Chapter 3
Physiological Background

Tomoaki Murakami

Abstract From the physiological view, the aorta has two functions: conduit function and reservoir function. The typical disorder with the failure of the conduit function is aortic coarctation. On the other hand, the typical condition with the reservoir dysfunction is aging. The histological findings of the aged aorta resemble to that in the aortopathy (decrease of elastin fiber, increase of collagen, calcium deposition, and cystic medial necrosis). The aged aorta increases the systemic ventricular workload, and this is disadvantageous for the coronary perfusion. One of the possible mechanisms of the damage of the aorta is the enhanced pressure wave reflection induced by the heterogeneity or discontinuity of the aortic wall property.

Keywords Conduit function • Reservoir function • Pressure wave reflection • Cystic medial necrosis

3.1 Introduction

From the physiological view, the aorta has two functions: conduit function and reservoir function. The conduit function is easy to understand. A typical disorder with the failure of the conduit function is aortic coarctation (Fig. 3.1) [1]. The disease brings about left ventricular hypertrophy and afterload mismatch. However, the reservoir function and the problem of it are not well known. In this section, the reservoir function of the aorta will be explained.

T. Murakami, M.D., Ph.D. (✉)
Department of Cardiology, Chiba Children's Hospital, 579-1 Heta-cho, Midori-ku, Chiba 266-0007, Japan
e-mail: murat@seagreen.ocn.ne.jp

K. Niwa, H. Kaemmerer (eds.), *Aortopathy*, DOI 10.1007/978-4-431-56071-5_3

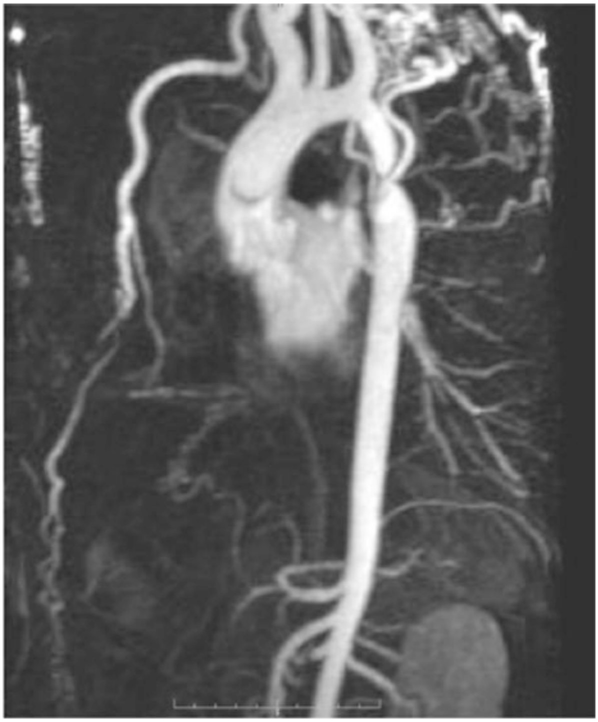

Fig. 3.1 Magnetic resonance image of a patient with conduit dysfunction of aortic arch (aortic coarctation) (Ref. [1])

3.2 Aortic Reservoir Function

The aorta is not only a simple conduit but also a functional reservoir. Figure 3.2 explains the reservoir function of the aorta [2]. During systole, the systemic ventricle ejects the blood into the aorta. However, the blood volume that runs off to organs during systole is less than half of the ejected blood. More than half of the ejected blood from the systemic ventricle is stored in the aorta during systole and runs off to the organs during diastole (Fig. 3.2a). When the reservoir function is damaged, the blood flow runoff during diastole is diminished, and the systolic blood pressure elevates, which is called isolated systolic hypertension (Fig. 3.2b). One of the most important organs that is mainly circulated during diastole is the heart. Therefore, the damage of the reservoir function is disadvantageous for the coronary circulation.

3.3 Aging of the Aorta

As with the other functions of the human body, the aortic reservoir function is deteriorating with aging. Therefore, we could study the aortic reservoir function by comparing the conditions of the function in young and old. With aging,

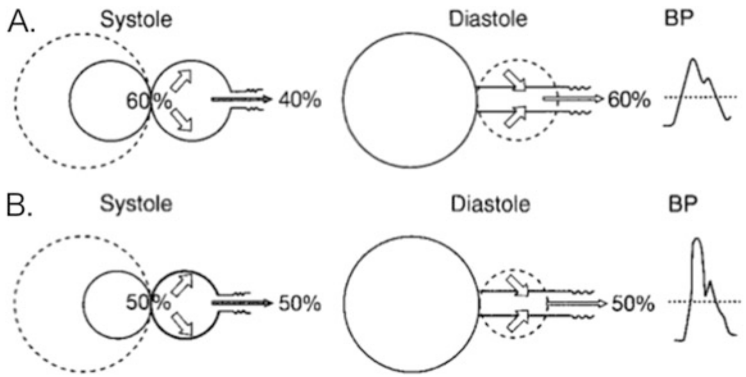

Fig. 3.2 Aortic reservoir function. Normal aorta stores more than half of the ejected blood during systole, and the stored blood runs off to the organs during diastole (**a**). The aorta with damaged reservoir function cannot store enough blood during systole. Therefore, the systolic blood pressure elevates and the diastolic blood flow decreases (**b**) (Ref. [2])

degeneration of elastin fibers in the aortic wall occurs, and collagenous material increases. Calcium deposition also occurs. The progression of the processes results in cystic medial necrosis, which is also well known as the histological characteristic of aortopathy. As a matter of course, the histological changes, the decrease of elastin fibers, and the increase of collagen cause damage to the elastic properties of the aorta. Figure 3.3 demonstrates the decreased aortic distensibility in the aging process [3]. As a result of the loss of the elasticity, the pulse wave velocity elevates with aging (Fig. 3.4) [4]. Because the ejection to the stiff aorta augments the cardiac workload, the myocardial blood flow increases (Fig. 3.5a). However, the stiff aorta, it means the damage for the reservoir function, could not increase the pooling of the blood in the aorta during systole. As a result, the myocardial flow reserve decreases with aging (Fig. 3.5b) [5].

Interestingly, it is well known that the aortic diameter enlarges with aging process (Fig. 3.6) [6]. Aortopathy is usually defined as a dilatation of the aorta. However, many reports demonstrated that the aortic root expansion and the stiffening of the aorta occur together in many clinical settings [7–10]. Moreover, it is reported that the pulse wave velocity of the dilated aorta is elevated in patients with aortopathy [11], although the increase of the diameter means the decreased pulse wave velocity based on physical laws. Therefore, it is possible that the damaged aortic distensibility precedes the dilatation of the aorta in the aortopathy. The reason why the aorta with the decreased distensibility dilates has not been fully elucidated. One of the possible mechanisms of the phenomenon is a compensation for the cardiac demand-coronary supply balance [12–14].

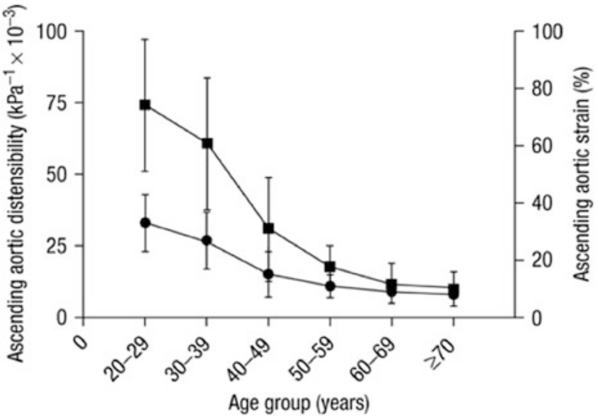

Fig. 3.3 Strain (●) and distensibility (■) of the ascending aorta decrease with aging (Ref. [3])

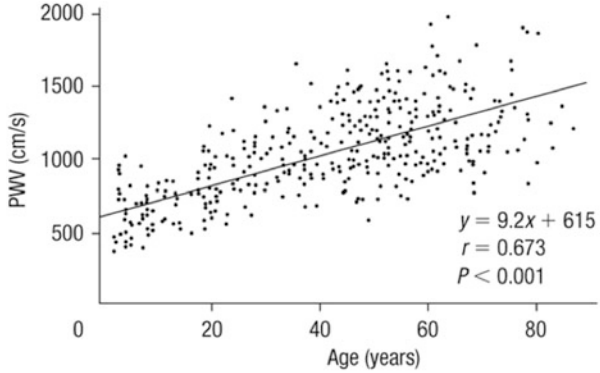

Fig. 3.4 Pulse wave velocity elevates with aging (Ref. [4])

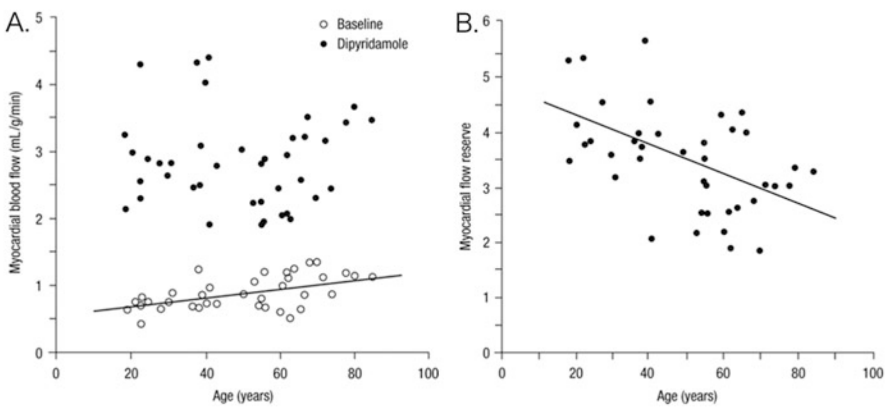

Fig. 3.5 Myocardial blood flow increases (**a**) and myocardial flow reserve decreases (**b**) with aging (Ref. [5])

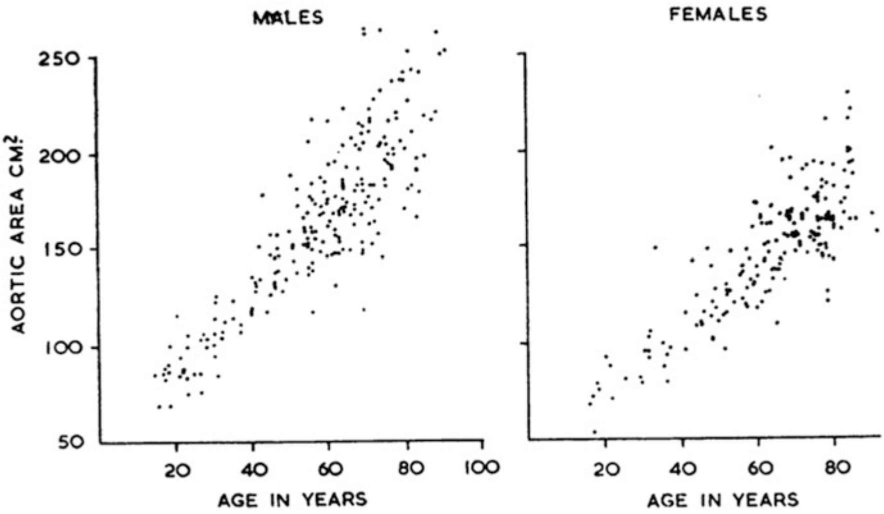

Fig. 3.6 Aortic diameter enlarges with aging (Ref. [6])

3.4 Pathophysiology of the Aortopathy

In patients with aortopathy, the change of vascular characteristics (dilation, decreased distensibility, and acceleration of pulse wave velocity) is usually limited in the ascending aorta in contrast to the aging process.

Several theories are proposed in order to explain the phenomenon.

One of the theories is that the enhanced aortic pressure augmentation caused by pressure wave reflection results in the localization of the abnormal aortic property. Aortic pressure waveform is composed of two pressure waveforms: the forward pressure wave and the reflected pressure wave. The forward pressure wave is generated by the systemic ventricular ejection, and the backward pressure is the sum of the pressure wave reflections. The pressure wave reflections arise from any discontinuity in elastic properties along the arterial tree in which there is a change (or mismatch) in impedance [15]. In young people, the reflected pressure wave returns to the heart during diastole, it means after closure of the aortic valve, because the pulse wave velocity in young is slow. Therefore, it enhances the coronary perfusion by pushing the aortic blood stored during systole. With aging, the pulse wave velocity gradually increases. It means the early return of the reflected pressure wave (in systole) impairs arterial and ventricular function. The opposite directional reflected pressure wave that returns to the heart during systole interferes with the systemic ventricular ejection and increases the workload of the systemic ventricle (Fig. 3.7).

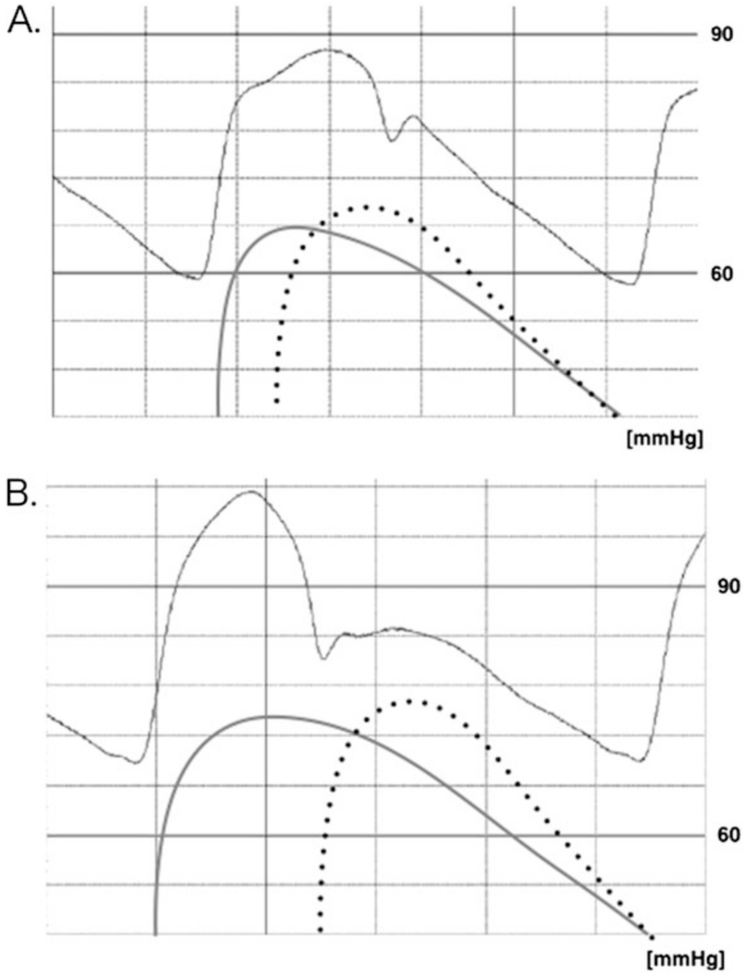

Fig. 3.7 Aortic pressure waveforms. A solid line means the forward pressure wave, and *dotted line* stands for the reflected pressure wave. Early return of the reflected pressure wave (**a**), namely, returns before closure of aortic valve, applies load to the systemic ventricle. On the other hand, late return of the reflected pressure wave (**b**) can enhance the coronary perfusion

3.5 Early Return of the Reflected Pressure Wave in Aortopathy

The mechanism of the early return of aortic pressure wave reflection in elderly people is the increase of the pulse wave velocity of the arterial tree. In congenital heart disease, the mechanism of the enhancement is not necessarily the same. In normal aortic tree, the reflecting point, which represents the integrated pressure wave reflections, exists in the region of the aortic bifurcation [16]. If there is a new

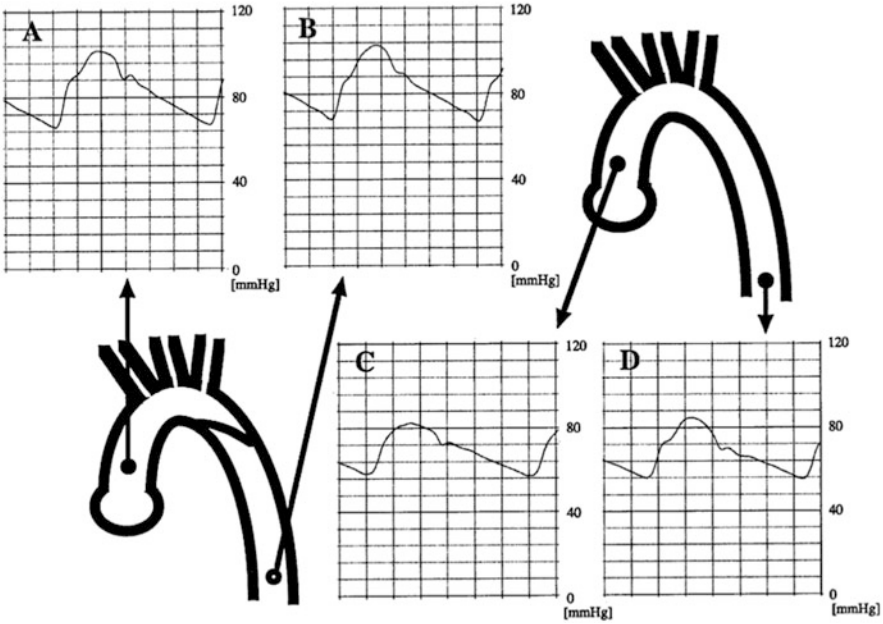

Fig. 3.8 Ascending (**a**) and descending (**b**) aortic pressure waveform in a 6-year-old patient after extended end-to-end anastomosis of the aortic arch. Ascending (**c**) and descending (**d**) aortic pressure waveform in a 6-year-old patient with normal aortic arch. The waveform A resembles D rather than C (Ref. [18])

site with impedance mismatch proximal to the aortic bifurcation, it could strongly enhance the aortic pressure augmentation. Therefore, if the heterogeneity or discontinuity of the aortic wall property that can generate a new pressure wave reflection exists proximal to the aortic bifurcation, it can damage not only the systemic ventricle but also the aorta proximal to the point of the impedance mismatch, resulting in aortic dilation [17].

In many conditions with aortic dilation, the heterogeneity of the aortic wall properties has been reported. In patients with aortic coarctation after surgical repair, the repaired site generates a new pressure wave reflection (Fig. 3.8) [18]. Moreover, it is also reported that aortic surgery is one of the risk factors for the enhancement of the pressure wave reflection [19]. In patients with a bicuspid aortic valve, it is reported that the regions of increased wall shear stress showed greater medial elastin degradation compared to adjacent areas with normal wall shear stress in the ascending aorta [20]. In patients suffering from cyanotic congenital heart disease, the shunt blood flow from systemic to pulmonary circulation increases the blood flow in the ascending aorta but not in the descending aorta. The excess blood flow in the ascending aorta could induce fatiguing effects of cyclic stress on elastin fibers and lamellae within the arterial media (elastin fracture) [15, 21]. Therefore, it makes the gap of vascular property between the ascending and the descending aorta [11]. As a result, the gap generates the new pressure wave reflection. Therefore, the heterogeneity or discontinuity of the aortic wall property should be one of the keys to the aneurysmal changes of the aorta [22].

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