Sudden Cardiac Death at Exertion

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In order to investigate sudden cardiac death at exertion (sports, and light work in daily life), 226 cases of sudden death during sports and 1,729 autopsy cases of sudden death were studied, and exercise tests were performed on 138 patients with various cardiac diseases.

Among sports, marathon or jogging caused sudden death most frequently (52.7%). It occurred often immediately after goal (41.3%) or before goal (28.0%), but cases with a history of heart disease died at the beginning of the race. Severe heat, overwork and other factors may precipitate the sudden death.

In autopsy cases of sudden cardiac death which occurred at exertion, coronary arteriosclerosis (C) was found in 67.0%, cardiac hypertrophy of unknown etiology (H) in 7.8% and valvular heart diseases (V) in 7.1%. Sudden death in patients with C or H were more frequent at exertion than at rest. Patients with C were older and died at light work. Those with H of a high degree also died at light work, but the younger ones with a mild H died at sports activity.

At exercise test, in patients with arrhythmia or hypertrophic cardiomyopathy, abnormalities may occur after exercise.

Sudden death at exertion may depend on the predisposing heart disease. Care should be taken especially at the end of the race.

SUDDEN and unexpected cardiac death has been a problem in clinical cardiology for many years. Numerous papers have described its incidence,¹⁻³ pathology^{4,5} and certain biochemical⁶ and psychological risk factors.⁷ In spite of them, the mechanisms of sudden cardiac death, especially occurring at exertion, are not clear. Sudden cardiac death at exertion is an important problem not only in cardiology and legal medicine but also in social life and in the field of sports medicine.

Key Words:

Sports
Light work
Hypertrophic cardiomyopathy
Coronary artery disease
Post exercise period

The purpose of the present study is to investigate the actual situations of sudden cardiac death at exertion (sports and light work) and their pathological findings, and to investigate their mechanisms and prevention.

METHODS

Sudden death was defined as a death which occurred within one hour (or 24 hours) from the onset of the symptoms. The onset was defined as the time when a subject was forced to change his activity because of distress.

The exertion, which caused sudden death, was divided into 2 groups: 1) sports, which require generally strenuous exertion and 2) light work such as performed in daily life.

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Fig.1. Distributions of sex and age in cases of sudden death at sports.

Fig.2. Kinds and incidence of sports which caused sudden death.

Traumatic accidents during sports, such as falling from mountain, drowning during swimming, striking during boxing and others, were excluded.

Study of Situations of Sudden Death at Sports Activity

The actual situations of sudden death at sports activity were investigated in 226 cases, whose deaths were reported in the main newspapers for the past 4 and half years. (Most cases of sudden death at sports activity are supposed to be reported in the main newspapers in Japan.) Most cases of this kind died within one hour from the onset of the symptoms, and the situation was witnessed by other persons.

Their ages at death, the kinds of sports which led to death, the detailed circumstances before the onset of the symptoms and their history of heart diseases, if any, were studied.

Pathoanatomical Study of Sudden Cardiac Death at Exertion

The pathoanatomical findings and their relationship to sudden cardiac death were investigated in 929 cases who underwent autopsy in Tokyo Examiner's Office due to sudden death at exertion. Those who died suddenly in an accident and those in whom non-cardiac diseases were revealed by autopsy were excluded from the present study. In some of the subjects of this group, in cases without witnesses, the interval between the onset of the symptoms and death might have been longer than one hour. As the controls, 800 consecutive cases of sudden cardiac death at rest, who also underwent autopsy in Tokyo Medical Examiner's Office, were investigated.

Clinical Study of the Mechanisms of Sudden Cardiac Death at Exertion

Exercise tests were performed on 56 healthy subjects and 138 cardiac patients, including 25 patients with hypertrophic cardiomyopathy (HCM), 8 with dilated cardiomyopathy (DCM), 60 with angina pectoris (AP), 14 with aortic regurgitation (AR) and 30 with various kinds of arrhythmia. The test was also performed on 20 athletes (runners). A symptom-limited supine exercise test was performed using a ergometer (Siemens), and M-Mode and two-dimensional echocardiography (Toshiba SSH-11A two-dimensional ultrasonoscope) and/or radionuclide angiocardiology (Baird Atomic Autofluoroscope System Seventy Seven Multicrystal Gamma Camera®) were performed before and during the exercise. The methods of measurement and analysis are the same as those reported in our previous studies.⁸⁻¹⁰

RESULTS

Situations of Sudden Cardiac Death at Sports Activity

Figure 1 shows the distributions of sex and age in cases of sudden death at sports. They consisted of 188 males and 38 females. Their ages ranged from 6 to 74 years, and cases between 10 and 19 years old were maximal in number.

Figure 2 shows the relative frequency of each sport which caused sudden death. Marathon or jogging caused it most frequently (199 cases, 52.7%). Ball games, such as baseball, rugby, tennis and others, were the 2nd, although baseball

Fig.3. Distribution of the timing of the onset of symptoms in a marathon or jogging in 80 cases.

Fig.4. Relationship between the timing of the onset of the symptoms in a marathon or jogging and the history or findings of heart diseases.

is a very popular sport in Japan.

In the 119 cases, who died in marathon or jogging, the time of death could be made clear in 80 cases. Figure 3 shows the onset time of the symptoms at exercise. Symptoms occurred immediately after goal in 41.3%, immediately before goal (including about 200 meters before goal) in 28.0%, at the beginning in 17.5% and on the way in 12.5%, although the period of "on the way" was much longer than that of the others.

Figure 4 shows the relationship between the onset time of the symptoms in marathon or jogging and the history of the organic heart

Fig.5. Analysis of the causes or circumstances, which may be related to sudden death during sports activity.

disease. Those who had had history of heart disease, such as valvular heart disease or congenital heart disease, died in most cases at the beginning of the exercise. In those who died immediately before or after goal, no history of heart diseases could be found. In one, who died immediately after goal, arrhythmia was found when the symptoms appeared.

Figure 5 shows the causes or circumstances, which were considered to be related to the occurrence of sudden death at sports activity. In only 15.5% of 226 cases, the causes or circumstances could be determined. Among them, severe heat accounted for 41.7%, overwork for 16.7%, preparation for examinations for 11.1%. Discomfort before the sports, or running as a punishment may be related to the sudden death in some cases. In 115 cases of sudden death at sports activity, 61.8% of the deaths occurred during a competition and the others during the training period. In all 226 cases of sudden death at sports activity, 26.1% were experts and the others were inexperienced.

Pathoanatomical Study of Sudden Cardiac Death at Exertion

During the period, in which 800 consecutive cases of sudden cardiac death at rest were seen, there were 216 cases (21.3%) of sudden cardiac

Fig. 6. Mean ages of sudden deaths in autopsy cases, mean $\pm$ SD.

Fig. 7. Pathological diagnosis of autopsy cases of sudden cardiac death.

The diagnoses were determined from the view point of legal medicine. "Acute heart failure" means those cases, in whom no morphological abnormalities were found by the routine autopsy examination.

death at exertion. In the last 15 years, 929 cases of sudden cardiac death have been observed at exertion, and 59 of them (6.4%) died at sports activity.

As shown in Fig. 6, cases of sudden cardiac death at rest were significantly older (61.3 ± 11.2 years old) than those at exertion (53.6 ± 17.5

Fig. 8. Mean ages of each heart disease group of sudden cardiac death at exertion.

C = coronary arteriosclerosis, A = "acute heart failure", H = cardiac hypertrophy of unknown etiology with or without dilatation, V = valvular heart diseases, O = other heart diseases

years old) ($p < 0.01$). In cases of sudden cardiac death at exertion, those at light work was significantly older (57.3 ± 13.7 years old) than those at sports activity (23.3 ± 12.9 years old) ($p < 0.001$).

Figure 7 shows pathoanatomical diagnosis of the present cases. As their diagnoses were determined on the basis of legal medicine, "acute heart failure" indicates those cases in whom no morphological abnormalities were found by the routine autopsy examinations. In cases of sudden cardiac death at rest, coronary arteriosclerosis (C) was found in 57.9%, "acute heart failure" (A) in 14.5%, cardiac hypertrophy of unknown etiology with or without dilatation (H) in 2.1%, valvular heart diseases (V) in 7.1% and other (O) in 18.4%. In those of sudden cardiac death at exertion, C was found in 67.0%, A in 3.0%, H in 7.8%, V in 7.3% and others in 14.2%. H and C were more frequent and A was less frequent during exertion than at rest.

Figure 8 shows the mean age of each cardiac disease group in the cases of sudden cardiac death at exertion. The Group C was the oldest (56.2 ± 7.9 years old), the Group A was the youngest (18.8 ± 4.7 years old) and the Group H ranged widely from young to old age (36.1 ± 17.2 years old).

Fig.9. Heart weight of 250 cases of sudden cardiac death at exertion in the past 3 years. About C, only mean $\pm$ SD are shown. Abbreviations are the same as in Fig. 8.

Fig.10. Relationship between the kinds of heart diseases and kinds of exertion in sudden cardiac death at exertion. Abbreviations are the same as in Fig. 8.

Figure 9 shows the heart weights of the 250 cases of sudden cardiac death at exertion in a 3-year period. They were 366 ± 64 g in C, 274 ± 47 in A, 504 ± 163 in H and 633 ± 208 in V. In H, some hearts were as heavy as 900 or

Fig.11. Relationship among age, heart weight and kinds of exertion in the cases of sudden cardiac death with cardiac hypertrophy of unknown etiology with or without dilatation.

1000 g, indicating the characteristics of hypertrophic obstructive cardiomyopathy. Nine cases of valvular heart diseases consisted of 2 with mitral valvular disease, 4 with aortic valvular disease and 3 with combined mitral and aortic valvular disease.

Figure 10 shows the relationship between the types of heart disease and kinds of exertion which induced sudden cardiac death. The Group C cases died at light work such as dancing or walking. The Group A cases died at heavy exertion such as jogging or ball games. The Group H cases died both at heavy work such as marathon, jogging or ball games, and at light work such as walking or other light work. The Group V cases died at light work in daily life such as bicycle riding.

Figure 11 shows the relationships among age, heart weight and kinds of exertion in the Group H. Young cases with markedly increased heart weight or old cases died at light work; the others died at sports activity. The case with the heaviest heart (1050 g) was a 19-year-old female, a maid-servant, who died suddenly while carrying dishes.

Among the Group H, those with cardiac hypertrophy without dilatation died more

Fig.12. The responses of mean circumferential shortening velocity of the left ventricle (mVcf) during exercise in healthy persons and in mild and moderately severe LV disease patients.

frequently at exertion than those with both hypertrophy and dilatation.

Clinical Study of the Mechanisms of Sudden Cardiac Death at Exertion

Left Ventricular Diseases: In dynamic exercise echocardiography (Fig. 12), the mean circumferential shortening velocity of the left ventricle (mVcf) increased throughout the exercise test period in normal healthy men, except for old persons. In mild left ventricular disease, it increased initially but decreased afterwards during the exercise test. In moderately severe cases, it decreased throughout the exercise test period. Athletes could tolerate well severe exercise by an increase of mVcf. These results are summarized in Fig. 13.

Hypertrophic Cardiomyopathy (HCM): In HCM, dynamic exercise echocardiography revealed an appearance or an increase of systolic anterior movement (SAM) of mitral leaflet during exercise, and it was further increased after exercise. At the same time, ventricular premature beat appeared in some of them. When SAM was intensified, blood pressure did not elevate so high as in the other cases. The details of the exercise test in HCM will be reported in a separate paper.

Coronary Artery Disease: In exertional angina, exercise induced a depression (in some, an elevation) of ST segment on an exercise ECG

Fig.13. Schematic presentation of the relationships between the responses of mVcf and work load in various states of LV function.

and dysfunction of the regional wall motion on an exercise radionuclide angiogram or exercise echocardiogram, with a decrease of exercise tolerance. Arrhythmia, especially of ventricular origin, may appear during the course of the test. All of them have the potency to induce sudden cardiac death and are summarized in Fig. 14. The details of the exercise study in coronary artery disease will also be reported in a separate paper.

Arrhythmia: Figure 15 shows exercise ECG in a 52-year-old female, in whom ventricular bigeminy appeared just after the end of the

Fig.14. Schematic presentation of functional changes in exertional angina during exercise test.

Fig.15. Exercise ECG of a 52-year-old female. No arrhythmia was seen before and during exercise, but immediately after the exercise ventricular bigeminy appeared.

exercise test. The occurrence of ventricular arrhythmia after the exercise test was recognized in many cases.

DISCUSSION

Sudden and unexpected nonviolent deaths are rarely studied as completely as other deaths. Many of the sudden deaths occur outside of the hospital. Especially, sudden death at exertion has not been investigated.

Situations of Sudden Cardiac Death at Exertion

In the present study, the exertions, which caused sudden cardiac death, were classified into

2 groups: severe exertion (sports) and mild exertion (light work in daily life).

Many cases with sudden cardiac death at exertion were old persons. This is probably due to the prevalence of coronary artery disease in this generation. Sudden cardiac death occurring in young persons at sports activity may be a more serious problem, because it is extremely unexpected.

Sudden death was seen most frequently in a marathon or jogging. Although baseball is very popular in Japan, sudden death induced by baseball games is rather rare. This may be related to the different severity of exertion in these sports. It has been reported that in South Africa rugby ranks first in inducing sudden

death.¹¹

The present study has revealed that sudden death occurred more frequently immediately after or before the goal of the marathon or the jogging. The reason for this fact is not clear, but the following mechanisms may be related: 1) Ventricular arrhythmia appears more commonly in the recovery period (post-exercise vulnerable period) than the actual exercise period, as noted by others.^{12,13} This can be explained by the interruption of overdrive suppression which occurs during exercise.¹⁴ 2) In HCM, SAM was intensified after exercise. This may cause a deterioration of pump function after exercise in the heart with HCM. It is not known why death also occurred frequently immediately before goal. Mental stress may be involved.

Circumstances related to sudden death at exertion have not been analyzed. In the present study, severe heat was the most frequently observed condition associated with sudden death. This has been pointed out by others as a complication during jogging.¹⁵⁻¹⁷ Other conditions such as overwork, examination preparation or running as a punishment may be related. The fact that sudden death occurred more frequently in competition than in training may also be influenced by mental stress. Sudden death has been seen not only in inexperienced persons but also in experts.

Predisposing Heart Diseases and Precipitating Mechanisms of Sudden Cardiac Death at Exertion

Mechanisms of sudden cardiac death can be analyzed from the following 2 factors: predisposing heart diseases and direct precipitating mechanisms.

Predisposing heart diseases are, as shown in the present study, coronary artery diseases, HCM, valvular heart diseases and others. As shown in the present study, the severity of exertion which induces sudden cardiac death was related to the kind of heart disease.

The direct precipitating mechanisms are lethal arrhythmia, especially of ventricular origin, coronary insufficiency and acute cardiac dysfunction.

HCM

Sudden and unexpected death is a well-known complication in symptomatic patients with HCM. Investigations have been performed concerning this problem.¹⁸⁻²⁰ Intensified LV outflow tract

obstruction due to increased myocardial contractility, decreased LV compliance and/or ventricular arrhythmia²¹ have been proposed to induce sudden death, but the details have not yet been clarified.

In the present study, autopsy cases with cardiac hypertrophy of unknown etiology may be considered HCM. In this group, young cases with much increased heart weight or old cases died at light work, and the others died at sports activity.

Morphological changes in the conduction system, such as fetal pattern or fibrosis of atrio-ventricular node or the His bundle have been reported in cases of HCM with sudden death.²²

Maron et al.²³ investigated the sudden and unexpected death in 29 highly conditioned, competitive athletes, aged from 13 to 30. In their series, sudden death occurred during or just after severe exertion in the athletic field in 22 of the 29 athletes. Structural cardiovascular abnormalities were identified at necropsy in 28 of the 29 athletes (97%), and in 22 cases (76%) these abnormalities were considered to be connected closely with the causes of death. The most common underlying disease in their series was HCM, which was present in 14 athletes. Other cardiovascular abnormalities noted in more than one athlete were anomalous origin of the left coronary artery from the right (anterior) sinus of Valsalva, idiopathic concentric left ventricular (LV) hypertrophy, coronary artery disease and ruptured aorta. These cardiac diseases were suspected before death in only 7 of the 29 patients, and in only 2 of the 7 was the correct diagnosis made clinically. Noakes et al.²⁴ have also reported a 42-year-old man with hypertrophic obstructive cardiomyopathy, who died suddenly during marathon racing.

It is known that in athletes participating in isotonic exercise, such as marathon racing, both LV end-diastolic volume and wall thickness increase similar to the heart in chronic volume overload, and that in athletes participating in isometric exercise, such as wrestling and Judo, an increased wall thickness with normal LV end-diastolic volume is observed similar to the heart in chronic pressure overload.^{25,26} In our previous echocardiographic study in competitive runners,²⁶ the LV radius to wall thickness ratio (R/Th) was maintained normal, but fractional shortening (FS) was slightly decreased. Compensating DCM cases had a normal R/Th ratio and a decreased FS. In Judo champions, FS was

maintained normal, but R/Th decreased. In HCM, FS was maintained normal, but R/Th decreased. That is to say, at rest the hearts of runners are similar to those in compensating DCM, with probably greater cardiac reserve, the hearts of Judo champions are similar to those in HCM with inappropriate hypertrophy. It is moreover known that some athletes' hearts have asymmetrical regional hypertrophy of the left ventricle.

These abnormalities may suggest the relationship between athletes' hearts and HCM. Disposition may be related, but this matter remains to be investigated.

Coronary Artery Disease (CAD)

In the present study, CAD was the main cause of sudden cardiac death both at rest and at exertion. Many investigators have studied about this problem.²⁷⁻²⁹ Electrophysiological derangement due to myocardial ischemia may be the key element in sudden death. The risk factors of sudden death in CAD have been investigated from the morphological^{28,29} or clinical³⁰ view point. Waller et al.³¹ investigated 5 cases who died while running, and they concluded that CAD appeared to be the major "killer" of conditioned runners aged 40 years or over who died while running. There is one report of sudden death during strenuous exercise due to mural left anterior descending coronary artery thrombus.³² In any case, no definite anticipative findings which suggest sudden death have been obtained.

Green et al.³³ have reported a 44-year-old trained marathon runner who died just after completing a 24-mile marathon. Extensive transmural anterior myocardial infarction was documented on ECG and proved at autopsy, although the coronary arteries were free of significant atherosclerosis. Concerning its origin, coronary artery spasm, thrombocytosis, platelet fibrin emboli, abnormal hemoglobin dissociation and heat stroke were considered. It was also reported that soldiers with heat stroke had ECG evidence of transmural infarction.³⁴ Other cases of sudden death during exertion with myocardial infarction and normal coronary arteries have also been reported.^{35,36}

In all of the autopsy cases in the present study, those of sudden death at exertion were older than those at rest. This may be attributable to the fact that CAD occupied a large part of the underlying disorder in sudden death at exertion.

Cases of CAD died suddenly at light work, such as dancing or walking. This may suggest a small reserve in patients with CAD.

LV Diseases

Patients with LV diseases may die suddenly at exertion probably of acute cardiac dysfunction due to a depressed cardiac reserve. The cardiac reserve can be detected clinically using exercise echocardiography as shown in Figs. 12 and 13. In the present study, those with valvular diseases died at light work or at the beginning of racing. These suggest a depressed LV reserve in these cases, similar to moderately severe cases, whose mVcf continued to decrease during exercise tests as shown in Fig. 12. Among LV diseases, volume-overload LV diseases have reduced their LV reserve more markedly than pressure-overload LV diseases. Usually, LV performance can be compensated by myocardial contractility and preload, but a dilated left ventricle cannot compensate the LV reserve by an increase of preload any more, because the preload-reserve has already been consumed at rest.³⁷

Acute cardiac dysfunction does not always induce sudden death. In acute cardiac dysfunction induced by other causes, an increase of heart rate can act as one of the compensatory mechanisms, but during exertion, this reserve has already been consumed by the exertion itself. Thus, acute cardiac dysfunction may cause sudden death.

Arrhythmia

Arrhythmia may exist without organic heart disease and induce sudden death at exertion.^{38,39} As mentioned above, in the patients with HCM or CAD, arrhythmia may be a precipitating factor.

It is well-known that arrhythmia often disappears during the actual exercise period and reappears after exercise. Thus, it may induce sudden death after exercise.

Risk factors related to sudden death due to arrhythmia after exercise are free fatty acid, plasma catecholamine⁴⁰ and smoking.¹¹

Morphological changes in cardiovascular system as the cause of sudden death have been reported.⁴¹

Prevention of Sudden Cardiac Death at Exertion

The mechanisms of sudden death at exer-

tion have not been clarified yet, as mentioned above. Therefore, it is difficult to prevent it completely.

Medical checks should be performed before exertion, in order to find latent heart diseases. It is well-known that HCM frequently reveals no subjective complaints. In order to detect HCM, echocardiography is excellent and very convenient. An exercise test, especially an exercise ECG, is also important before exertion. During the exercise test, work load should correspond to that during the exertion which the subject wants to do. However, to be sure, these are not perfect methods to prevent sudden cardiac death.

In racing, such as a marathon, care should be taken especially around the end of the race, and "cooling down" after the goal may be desirable.

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