SHORT REPORT

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Mechanism of pulsus bisferiens in thoracoabdominal thoracic aneurysms: Insights from wave intensity analysis

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Abstract

Aortic pulsatile hemodynamics are important in various clinical conditions. Whereas the importance of wave reflections of the closed type in pulsatile hemodynamics has been extensively studied, less is known about the impact of reflections of the open type, in which reflected waves changes both direction and type (compression vs suction) compared to the incident wave. In this report, we present careful pulsatile hemodynamic analyses of a case in which prominent reflections of the open type occur in a patient with a thoracoabdominal aortic aneurysm, causing a highly abnormal proximal aortic and peripheral arterial hemodynamic pattern, known as pulsus bisferiens. Wave intensity analysis of central pressure-flow data demonstrated an early systolic forward-traveling compression wave followed by a prominent late systolic forward-traveling expansion wave, along with an abnormal prominent late systolic/early diastolic backward-traveling compression wave which produced a sharp rise in diastolic pressure, and was responsible for the pulsus bisferiens pattern.

Pulsatile hemodynamics play an important role in hypertension, heart disease, renal disease, cerebrovascular disease, and various other clinical conditions.[1,2] The arterial tree is largely responsible for transforming the pulsatile pressure caused by left ventricular ejection into continuous flow at the capillary level. Whereas assessments of maximum (systolic) and minimum (diastolic) pressure in arteries have generally been the norm in hypertension research, there is increasing availability of devices that allow the non-invasive recording of arterial pressure waveforms. In general, the arterial pulse results from forward- and backward-traveling waves interacting with each other at a given location. Proximal aortic pressure waveforms are interpreted as the sum of the forward-traveling wave generated by the heart and a composite reflected wave which is composed of the sum of a multitude of tiny reflections traveling back to the heart. In younger healthy adults, the reflected wave arrives at the proximal aorta in diastole, augmenting diastolic pressure and thus coronary perfusion pressure, without increasing left ventricular afterload (since the aortic valve is closed). As the aorta stiffens and pulse wave velocity increases with aging and disease, the reflected wave arrives at the proximal aorta in systole, increasing mid-to-late systolic left ventricular afterload, rather than diastolic pressure.[3,4]

This simplified narrative assumes that reflected waves are of the "closed" type in which reflected waves behave like the primary forward-traveling waves, changing only their direction. That is, the systolic forward-traveling compression wave from left ventricular ejection (which increases forward pressure and forward flow) is reflected as a backward-traveling compression wave (which increases backward pressure and flow). Waves can, however, be also of the "suction" or "expansion" type, which reduce pressure and flow; in fact, a forward-traveling suction wave is normally generated in late
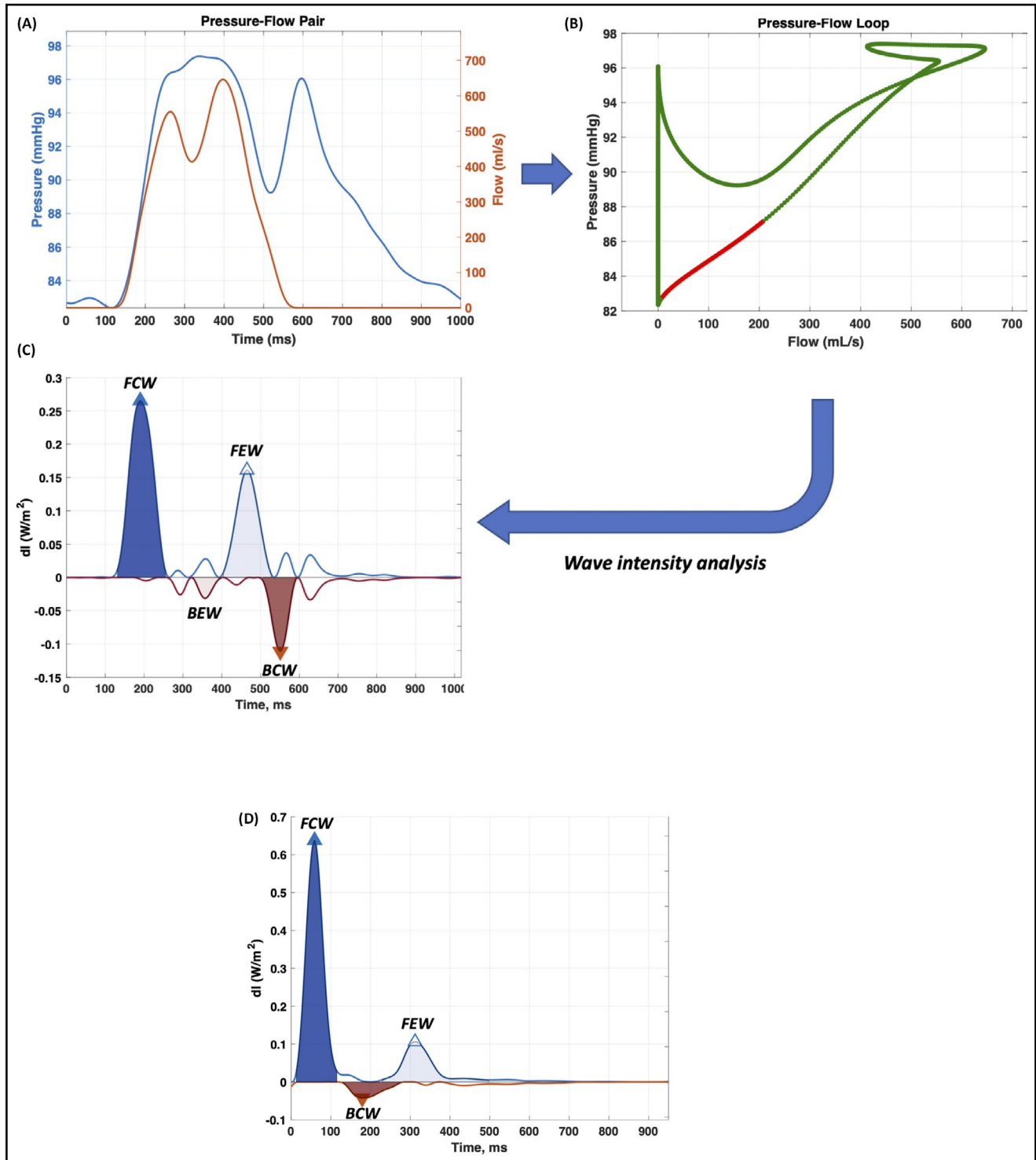
FIGURE 1 After digitizing the time-resolved radial pressure waveform printouts by Rubin and colleagues, as well as the left ventricular outflow tract Doppler velocities, we applied a generalized radial-to-aortic transfer function to the radial pressure profile, to obtain the corresponding aortic pressure waveform. We thus obtained the central pressure-flow pair (panel A) and constructed a pressure-flow loop to assess the pressure-flow relation in the absence of wave reflections (aortic characteristic impedance), from the early systolic pressure-flow slope (marked in red in panel B). We then applied wave intensity analysis (WIA) (panel C) which quantifies forward- (positive sign) and backward-traveling (negative sign) wave fronts. Compression waves are shown in dark blue (forward) or dark red (backward), whereas expansion waves are shown in lighter red and blue shades. WIA demonstrated an early systolic forward-traveling compression wave (FCW) from ventricular ejection followed by a prominent late systolic forward-traveling expansion (suction) wave (FEW). An abnormally prominent late systolic/early diastolic backward-traveling compression wave (BCW) which produced a sharp rise in pressure was seen, which was responsible for the *pulsus bisferiens* pattern. A smaller mid-systolic backward-traveling expansion wave (BEW) was also present. For comparison, a normal proximal aortic WIA pattern is shown (panel D), which demonstrates an early systolic forward-traveling compression wave (FCW) which is reflected as a backward-traveling compression wave (BCW) in mid-systole. A small late systolic forward-traveling expansion wave (FEW) from ventricular relaxation is also seen

systole by the initiation of left ventricular relaxation, which decelerates blood flow in the proximal aorta. Moreover, wave reflections can be of the "open type" in which reflected waves not only change direction, but also change type; that is, compression waves are reflected as suction waves and vice versa. In this report, we present careful pulsatile hemodynamic analyses of a case in which reflections of the open type occur in a patient with a thoracoabdominal aortic aneurysm, causing a highly abnormal proximal aortic and peripheral arterial hemodynamic pattern, known as *pulsus bisferiens*.

Pulsus bisferiens, a classic cardiovascular sign, has been described in severe aortic regurgitation, hypertrophic cardiomyopathy, subaortic stenosis, and contained rupture of a thoracoabdominal aortic aneurysms.[5] However, its hemodynamic mechanism is incompletely understood and likely varies in different disease states. Analyses of aortic pressure-flow relations allow for precise assessments of pulsatile hemodynamics and can be used to comprehensively characterize pulsatile hemodynamic abnormalities using basic measurements of time-varying pressure and flow.[2,6,7]

We previously demonstrated that the bisferiens pulse in severe aortic regurgitation is caused by a forward-traveling mid-systolic suction wave. This wave, not present under normal conditions, arises from blood inertia as a result of ejection of a large stroke volume into a vasodilated arterial tree.[8] This mechanism differs from the classic explanation of a Venturi effect in the ascending aorta in due to the high flow produced by left ventricular (LV) ejection, demonstrating the usefulness of pressure-flow analyses to precisely characterize pulsatile hemodynamics. Aortic pressure-flow analyses have also been instrumental in understanding the role of reflected waves in LV remodeling, diastolic dysfunction, incident heart failure risk, and to assess the hemodynamic effects of novel therapeutics.[2,6]

The mechanism of *pulsus bisferiens* in aortic aneurysms is unknown. Modeling studies indicate that prominent wave reflections at the inlet of aneurysms can produce unusual hemodynamic phenomena, including wave reflections of the open type, in which pulse waves reflect with an opposite sign (ie, forward-traveling compression waves reflect as a backward-traveling suction waves, and vice versa), particularly with larger diameters and more compliant aneurysms.[9] We studied the bisferiens pulse recently reported by Rubin and colleagues in contained rupture of a thoracoabdominal aneurysm.

After digitizing the time-resolved radial pressure waveform printouts by Rubin and colleagues, we applied a generalized radial-to-aortic transfer function to the radial pressure profile as previously described.[10-12] This frequency-domain approach estimates an aortic pressure waveform from the radial pressure waveform using coefficients that express the relationship between the magnitude and phase at various frequencies between these 2 locations. We also digitized the left ventricular outflow tract Doppler waveform and utilized the pressure-flow pair for wave intensity analysis (WIA), a novel technique applied to arterial hemodynamics in which pulse wave fronts are assessed with measurements of local pressure and flow to determine their intensity, direction (forward vs backward) and type (compression vs. suction) (Figure 1).[13]

WIA clearly demonstrated an early systolic forward-traveling compression wave from ventricular ejection followed by a prominent late systolic forward-traveling suction wave. A prominent late systolic/early diastolic backward-traveling compression wave which produced a sharp rise in pressure was seen, which was responsible for the *pulsus bisferiens* pattern. This latter wave is likely due to an "open-type" reflection of the late systolic suction wave generated by the initiation of LV relaxation. Interestingly, an open-type reflection of the early systolic forward compression wave may have also occurred, given the presence of a mid-systolic backward-traveling suction wave. This mid-systolic wave was less prominent, presumably due to partial cancelation from backward-traveling compression waves that normally arise from aortic branching and tapering. The resolution of this pattern with aneurysm stenting is consistent with the high stiffness of the stent, which would eliminate open-type reflections at the aneurysm inlet.

Our report also demonstrates the prominent hemodynamic effects of aortic aneurysms and stents, which have important clinical implications. Based on biophysical principles, it is well known that stent stiffness and diameter can profoundly impact the proximal aortic hemodynamics, therefore affecting pulsatile LV afterload and ventricular-arterial coupling. Clearly, more detailed studies of pulsatile hemodynamics in this patient population are warranted.

In summary, our report demonstrates a novel pulsatile hemodynamic mechanism for the bisferiens pulse in abdominal aortic aneurysms and illustrates the important effects of aortic aneurysms and stents on proximal aortic pulsatile hemodynamics. Pressure-flow analyses can now be applied using readily available signals in the clinic to characterize pulsatile hemodynamics in specific patients.

CONFLICT OF INTEREST

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, JAC, upon reasonable request.

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