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Analysis of Doppler Blood Flow Waveform of Cerebral Arteries and Common Abnormal Findings

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Introduction

The recording and analysis of Doppler blood flow waveforms have been an important part of ultrasound examination of cranial arteries. The characteristics of Doppler blood flow waveforms can provide abundant information, including the degree of artery stenosis, blood flow in collateral circulation, and downstream vascular resistance [1]. However, the descriptions of changes in Doppler spectral waveforms are not definite among reports. This article elaborates a systemic analysis of Doppler blood flow waveform and the terminology of the common abnormal findings during Doppler blood flow examination of cranial arteries.

Analysis of Doppler blood flow waveforms

Directionality

The blood flow direction recorded by Doppler flow examination may vary with respect to the position of the ultrasound probe and the incident angle of the emitted ultrasound beam. The direction of blood flow is defined as antegrade if it flows with normal circulation and retrograde if it is directed against normal circulation. The presence of retrograde blood flow could be observed in: (1) tortuous or looping arteries; (2) collateral arteries for occluded or stenotic artery (for example, flow reversal in the ophthalmic artery results from severe stenosis or occlusion of the ipsilateral carotid artery); and (3) normal curvature of an artery (for example, bidirectional blood flow in siphon of internal carotid artery). In some blood vessels, the direction of blood flow varies in normal individuals, such as the anterior and posterior communicating arteries.

Inflection points

A normal Doppler blood flow waveform in cerebral circulation consists of four main inflection points within a cardiac cycle (Fig. 1). These inflection points provide important information of blood flow characteristics, including velocity of initial flow upstroke, peak systolic velocity, position of dicrotic notch and end diastolic velocity (Fig. 1). The period between the upstroke inflection point and peak systole is defined as acceleration time (AT, normal value < 70 milliseconds), and the increment of flow velocity divided by the acceleration time is called flow acceleration rate (FAR, normal value > 5 m/second²). Slow FAR and prolonged AT may imply significant stenosis in the proximal part of the artery (see Fig. 4 and its caption). By contrast, the period between peak systole and dicrotic...
notch is referred to as the contraction deceleration phase. A well-known abnormality which occurs during this phase is subclavian steal phenomenon [2]. When stenotic arterial lesion in the proximal subclavian artery or the innominate artery results in flow shunting from the ipsilateral vertebral artery, the flow deceleration will accentuate and is followed by flow acceleration in the ipsilateral vertebral artery during the contraction deceleration phase, thus forming a cleft at mid-systole (Fig. 2). When the lowest point of the blood flow velocity of the mid-systolic cleft is higher than zero, the waveform looks like a squatting bunny; hence, it is known as the bunny waveform (Fig. 2). As the stenotic lesion in the subclavian (or innominate) artery becomes more severe, more blood flow in the ipsilateral vertebral artery is shunted into the subclavian artery, leading to a lower mid-systolic cleft. Retrograde blood flow then appears as this condition worsens.

**Pulsatility index and resistance index**

The calculation of the pulsatility index (PI) and resistance index (RI) are not influenced by the angle of Doppler flow measurements. Both PI and RI can be used to describe the blood vessel elasticity and resistance of downstream blood vessels. The PI is calculated by subtracting the end diastolic velocity from the peak flow velocity, then dividing by the mean velocity; the RI is calculated using the peak systolic velocity as the denominator. Because the angle between the vessel and incident ultrasound beam is difficult to measure precisely for intracranial arteries, the PI is primarily used to reflect downstream vascular resistance for intracranial circulation. Generally, a PI < 0.6 is defined as very low resistance, PI between 0.6 and 1.1 is low resistance, PI between 1.2 and 1.6 is high resistance, PI between 1.7 and 1.9 is moderately high resistance and PI ≥ 2 is very high resistance. Normal PI values in cerebral arteries are approximately 0.5–1.1. RI values of < 0.5, 0.5–0.7 and > 0.7 represent very low, low, and high resistance, respectively.

**Doppler flow velocity**

Increased blood flow velocities may indicate arterial stenosis, a hyperdynamic state, downstream blood flow shunting, or blood supply to a hypervascular tumor. Increased blood flow velocity due to significant arterial stenosis may be accompanied with increased pulsatility (resistance) in the prestenotic artery, decreased flow velocities and changes in Doppler blood waveform in the poststenotic artery (arteries), and increased velocities and/or change flow direction in collateral vessels. Arterial stenosis should be also taken into account when there is a discrepancy in blood flow velocities (>30% difference, so-called damped flow) between corresponding arteries, without changes in pulsatility and spectral waveform. Increased blood flow velocities with low resistance usually represent a hyperdynamic state (for example, anemia and
hyperthyroidism), or a high demand for blood flow (for example, arteriovenous fistulae and tumors).

Spectral window

In normal straight vessels, blood flows are mostly in parallel and of constant velocities. Thus, Doppler spectral waveforms appear concentrated and have no low velocity blood flow, thereby forming a so-called spectral window due to the absence of Doppler signal below the spectrum (Fig. 3A, indicated by the arrows). When blood flow velocity is less congruent (non-parallel flow), a wide range of blood flow velocities can be recorded simultaneously, resulting in spectral broadening of Doppler spectral waveforms (Fig. 3B). When low velocity turbulence arises in blood vessels, the turbulent signals will appear in the original spectral window, causing a disappearance or decrease in the spectral window, which is called spectral fill-in (Fig. 3C).

Definitions and examples of common abnormal Doppler blood flow waveforms

Damped waveform

The average blood flow velocity is decreased by >30% compared to the ipsilateral proximal or contralateral vessels, but normal FA and waveform are still retained.

Low resistance waveform (Fig. 4)

The waveform of high end diastolic blood flow velocity indicates a more constant blood supply throughout an entire cardiac cycle, which is usually observed in arteries to vital organs such as the brain and kidney. A PI < 1.2 and a D/S ratio > 25% represents low resistance in downstream vasculature. A PI < 0.6 and a D/S ratio > 50% represents very low resistance.

High resistance waveform (Fig. 5)

The waveform of low end diastolic blood flow velocity indicates higher resistance in downstream vasculature. In general, a RI > 0.7 or PI > 1.2 is referred to as a high resistance waveform.

Blunted waveform (tardus-parvus waveform; Fig. 6)

In the early phase of systole, slow FAR (i.e., <5 m/second²) and prolonged AT to reach the highest blood flow velocity (i.e., >70 milliseconds) appear to be a more blunt waveform. A blunted waveform has a low PI (PI < 1.2). When accompanied by decreased systolic blood flow velocity, the blunted waveform usually indicates severe stenosis in the upstream artery. Pulsus parvus represents a reduction in the highest blood flow velocity and pulsus tardus represents prolongation of the time to reach the highest blood flow velocity owing to decreased FAR.
Seagull sound (harmonic bruits; Fig. 7)

Musical bruits, which may sound like the call of a seagull, result from turbulent flow in a stenotic artery. A bruit is usually a low pitch noise. With the occurrence of resonance, high pitch, harmonic bruits may present. Harmonic bruits appear as parallel turbulent signals in Doppler spectra (Fig. 7).

Minimal waveform (Fig. 8)

Minimal waveform represents residual low, discontinuous blood flow during systolic period in an occluded artery.

Reverberating waveform (to-and-fro waveform; Fig. 9)

Discontinued, alternative antegrade and retrograde flow indicates arterial occlusion.

Wall covibration (wall fluttering; Fig. 10)

Loud, low frequency noises result from vibrations of a vessel wall. The Doppler spectral waveform demonstrates a characteristic irregular, spiny border. Wall covibration usually occurs in vessels with increased flow volume.

References
