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# Arterial waveform analysis

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The bedside measurement of continuous arterial pressure values from waveform analysis has been routinely available via indwelling arterial catheterization for >50 years. Invasive blood pressure monitoring has been utilized in critically ill patients, in both the operating room and critical care units, to facilitate rapid diagnoses of cardiovascular insufficiency and monitor response to treatments aimed at correcting abnormalities before the consequences of either hypo- or hypertension are seen. Minimally invasive techniques to estimate cardiac output (CO) have gained increased appeal. This has led to the increased interest in arterial waveform analysis to provide this important information, as it is measured continuously in many operating rooms and intensive care units. Arterial waveform analysis also allows for the calculation of many so-called derived parameters intrinsically created by this pulse pressure profile. These include estimates of left ventricular stroke volume (SV), CO, vascular resistance, and during positive-pressure breathing, SV variation, and pulse pressure variation. This article focuses on the principles of arterial waveform analysis and their determinants, components of the arterial system, and arterial pulse contour. It will also address the advantage of measuring real-time CO by the arterial waveform and the benefits to measuring SV variation. Arterial waveform analysis has gained a large interest in the overall assessment and management of the critically ill and those at a risk of hemodynamic deterioration.



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## Introduction

The bedside measurement of continuous arterial pressure values from waveform analysis has been routinely available via indwelling arterial catheterization for >50 years. Invasive blood pressure monitoring has been utilized in critically ill patients, in both the operating room and critical care units, to facilitate rapid diagnoses of cardiovascular insufficiency and monitor response to treatments aimed at correcting abnormalities before the consequences of either hypo- or hypertension are seen.

Arterial blood pressure was first directly measured by Stephen Hales in 1733, when he used a 9′-long glass tube with a flexible connector (the trachea of a goose) and measured the pressures at the femoral and carotid arteries [1]. Other scientists and physicians improved on this method, including Daniel Bernoulli [2] and Jean-Louis Poiseuille who, in 1828, used a mercury-filled U-tube to determine the pressure at multiple points along the aorta [3]. The first clinically relevant placement of an arterial catheter was accomplished in 1949 by Peterson and colleagues who described the following methodology: "A small plastic catheter, inserted into an artery through a needle, is left in the artery when the needle is withdrawn. Attached to a capacitance manometer, this technique permits recording for long periods of time without discomfort and allows relatively free mobility of the subject." [4] Since that time, multiple techniques have been elucidated by Peirce [5] and Seldinger [6]. Seldinger described the "catheter-over-wire" technique commonly used today. As of 1990, >8 million invasive arterial catheters had been placed. One added advantage of an invasive arterial catheter is the ability to easily draw blood samples to measure levels of various including hemoglobin and electrolytes, allowing greater ease at diagnosis and managing disease. As medical technology improved, noninvasive technology was developed to provide continuous arterial waveform monitoring using plethysmographic principles with devices placed on a finger or wrist, that is, a continuous noninvasive arterial pressure (CNAP) monitor [7] and NexFin [8] (BMEYE, Amsterdam, the Netherlands) devices. Some noninvasive devices require calibration and others do not.

Hemodynamic monitoring in the operating room and the intensive care unit has evolved over time by the use of both arterial pressure monitoring and pulmonary artery catheter (PAC)-derived measures. PAC-derived measures include pulmonary artery pressure, pulmonary artery occlusion pressure, mixed venous oxygen saturation, and cardiac output (CO) by the thermodilution technique. Although it would seem that these invasive monitoring techniques to estimate CO would be useful in patient management, studies do not show improved outcomes when compared to their lack of use. There have been multiple randomized controlled trials that have reported no evidence of benefit or harm from the use of the PAC [9], and some literature has indicated that there may be an increase in complications secondary to the use of pulmonary artery catheterization [10–12]. There may be a few reasons why there has been a failure to show the benefit of PAC: some of the studies may not have used treatments requiring CO values to drive resuscitation, the treatments in the studies may not have been proven to improve outcome, and the groups studied are too heterogeneous to document a benefit [13].

Because of this overall lack of interest in the continued widespread use of the PAC, minimally invasive techniques to estimate CO have gained increased appeal. This has led to increased interest in arterial waveform analysis to provide this important information. The arterial waveform is measured continuously in many operating rooms and intensive care units, and obtaining the arterial pressure waveform can be accomplished by simple catheterization and even noninvasively. The benefit is the continuous measurement of arterial pressure with decreased risk to the patient. The cost that exists is the purchase of a device that allows for numerical computation but does not require further specialty staff. Arterial waveform analysis also allows for the calculation of many so-called derived parameters intrinsically created by this pulse pressure profile. These include estimates of left ventricular stroke volume (SV), CO, vascular resistance, and during positive-pressure breathing, SV variation, and pulse pressure variation (PPV). This article focuses on the principles of arterial waveform analysis and their determinants, components of the arterial system, and arterial pulse contour. It also addresses the advantage of measuring real-time CO by the arterial waveform and the benefits to measuring stroke volume variation (SVV). Thus, arterial waveform analysis has gained a large interest in the overall assessment and management of the critically ill and those at a risk of hemodynamic deterioration.