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Pathological wave dynamics: A postulate for sudden cardiac death in athletes

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ABSTRACT

Sudden death (SD) in young athletes is a shocking and disturbing event with significant societal impact. Previous studies have demonstrated that sudden cardiac death (SCD) is the leading medical cause of SD in athletes. Various structural and pathological cardiovascular abnormalities have identified as the underlying causes of SCD in young athletes. However, there have been reported cases of SCD in athletes with no structural or pathological cardiovascular disorders. Our proposed hypothesis in this article is that abnormalities in aortic wave dynamics and coronary wave dynamics may be responsible for SCD in these athletes. These abnormal waves—pathological waves—can act as a trigger toward cardiac death in the presence of cardiovascular diseases. These waves may initiate SCD in the absence of apparent cardiovascular abnormalities. In summary, when the aortic and coronary wave dynamics are abnormal, the myocardial oxygen demand can exceed the oxygen delivery during exercise, hence creating acute ischemia which leads to death. It is explained in this article how increased oxygen demand may be the result of pathological aortic waves while reduced oxygen delivery is mainly due to pathological coronary waves. Additionally, our pathological wave hypothesis is able to provide a plausible explanation for Commotio Cordis.

Introduction

Sudden death is always a disturbing event regardless of the cause or the age. The societal impact of the sudden death of an athlete significantly increases when it happens during a live broadcast game or in an international competition. SCD is an unusual event and its actual frequency in athletes is unknown. In fact, the risk of SCD has been underestimated due to inappropriate data collection methods [1]. Recent statistical studies of NCAA compiled lists of athlete deaths have demonstrated that sudden cardiac death (SCD) (16%) is the second leading cause of all sudden deaths in young athletes after accidents (51%), occurring at a higher frequency than athlete deaths by suicide (9%), cancer (7%), homicide (6%), and drug overdose (2%) [1]. This suggests that SCD is the leading medical cause of sudden death in young athletes and demonstrates the need to further investigate the underlying causes of SCD in athletes and young adults.

Various structural and pathological cardiovascular abnormalities have identified as the underlying causes of SCD in young athletes [2]. These abnormalities include but are not limited to hypertrophic cardiomyopathy (HCM), dilated cardiomyopathy (DCM), coronary artery diseases (CAD), left ventricle hypertrophy (LVH), valvular diseases, myocarditis, aneurysms, aortic diseases, congenital heart diseases, rhythm and conduction disorders, cardiopulmonary diseases, etc. Among all of these identified causes, cardiomyopathies are the number one cause of SCD in athletes younger than 35 years old, and CAD is by far the leading cause of SCD in athletes older than 35 [3].

There have also been reported cases of SCD with no structural or pathological cardiovascular disorders. The subjects appeared to be normal during autopsy and their cause of SCD remained unknown [4,5]. The reported incidence of SCD in athletes with no cardiovascular abnormality varies in different studies. However, in general, these account for approximately 21% of total SCD cases [4,5], and occur more frequently in athletes younger than 21 years old [5]. Given that nearly 1 out of 5 SCD cases happen in the absence of cardiovascular abnormalities, it is reasonable to assume that these cases account for roughly 3.4% of all sudden deaths in athletes.

In this article we briefly explain the concept of wave dynamics in cardiovascular systems, and propose abnormal wave dynamics as a form of dynamic pathology that can lead to SCD in athletes. We then investigate different scenarios where abnormalities in aortic and/or coronary waves can cause SCD through acute myocardial ischemia.

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Background

Dynamic pathology: the neglected element

The term dynamic pathology was first introduced by Zamir [6], which refers to a pathological condition in which the dynamic of the system is away from its normal condition. The structural and functional pathology may coexist with the dynamic pathology. However, the absence of structural and functional abnormalities does not preclude the presence of dynamic pathology. SCD does not always occur in all athletes with functional or structural abnormalities and can occur in apparently healthy young athletes suggesting that there is a form of special abnormality that does not leave any footprint. We refer to this special abnormality as a form of dynamic pathology. In other words, if a sudden cardiac death is caused solely by a form of dynamic pathology, the subject will appear normal during autopsy. A simple and well-known example of the dynamic pathology is arrhythmia. The dynamic of the heart pumping condition changes during arrhythmia. This alters the optimum coupling between the heart and the aorta. The disturbed heart-aorta coupling affects the arterial network dynamics which results in altered cardiac output [6].

The dynamic pathology can contribute to SCD in young athletes through three different forms: (1) acting acutely as the main cause; (2) acting as the trigger (a trigger is the final component that is necessary for the initiation of the corresponding medical complication); or (3) acting chronically to develop a so-called idiopathic condition (e.g. idiopathic-LVH). If dynamic pathology acts as the main cause of death, the underlying cause remains unknown during autopsy since this form of pathology cannot be identified after the event. Since dynamic pathology can coexist with a structural or functional pathology, it can instigate some fatal event. This could explain why SCD does not occur in all athletes with certain structural abnormality.

Wave dynamics in compliant aorta as a tube

Aorta is a compliant tube that acts as a conduit for propagation and reflection of the waves. The wave dynamics in a compliant tube is a complex nonlinear phenomenon that includes wave interactions and resonance [7–9]. Waves in compliant tubes can create a pumping effect as observed in impedance pumps (Liebau pump) [7,8,10–13]. In its simplest form, an impedance pump is composed of a compliant tube connected to two rigid tubes at both ends and a pincher. The pincher hits the compliant tube and creates waves. These waves propagate toward both ends where they reflect upon the impact on the rigid boundary. The wave propagation and reflection in the elastic tube create wave dynamics which may produce pumping effects. The direction and magnitude of the net flow in the impedance pump depends on the state of the wave dynamics which are mainly dominated by three factors: (1) material properties of the compliant tube (defined the wave speed), (2) frequency of the excitation (pincher's frequency), and (3) locations of reflection sites (distance between pincher and rigid tubes) [7,8,10–13].

Despite the complicated physics of the impedance pump, it provides a simple message: *waves can assist circulating fluid in a compliant tubing system in a certain direction*. Note that assisting the flow in one direction means impeding the flow in the opposite direction. The direction and the magnitude of the net flow depend on the wave dynamic characteristics that show nonlinear-type behavior and resonance [7,8,13].

Wave dynamics in cardiovascular system

The heart creates pulsatile flow. The pulsatile flow generates waves when it enters the compliant aorta. These waves propagate as forward and reflected pressure, flow, and wall displacement waves in arterial network. The mere existence of these waves establishes unique "wave dynamics" in the arterial system. Previous studies have shown that the cardiovascular system in mammals is designed to optimize the effects of arterial wave dynamics to benefit arterial circulation [14–16]. These studies have provided valuable information about the constructive interaction, destructive interaction, and resonance behavior of the arterial waves.

The pulsatile workload on the heart is the result of the above-mentioned complex wave interactions in the aorta and the arterial network. It has been shown that reducing the heart pulsatile load through optimization of the arterial wave reflection is one of the apparent design criteria in the mammalian cardiovascular system [14,15]. The aortic (arterial) wave dynamics can reduce the workload on the heart by assisting blood circulation in a forward direction (from heart to the organs) or increase the workload by impeding it (in other words, pushing the blood in the opposite direction). In fact, aortic waves can potentially make the aorta act as a passive pump similar to an impedance pump (for more details see Pahlevan and Gharib [17]). Fig. 1 depicts this phenomenon.

Another important effect of arterial wave dynamics is the perfusion of coronary arteries. Zamir [18] showed that the effect of wave dynamics in coronary perfusion is far more significant than what was previously assumed. Subsequent clinical studies have confirmed Zamir's finding by showing that the coronary blood flow is completely dominated by the wave dynamics in the coronary arteries [19,20]. It has been shown in clinical studies that coronary wave dynamics are the result of the interaction of two different wave dynamics: one is created by aortic waves that enter coronary vasculature; the other one is generated at the coronary microcirculation (myocardium) level by the contraction and relaxation of the heart (see Fig. 1c) [20]. Note that the coronary flow is affected by both the timing and magnitude of these waves. Any abnormality in each of these waves and their timing can adversely affect coronary blood flow. For example, Davies et al. [20] have shown that in LVH patients the reduction of waves generating at the myocardial end is responsible for the impairment of coronary perfusion.

Pathological waves

Despite the complicated physics of waves in the aorta and coronary vessels, the message is rather simple: (1) aortic waves affect the workload on the heart; (2) waves generated at the myocardial end of coronary vasculature and aortic waves create coronary wave dynamics which determine the coronary blood flow (myocardial perfusion); (3) these waves can act constructively or destructively. Under normal conditions, these waves act constructively where they minimize the heart workload and maximize coronary perfusion. Under abnormal conditions, the waves act destructively which results in the elevation of the heart workload and/or reduction of the coronary blood flow. This abnormal wave condition is a form of dynamic pathology. Here, we refer to them as *pathological waves*. Similar to other forms of dynamic pathology, pathological waves can be the result of a structural pathology or they can be generated by a destructive dynamic interplay among heart, aorta and coronary arteries. The previously mentioned LVH and coronary wave dynamics case is an example of dynamic pathology (abnormal coronary waves) that is caused by a structural pathology (hypertrophied left ventricle).

There are certain structural abnormalities for which an underlying cause cannot be identified; these abnormalities are called idiopathic. Chronically, pathological waves may also be responsible for creating these so-called idiopathic structural pathologies such as idiopathic-LVH. For example, chronic pathological aortic waves