FloTrac Algorithm
Calculating stroke volume and cardiac output getting mL/beat from mmHg

Summary

The FloTrac algorithm, an arterial pressure-based cardiac output (APCO) method in which cardiac output can be continuously calculated using an arterial catheter. This technology is based on the basic principles of physics and the application of a sophisticated algorithm.

Physics and physiology

Flow is determined by a pressure gradient along a vessel and the resistance to that flow ($F = \Delta P/R$). The FloTrac algorithm uses a similar principle to calculate pulsatile flow by incorporating the effects of both vascular resistance and compliance through a conversion factor known as Khi (x).

Cardiac output is an important component of global oxygen delivery (DO_2) and is the most often manipulated variable when improving oxygen delivery. Cardiac output is calculated by multiplying heart rate by the stroke volume. The FloTrac algorithm uses these same components but substitutes heart rate with the pulse rate (PR), capturing only truly perfused beats, and multiplies PR by a calculated stroke volume. Stroke volume is calculated from the patient's arterial pressure to analyze the arterial pressure waveform using the unique FloTrac algorithm. The FloTrac algorithm analyzes the pressure waveform at one hundred times per second over 20 seconds, capturing 2,000 data points for analysis. These data points are used along with patient demographic information to calculate the standard deviation of the arterial pressure (σ_{AP}). This (σ_{AP}) is proportional to pulse pressure (PP). The σ_{AP} is multiplied by a conversion factor known as Khi (x) which incorporates both the effects of resistance and compliance (vascular tone) and also converts σ_{AP} in (mmHg) into mL/beat. Therefore, with the variables σ_{AP} and vascular tone (x), flow or stroke volume can be calculated.

Traditional: $CO = HR * SV$

FloTrac system: $APCO = PR \times (\sigma_{AP} * x)$

Where $x = M(HR, \sigma_{AP}, C(P), BSA, MAP, \mu 3_{ap}, \mu 4_{ap} \ldots)$

σ_{AP} = standard deviation of arterial pulse pressure in mmHg is proportional to pulse pressure

x = scaling multivariate parameter proportional to the effects of vascular tone on pulse pressure

M = multivariate polynomial equation

BSA =body surface area calculated by Dubois' equation for body surface area

MAP = mean arterial pressure calculated by taking sum of sampled pressure point values over 20 seconds and dividing it by the number of pressure points

μ = statistical moments determined by skewness (symmetry) and kurtosis (distinctness of a peak) calculated along several mathematical derivatives

Arterial pressure-based cardiac output

The FloTrac algorithm is based on the principle that aortic pulse pressure is proportional to stroke volume (SV) and inversely related to aortic compliance.

Standard deviation of arterial pressure

Initially, the FloTrac algorithm assesses pulse pressure by using the standard deviation of the arterial pressure (σ_{AP}) around the MAP value, measured in mmHg, making it independent of the effects of vascular tone. This standard deviation of the pulse pressure is proportional to the volume displaced or the stroke volume. This is calculated by analyzing the arterial pressure waveform over 20 seconds at 100 times per second, creating 2,000 data points from which σ_{AP} is calculated.

Edwards

Khi and the conversion of mmHg to mL/beat

The conversion of standard deviation of arterial pressures (mmHg) into mL/beat is performed by multiplying it by a conversion factor known as Khi (x). Khi is a multivariate polynomial equation which assesses the impact of the patient's ever-changing vascular tone on pulse pressure. Khi is calculated by analyzing the patient's pulse rate, mean arterial pressure, standard deviation of mean arterial pressure, large-vessel compliance as estimated by patient demographics, and skewness and kurtosis of the arterial waveform. Khi is updated and applied to the FloTrac algorithm on a rolling 60-second average.

- Pulse rate: The patient's pulse rate is calculated by counting the number of pulsations in a 20 second period and extrapolated to a per minute value

- Mean arterial pressure (MAP): An increase in average pressure often indicates an increase in resistance, and vice versa

- Standard deviation of arterial pressure (σ_{AP}): Pulse pressure is proportional to σ_{AP} and to stroke volume; increases and decreases in the standard deviation also provide information on pressure amplitude; when this pressure amplitude is correlated with kurtosis, it compensates for differential compliance and wave reflectance that vary from one arterial location to another; this then allows the monitoring of cardiac output from different arterial locations

- Large vessel compliance: Work reported by Langewouters found a direct correlation among age, gender, and MAP with respect to aortic compliance; an equation was derived from these studies by which a patient's compliance could be estimated with the inputs of age and gender; according to Langewouters et al, the arterial compliance (C), as a function of pressure, could be estimated using the following equation:

$$C(P)=L \bullet \frac{\dfrac{A_{max}}{\pi \bullet P_1}}{1+\left(\dfrac{P-P_0}{P_1}\right)^2}$$

L = estimated aortic length

Amax = aortic root cross sectional area maximum

P = arterial pressure

P_0 = pressure at which compliance reaches its maximum

P_1 = the width of compliance curve at half of maximum compliance; additional measures of weight and height (BSA) were also found to correlate with vascular tone and were added to enhance the calculation of aortic compliance

- Skewness (a measure for lack of symmetry, μ3ap): Symmetry characteristics on arterial pressure can indicate a change in vascular tone and/or resistance; two different functions may have the same mean and standard deviation but will rarely have the same skewness; for example, an arterial pressure waveform in which the data points increase quickly in systole and fall slowly can result as an increase in vasoconstriction and would have increased skewness

Figure 1 - Decreased skewness low resistance

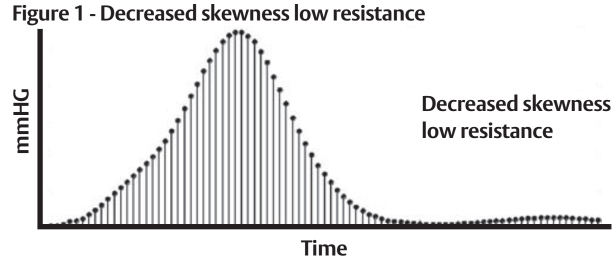
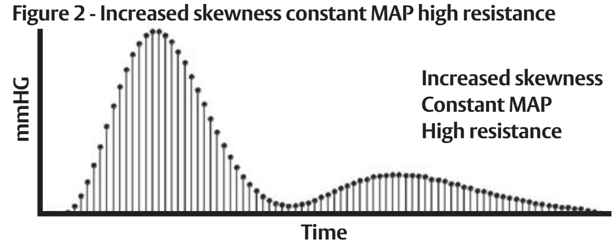


Figure 2 - Increased skewness constant MAP high resistance



- Kurtosis (a measure of how peaked or flat the pressure data points are distributed from normal distribution, μ4ap): Pressure data with high kurtosis has the pressure rise and fall very quickly relative to the normal pulse pressure and can be directly associated with large vessel compliance;
  1) A high kurtosis value will indicate a distinct peak near the mean, with a drop thereafter, followed by a heavy "tail" (Figure 3)
  2) A low kurtosis value will tend to indicate that the function is relatively flat in the region of its peak and suggests decreased central tone, as is often seen, for example, in the neonatal vasculature (Figure 4)

Figure 3 - High compliance of large vessels

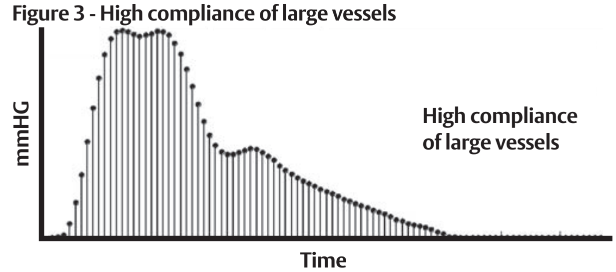
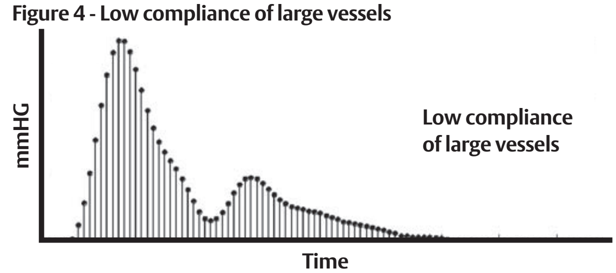


Figure 4 - Low compliance of large vessels



Khi (x) mmhg to mmHg to mL/beat
Taking all of these variables into consideration, the FloTrac algorithm continuously assesses the impact of vascular tone on pressure every 60 seconds. The result of the analysis is a conversion factor known as Khi (x). Khi is then multiplied by the standard deviation of the arterial pressure to calculate stroke volume in milliliters per beat. This stroke volume is multiplied by the pulse rate to obtain cardiac output in liters per minute.

Stroke volume (mL/beat) = σ_{AP} (mmHg)* x (ml/mmHg)

Developed with the clinical gold standard
The vascular tone factor (Khi) was developed based on cardiovascular hemodynamics principles, advanced signal processing of the arterial pressure waveform, and comparative analysis with the clinical gold standard thermodilution cardiac output.

Khi (x) was modeled and compared across a wide range of cardiac output values, patient profiles, pathologies, and hemodynamic conditions. Since clinically available, the FloTrac system has been validated against various cardiac output technologies including thermodilution cardiac output.

No manual calibration needed
Other arterial pressure cardiac output devices (pulse contour or pulse power) require calibration as they cannot auto correct for the patient's changing vascular tone. Since the FloTrac algorithm continuously adjusts for the patient's ever changing vascular tone, it does not require external calibration. As a component of the calibration, Khi auto corrects for changes in vascular tone through a complex waveform analysis. This feature also eliminates the need for a central or peripheral venous line, required for indicator dilution methods used in external calibration.

Technical considerations
FloTrac algorithm is dependent upon a high fidelity pressure tracing. Attention to best practice in pressure monitoring is important by; priming with gravity, pressure bag kept to 300mmHg, adequate I.V. bag flush volume, sensor stopcock is kept level to phlebostatic axis, and periodic testing of optimal dampening with a square wave test. The FloTrac sensor kits are especially configured to optimize frequency response therefore adding additional pressure tubing or stopcocks is highly discouraged.

Limitations
As of this publication, absolute values during aortic regurgitation may be affected although trending may be appropriate. Severe peripheral constriction during shock states or hypothermic episodes may influence values with radial arterial locations, consideration to femoral sites during these episodes or insertion of a pulmonary artery catheter may be considered.

The FloTrac system can be used in patients with arrhythmias and who are spontaneously breathing. Arrhythmias and spontaneous breathing are **NOT** a limitation of the FloTrac algorithm in calculating cardiac output.

FloTrac system 4.0
The FloTrac system algorithm has evolved based on a broad and expanding patient database that allows ongoing system performance improvements. The following high-risk surgical patients were added to the database including, but not limited to, gastrointestinal, esophageal, pancreaticoduodenectomy (whipple) and esophagectomy. The expanded patient database has informed the algorithm to recognize and adjust for more patient conditions.

Additional physiologically-based variables were added to the algorithm's vascular tone *Khi* factor in order to adjust automatically for hyperdynamic and vasodilated patients. Once identified it accesses a specially designed algorithm to account for such conditions.

Figure 5 - Pulsatility of the wave

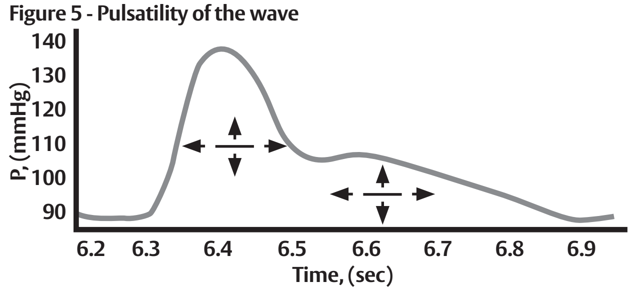
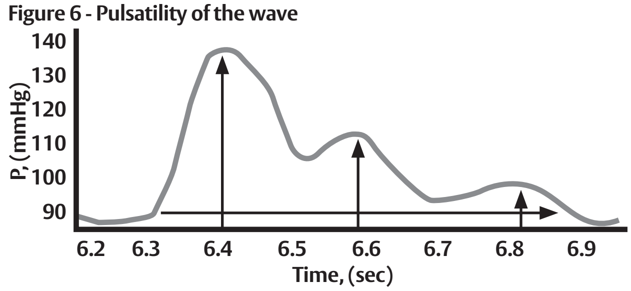


Figure 6 - Pulsatility of the wave



In addition to a broader database the FloTrac system 4.0 algorithm adjusts for rapid changes in pressure that occur during vasopressor administration through *Khi*-fast. *Khi*-fast is assessed every 20 seconds and is inversely affected by pressure. *Khi* continues to assess vascular tone every 60 seconds and *Khi*-fast every 20 seconds resulting in a more physiologic response to changes in resistance.

Conclusion

Edwards Lifesciences has converted the complexity and invasiveness traditionally associated with continuous cardiac output monitoring into the simplicity of connecting to an arterial catheter. The proven FloTrac system allows for earlier implementation of hemodynamic instability in surgical and critically ill patients.

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Information contained in this document is based on the following references:

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