec/mm Hg)</td>
<td>18.1 ± 2.6</td>
<td>20.7 ± 3.4</td>
<td>21.5 ± 5.9</td>
<td>21.1 ± 2.8 (NS)</td>
</tr>
<tr>
<td>HR slope (beats/mm Hg)</td>
<td>-1.27 ± 0.24</td>
<td>-1.09 ± 0.18</td>
<td>-1.53 ± 0.46</td>
<td>-1.18 ± 0.41 (NS)</td>
</tr>
<tr>
<td>ΔHR 30 mm Hg (beats/min)</td>
<td>-49.8 ± 9.0</td>
<td>-45.8 ± 11.5</td>
<td>-51.5 ± 13.8</td>
<td>-43.3 ± 18.9 (NS)</td>
</tr>
<tr>
<td>HR (beats/ min)</td>
<td>81.8 ± 28.5</td>
<td>81.0 ± 15.4</td>
<td>93.0 ± 24.2</td>
<td>85.8 ± 11.9 (NS)</td>
</tr>
<tr>
<td>APsys (mm Hg)</td>
<td>135.0 ± 12.9</td>
<td>140.0 ± 18.3</td>
<td>143.8 ± 7.5</td>
<td>143.3 ± 11.6 (NS)</td>
</tr>
<tr>
<td>Susceptible + exercise (n = 8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR slope (msec/mm Hg)</td>
<td>5.4 ± 1.2</td>
<td>13.2 ± 4.0b</td>
<td>15.7 ± 6.8b</td>
<td>16.3 ± 5.0b</td>
</tr>
<tr>
<td>HR slope (beats/min)</td>
<td>-0.64 ± 0.33</td>
<td>-23 ± 0.32b</td>
<td>-1.36 ± 0.38b</td>
<td>-1.51 ± 0.40b</td>
</tr>
<tr>
<td>ΔHR 30 mm Hg (beats/min)</td>
<td>-14.6 ± 8.7</td>
<td>-53.9 ± 15.2b</td>
<td>-58.0 ± 11.5b</td>
<td>-60.8 ± 16.6b</td>
</tr>
<tr>
<td>HR (beats/ min)</td>
<td>105.4 ± 17.3</td>
<td>103.1 ± 28.2</td>
<td>104.4 ± 22.7</td>
<td>105.5 ± 25.4 (NS)</td>
</tr>
<tr>
<td>APsys (mm Hg)</td>
<td>130.0 ± 19.4</td>
<td>135.6 ± 19.4</td>
<td>137.5 ± 19.1</td>
<td>132.8 ± 16.0 (NS)</td>
</tr>
<tr>
<td>Susceptible + rest (n = 8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR slope (msec/mm Hg)</td>
<td>4.7 ± 1.3</td>
<td>4.7 ± 2.6</td>
<td>5.7 ± 3.8</td>
<td>6.1 ± 4.8 (NS)</td>
</tr>
<tr>
<td>HR slope (beats/min)</td>
<td>-0.47 ± 0.19</td>
<td>-0.48 ± 0.18</td>
<td>-0.54 ± 0.20</td>
<td>-0.72 ± 0.19 (NS)</td>
</tr>
<tr>
<td>ΔHR 30 mm Hg (beats/min)</td>
<td>-14.3 ± 9.3</td>
<td>-16.6 ± 7.7</td>
<td>-21.6 ± 7.7</td>
<td>-27.4 ± 11.0b</td>
</tr>
<tr>
<td>HR (beats/ min)</td>
<td>107.9 ± 18.8</td>
<td>100.0 ± 18.8</td>
<td>100.5 ± 23.4</td>
<td>110.6 ± 26.0 (NS)</td>
</tr>
<tr>
<td>APsys (mm Hg)</td>
<td>130.0 ± 22.7</td>
<td>132.5 ± 9.6</td>
<td>132.5 ± 12.6</td>
<td>132.5 ± 11.6 (NS)</td>
</tr>
</tbody>
</table>

HR = heart rate, APsys = systolic arterial pressure; ΔHR 30 mm Hg = change in heart rate produced by 30 mm Hg increase in APsys.

*Four animals entered the exercise program after completion of 6 weeks of rest; two animals, one resistant and one susceptible, died during the exercise program and their data are not included in the table.

bP < .01 from control.

should note that baroreflex slope did not change in seven of eight animals but showed a large increase in the remaining animal (RR slope before rest 4.4 vs 16.7 msec/mm Hg by 6 weeks of rest). The relationships among susceptibility to sudden death, baroreflex slopes, and exercise or rest are shown in figure 4. It is noteworthy that the one susceptible dog treated with rest that showed a marked improvement in the baroreflex slope was also the only one of its group to survive the exercise plus ischemia test.

In a similar manner, the absolute change in heart rate to a 30 mm Hg increase in arterial pressure significantly increased for the susceptible dogs (i.e., a large reduction in heart rate) in the exercise program. The heart rate response did not change for either the resistant animals subjected to exercise or the susceptible animals that received rest (table 2). Note that one of the susceptible animals receiving rest exhibited a large increase in the heart rate response by the sixth week of the rest period. The prephénylèphrine heart rate and systolic arterial pressure did not change over time in any group. It is important to note once again that myocardial infarct sizes were not significantly different (table 1) between the susceptible and resistant groups.

Discussion

The results of this study demonstrate that daily exercise can prevent sudden cardiac death in a subpopulation of animals previously identified to be particularly vulnerable to VF. It was further demonstrated that daily exercise altered cardiac autonomic activity as measured by the baroreflex control of heart rate in the susceptible animals but not in the resistant animals. These results confirm the critical role played by the autonomic nervous system in the genesis of life-threatening arrhythmias.

Exercise and sudden death. The effects of daily exercise on the incidence of cardiac arrhythmias and sudden death have not been extensively investigated. However, numerous epidemiologic studies indicate
that high levels of physical activity may protect against coronary artery disease.\textsuperscript{24, 25} For example, Paffenbarger and Hale\textsuperscript{24} found that longshoremen with the highest energy outputs at work had the lowest incidence of myocardial infarction and other manifestations of ischemic heart disease, including sudden death.

The available clinical evidence pertaining to the effects of daily exercise on cardiovascular mortality in patients recovering from myocardial infarction is, as of yet, both scanty and inconclusive. A significant reduction in coronary mortality has been reported for patients enrolled in a multifactorial intervention program that included daily physical exercise.\textsuperscript{15} The decreased cardiovascular mortality resulted primarily from a reduction in the incidence of sudden death (5.8\% vs 14.4\% in the control group). Since exercise was but one factor among many, neither the effects of daily exercise per se on sudden death nor the intensity of the exercise program can be addressed.

In contrast, several recent studies\textsuperscript{16-18} failed to demonstrate a significant reduction in either mortality or the reinfarction rate of patients placed on either supervised or unsupervised exercise programs. However, exercise did tend to reduce the incidence of cardiovascular-related deaths in two of these studies.\textsuperscript{17, 18}

Clinical prospective studies are subject to several inherent limitations. First, with few exceptions,\textsuperscript{16} the exercise programs used have been either poorly described or of insufficient intensity to result in cardiovascular conditioning. Second, all of the studies failed to differentiate between high- and low-risk groups of patients. In fact, higher-risk patients have often been specifically excluded from the studies.\textsuperscript{16} As a result, the sample sizes may have been inadequate to identify any beneficial effects of daily exercise on patients at low risk for sudden death. Furthermore, patient motivation may contribute significantly to the results of prospective studies; that is, higher-risk individuals may be less fit and thus more likely to become discouraged and drop out. Therefore clinical prospective studies may have a considerable bias toward low-risk individuals.

FIGURE 3. The composite data from each group of animals. RR interval slope is plotted as a function of time. The shaded area represents the area bounded by the lower limit of the 99\% confidence interval of the preexercise mean for the resistant animal (upper line) and the upper limit of the 99\% confidence interval of the susceptible group (lower line). All data plotted as mean ± SD. **p < .01, compares susceptible plus exercise with preexercise values. Exercise did not significantly affect the RR slope in resistant group. The improvement noted for the susceptible group receiving rest occurred primarily from a large increase noted in only one animal.

FIGURE 4. Effect of exercise on baroreflex slopes and survival. Baroreflex slopes are shown before and after dogs received 6 weeks of either daily exercise or of rest. All animals were tested with exercise plus ischemia at these two times. Sudden death on the treadmill is indicated by the closed circles, survival by the open circles. It is evident that although the resistant dogs were unaffected by exercise, the susceptible dogs showed a clear increase in the baroreflex slopes that was matched by survival during the exercise plus ischemia test. The only susceptible dog in the rested group that survived the exercise plus ischemia test is also the only one whose baroreflex slope had returned to the "resistant" range.
Evidence obtained from experimental studies is similarly lacking. There is, in fact, only one report that relates directly to the findings of our study. Nokes et al.26 found that exercise training increased the VF threshold during coronary occlusion of the isolated rat heart. The amount of electrical current necessary to elicit VF was much greater in hearts obtained from exercise-trained rats than those obtained from untrained rats. They attributed these differences to subcellular changes, namely reductions in cyclic AMP, which could in part reflect changes in cardiac autonomic neural activity.

Exercise and the autonomic nervous system. The mechanism responsible for the exercise-induced protection from VF remains to be determined. Important changes within the autonomic nervous system may play a critical role in development of this protection. Daily exercise altered the baroreceptor reflex control of the heart rate in the susceptible animals but not in the resistant animals (figures 3 and 4, table 2). Baroreceptor slope improved rapidly (by the second week of exercise) in the susceptible animals, passing from the susceptible to resistant range, as was confirmed by the fact that no susceptible animal developed VF after completion of the 6 week exercise period. Thus alterations within the autonomic nervous system at least paralleled the protection from VF.

These changes in baroreceptor control of heart rate and susceptibility to VF did not result from a time-dependent healing process alone. First, autonomic function and susceptibility to sudden death did not improve in most of the sedentary (rested) animals. In fact, only one of the sedentary dogs proved to be resistant to VF at the end of the program, protection that was also associated with a marked improvement in baroreflex function (RR slope, 4.4 before and 16.7 msec/mm Hg at the end of 6 week rest period). Second, two susceptible animals were rested for 6 weeks after completion of the exercise program. Baroreflex function returned toward preexercise values, and when the exercise plus ischemia test was repeated, one animal developed VF while the other exhibited numerous premature ventricular contractions.

The factors responsible for these changes in cardiac neural activity in the susceptible dogs are as yet unknown. One may speculate, however, that since myocardial infarction results in a reduced ejection fraction and thereby stroke volume,14 ventricular pump function could be impaired to a greater extent in the susceptible animals. An increased sympathetic activity would then be necessary to compensate for a fall in stroke volume; that is, changes in heart rate and cardiac contractility elicited by sympathetic stimulation are necessary to maintain a constant cardiac output and mean arterial pressure.

If this hypothesis should prove to be correct, then interventions that improve cardiac pump function should also decrease the vulnerability to sudden cardiac death by reducing any compensatory sympathetic activity. Froelicher et al.,27 among others,28,29 have demonstrated that exercise training programs can improve cardiac function, including ejection fraction and stroke volume. In addition, it is well established that exercise training in and of itself will alter the autonomic regulation of the heart, resulting in a reduced cardiac sympathetic tone as well as an increased parasympathetic tone.30 Daily exercise, by improving pump function and altering autonomic tone, may reduce the apparent sympathetic dominance in the susceptible animals and thereby reduce the incidence of VF.

Clinical implications. This study demonstrated that daily exercise modifies cardiac electrical stability and the autonomic control of heart rate in such a way to decrease susceptibility to VF. These changes occur rapidly. They are likely to depend on an increase in parasympathetic or a decrease in sympathetic tone, possibly associated with an improvement in left ventricular function. If these data obtained from animal studies can be extrapolated to the clinical setting, then exercise may provide a physiologic means of reducing the incidence of sudden cardiac death in high risk populations of postinfarction patients. This appealing prospect clearly merits further investigation.

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