Theory of Operation

Pressure-Volume Technology

Conductance Theory of Operation

Deriving ventricular volume from a Conductance Catheter is based on a very simple electrical principle: Ohm's Law:

Voltage (V) = Current (I) X Resistance (R)   V = IR

Conductance (G) rather than resistance is the parameter of interest. Since conductance is the inverse of resistance, Ohm's Law can be rewritten as:

Voltage = Current/Conductance   V = I/G

Conductance Catheters are comprised of both excitation electrodes and recording electrodes. The excitation electrodes (most distal and proximal electrodes on the Catheter) generate an electrical field inside the heart from the aortic valve to the apex. This field is generated as a result of an alternating current being applied (at a constant magnitude) between these 2 outermost electrodes. The inner recording electrodes measure voltage change which is proportional to a change in resistance.

The electrical field cannot be restricted to just the blood volume and must pass through some of the cardiac muscle. This means that the measured conductance value (G_x) is actually a combination of blood conductance (G_b) and muscle or parallel conductance (G_p).

In 1981, Dr. Baan et. al. proposed a relationship between time-varying measurements of total conductance (G_x) to time-varying changes in ventricular volume (Vol). This volume formula takes into account the distance between the recording electrodes (L), blood resistivity (ρ), and the parallel conductance (G_p). It also takes into account the non-uniform nature of the electrical field with the field correction factor, alpha (α).

BAAN'S EQUATION

$$Vol = \frac{1}{\alpha}\rho L^2 (G_x - G_p)$$

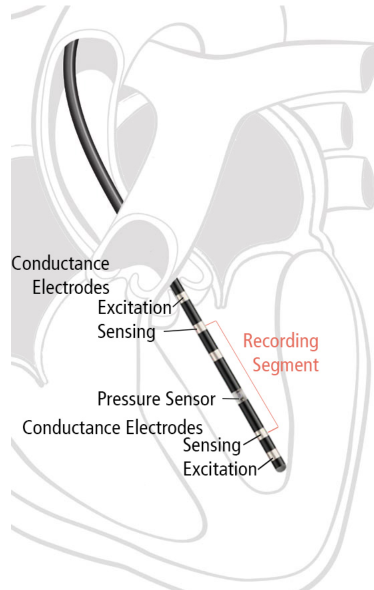
ρ = Blood resistivity

L = Measuring electrode distance

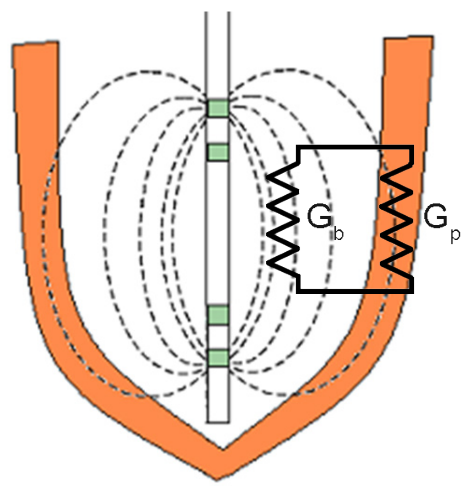
α = Baan's SV correction factor = $\left(\frac{SV_{conductance}}{SV_{reference}}\right)$

G_x = Measured total conductance

G_p = Baan's parallel/muscle conductance (assumed to be removed by hypertonic saline injection)



Conductance excitation electrodes create an electric field while sensing electrodes measure the voltage change which allows for the calculation of resistance and conductance.



Conductance uses a circuit model where both blood (G_b) and cardiac muscle (G_m) are conductive and measured together as a single conductance value (G_x) and phase components are ignored.

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Pressure-Volume Technology Theory of Operation Cont.

Conductance Theory of Operation Cont.

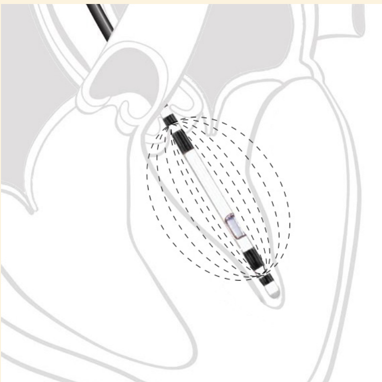
However, Baan assumed alpha to be a constant with a value of one for a uniform current field distribution (in reality electrical field strength decreases non-linearly with distance). Alpha can be calculated from the SV conductance ratio (see equation on page 1) or by cuvette calibration. Both of these methods give a single constant value for alpha. Parallel or muscle conductance (G_p) is often determined by hypertonic saline injection which temporarily changes blood conductance but not myocardial conductance; allowing for the parallel conductance value to be determined from the graph of changing conductance. This produces a single constant value for parallel conductance.

IMPACT OF PHYSIOLOGY ON CONDUCTANCE MEASUREMENTS

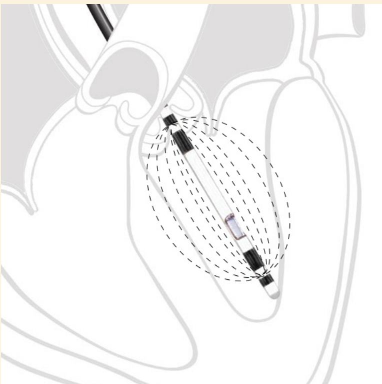
At systole there is relatively little blood in the ventricle which means that a larger portion of the electrical field passes through the myocardium. Thus, myocardial resistance contributes more to the total measured conductance than blood at this time. However, because the hypertonic saline bolus method provides an average measurement of muscle contribution, it is typical for the derived volume to be overestimated at systole.

At diastole there is a large quantity of blood in the ventricle and the heart walls have expanded. This means that most of the electrical field is passing though blood with a very small contribution from the myocardium. Thus, the measured conductance value is almost entirely blood conductance. However, the same value of parallel conductance is still subtracted from the total conductance which leads to an under estimation of blood volume.

The electrical field strength decreases in a non-linear manner with increasing field size. This means measurements of blood conductance further from the Catheter do not have the same strength as those nearer to the Catheter. Without correction this leads to an under estimation of total volume. The larger the volume which is being measured, the greater the under estimation: volume measurements at diastole are thus more prone to under estimation than those at systole. Alpha attempts to correct some of this error but fails to address the non-linearity of the electric field or the varying strength the under estimation has at different phases of the heart cycle.



At Systole



At Diastole

Pressure-Volume Technology Theory of Operation Cont.

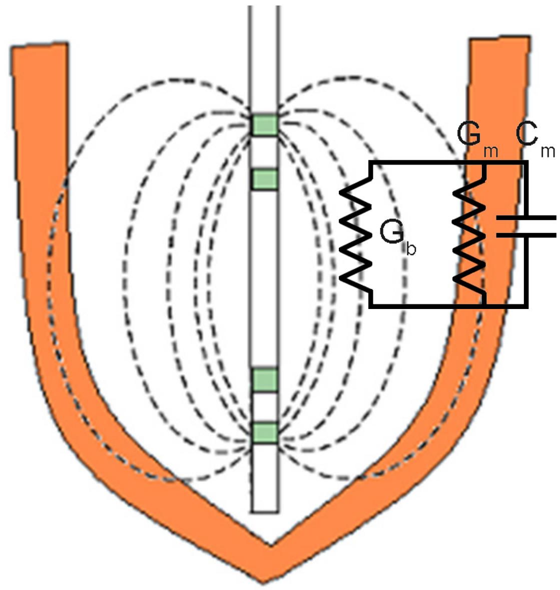
Admittance Theory of Operation

Admittance technique is an extension of the Conductance method which measures both resistive and capacitive properties of blood and muscle. In the electric field blood is purely resistive, but muscle has both capacitive and resistive properties. This allows separation of the muscle component of conductance from that of blood, using electric field theory.

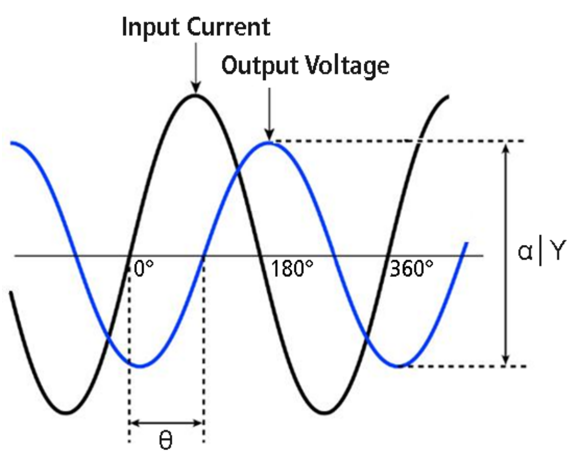
The capacitive property of muscle causes a time (phase) delay in measured signal (see graph at bottom right). By tracking this delay known as the phase angle in real time and mathematically relating it to the resistance of the myocardial tissue, the ADV500 System allows continuous, non-invasive tracking of muscle/parallel conductance (G_m) throughout the heartbeat. The phase angle reports heart tissue intrusion into the field as the heart contracts and expands, and as expected, this measurement is greatest at systole and lowest at diastole. This provides a great advantage over classical conductance volumetry which treats parallel conductance as a constant, rather than a dynamic variable which changes throughout the cardiac cycle.

The ADV500 system employs an equation developed by Dr. Chia-Ling Wei to convert conductance to volume instead of the traditional Baan's equation. In Baan's equation the Field Correction Factor, alpha (α), is assumed to be constant despite the non-linear nature of the electrical field. However, Wei's equation corrects for the nonhomogeneous nature of the Catheter's electrical field distribution by assuming a non-linear relationship between conductance and volume, gamma (γ), thus improving accuracy over a wider volume range.

To measure blood volume in real time values are needed for myocardial conductivity and permittivity (for σ/ε ratio/heart type), blood resistivity (ρ), and reference stroke volume (SV). Default values for 'Heart Type' (S/E ratio) are provided and most commonly used. However, researchers can study this value using a tetrapolar surface probe provided with the ADV500. Stroke volume can be measured via other technologies.



Admittance uses a circuit model where blood is conductive (G_b) and cardiac muscle is both conductive (G_m) and capacitive (C_m).



The output voltage shows a "delay" compared to the input voltage signal used to generate the electric field. The signal delay, caused by myocardial capacitance, is measured in terms of degrees and is referred to as "Phase angle θ." The admittance magnitude (conductance) is impacted by both the blood and muscle.

WEI'S EQUATIONS

$$Vol = \frac{1}{(1-\frac{G_b}{\gamma})}\rho L^2(G_b)$$

ρ = Blood resistivity

L = Measuring electrode distance

G_b = Measured blood conductance

SV = Stroke volume

Field Correction Factor:

$$\gamma = \frac{-b \pm\sqrt{b^2-4ac}}{2a}$$

$$a = SV - \rho L^2(G_{b-ED} - G_{b-ES})$$

$$b = -SV \cdot (G_{b-ED} + G_{b-ES})$$

$$c = SV \cdot G_{b-ED} \cdot G_{b-ES}$$

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Comparing Conductance vs Admittance

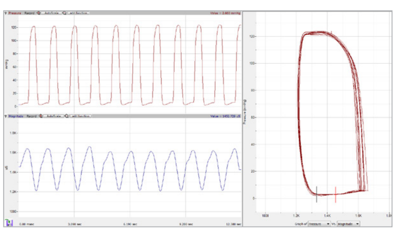
The Scisense ADV500 Pressure-Volume System is capable of being used in either Conductance or Admittance mode. Both methods have value depending on what the researcher is looking to observe.

Conductance

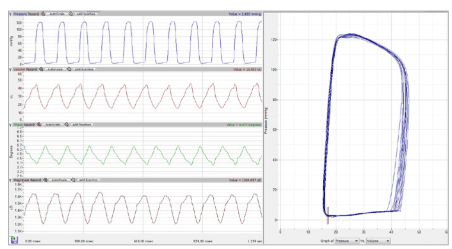
- Measures voltage magnitude
  - Harder to determine position of Catheter in ventricle
- Uses Baan's equation to determine volume
- Parallel conductance (G_p) is assumed constant
  - Parallel conductance determined from hypertonic saline injection after the experiment
- Field Correction Factor is assumed constant (alpha)
  - Requires empirical reference stroke volume to derive α or an approximation (typically 1) can be used
- Volume calculation is done post experiment with no chance to correct for protocol or surgical errors.
- Tends to overestimate volume due to constant nature of α as observed with echocardiography.
- Traditional technique with a solid body of papers that validate the basic principle of conductance catheter volumetry.

Admittance

- Measures voltage magnitude and phase angle
  - Phase angle useful in locating Catheter in ventricle
- Uses Wei's equation to determine volume
- Muscle conductance (G_m) varies throughout cardiac cycle
  - Parallel conductance determined from phase shift in real-time (no hypertonic saline injection required)
  - Requires sigma/epsilon ratio (conductivity/permittivity) of heart muscle. Default values are commonly used, or can be measured using tetrapolar Calibration Probe.
- Field Correction Factor is non-linear (gamma)
  - Requires empirical reference stroke volume to derive gamma (γ)
- Volume calculation is in real time. Corrections to experimental protocol or surgery can be made before experiment is concluded.
- Closer approximation to absolute systolic and diastolic volume as observed with echocardiography.
- Innovative technology that builds directly on the foundation of conductance catheter volumetry.



Conductance method measure pressure and magnitude in real-time, creating pressure-magnitude loops. Volume can only be calculated post-experiment.



Admittance method measure pressure, volume, phase and magnitude in real-time, creating pressure-volume loops.

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Transonic Systems Inc. is a global manufacturer of innovative biomedical measurement equipment. Founded in 1983, Transonic sells "gold standard" transit-time ultrasound flowmeters and monitors for surgical, hemodialysis, pediatric critical care, perfusion, interventional radiology and research applications. In addition, Transonic provides pressure and pressure volume systems, laser Doppler flowmeters and telemetry systems.

AMERICAS
Transonic Systems Inc.
34 Dutch Mill Rd
Ithaca, NY 14850
U.S.A.
Tel: +1 607-257-5300
Fax: +1 607-257-7256
support@transonic.com

EUROPE
Transonic Europe B.V.
Business Park Stein 205
6181 MB Elsloo
The Netherlands
Tel: +31 43-407-7200
Fax: +31 43-407-7201
europe@transonic.com

ASIA/PACIFIC
Transonic Asia Inc.
6F-3 No 5 Hangsiang Rd
Dayuan, Taoyuan County
33747 Taiwan, R.O.C.
Tel: +886 3399-5806
Fax: +886 3399-5805
support@transonicasia.com

JAPAN
Transonic Japan Inc.
KS Bldg 201, 735-4 Kita-Akitsu
Tokorozawa Saitama
359-0038 Japan
Tel: +81 04-2946-8541
Fax: +81 04-2946-8542
info@transonic.jp