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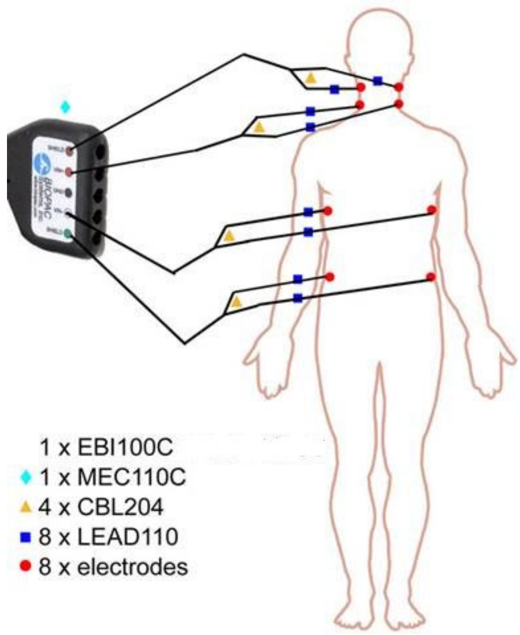
Application Note 196: Cardiac Output Measurement—Using EBI100C and LEAD110s



Overview: Cardiac Output using Bioimpedance Techniques

Cardiac Output can be noninvasively determined by employing electrical bioimpedance measurement techniques. Electrical bioimpedance is simply the characteristic impedance of a volume of tissue and fluid. In the case of Cardiac Output measures, the relevant tissue includes the heart and the immediate surrounding volume of the thorax. The relevant fluid is blood. The electrical impedance of the thorax can be thought of as composed of two types of impedances:

1. *The base impedance (Zo) corresponding to non-time varying tissues, such as muscle, bone and fat. Zo is measured when the pulsatile volume is minimal.*
2. *The impedance (delta Z) corresponding to time-varying fluid volume (blood).*

   The electrical bioimpedance of the thorax [Z(t)] cyclically drops with each pulsatile volume of blood ejected from the heart.

$$Z(t) = Zo - \text{delta } Z$$

The EBI100C module can be used to measure Z(t) and dZ(t)/dt directly. In the case of Cardiac Output, delta Z is empirically determined to be:

$$\text{delta } Z = T \times dZ(t)/dt_{(max)}$$

Where:

T = Systolic [LVET] ejection time (seconds)
$dZ(t)/dt_{(max)}$ = Magnitude of the largest impedance change during Systole (Ohms/sec)

The pulsatile volume of blood ejected by the heart is called the Stroke Volume (SV). The expression relating SV to Zo, T and dZ(t)/dt is:

$$SV = R \times (L^2/Zo^2) \times T \times dZ(t)/dt_{(max)}$$

Where:

SV = Stroke volume (ml)

R = Resistivity of blood (Ohms·cm)
L = Length between inner band electrodes (cm)

Cardiac Output (CO) is related to SV as follows:

$$CO = SV \times HR$$

Where:

CO = Cardiac Output (liters/minute)
HR = heart rate (BPM)

The EBI100C is designed to record the parameters associated with CO measurements. The EBI100C incorporates a precision high frequency current source, which injects a very small (100 µA rms or 400 µA rms) current through the measurement tissue volume defined by the placement of a set of current source electrodes. A separate set of monitoring electrodes then measures the voltage developed across the tissue volume. Because the current is constant, the voltage measured is proportional to the characteristics of the biological impedance of the tissue volume.

The EBI100C measures both impedance magnitude and dZ(t)/dt simultaneously. The EBI100C is capable of recording impedances at four different operational frequencies, from 12.5 kHz to 100 kHz. Usually, CO measurements are performed at a measurement frequency of either 50 kHz or 100 kHz.

Setup - *Amplifier Setup*

EBI100C as follows:

Magnitude Range:	5 Ohms/volt
LP-Magnitude:	10 Hz
HP-Magnitude:	DC
Frequency Select:	50 kHz
Channel Select:	MAG is Channel 1

ECG100C as follows:

Gain:	1000
Mode:	NORM
35HzLPN:	ON
HP:	0.5 Hz
Channel Select:	Channel 2

Although the heart rate can be calculated directly from the dZ(t)/dt waveform, it's often useful to record ECG directly. Use two LEAD110S electrode leads with EL503 electrodes. A Ground lead is not required, as the subject is referenced via the EBI100C module.

DA100C as follows:

Gain:	50
10Hz LP:	OFF
LP:	300 Hz
HP:	0.05 Hz
Channel Select:	Channel 3

It's important to provide a mechanism to determine the Left Ventricular Ejection Time (T). Using the TSD108 heart sounds microphone with the DA100 differential amplifier and by running a selective bandpass filter in Acq*Knowledge*, it's possible to record the aortic valve activity.

IMPORTANT NOTE

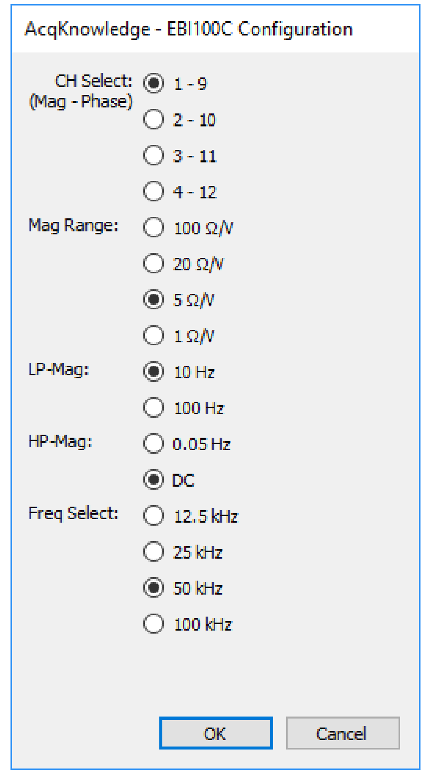
Do not connect the GROUND pin of the TSD108 to the DA100 module when using this transducer with the EBI100C module. Doing so will cause inaccurate impedance measures, because the TSD108 contact surface is tied to isolated ground. An alternative is to insulate the TSD108 from the skin surface by using a latex balloon or some other non-conductive barrier. If this latter procedure is followed, the GROUND pin may be attached to the DA100 module.

AcqKnowledge Setup

Setup Acquisition as follows:

Sample Rate: 1000 Hz

Setup Channels as follows:



Analog Channels: Acquired Channels: 1, 2, 3

Channel **1**: Z(t) from EBI100C module, with Scaling set as follows, (using EBI100C MAG range of 5 Ohms/volt):

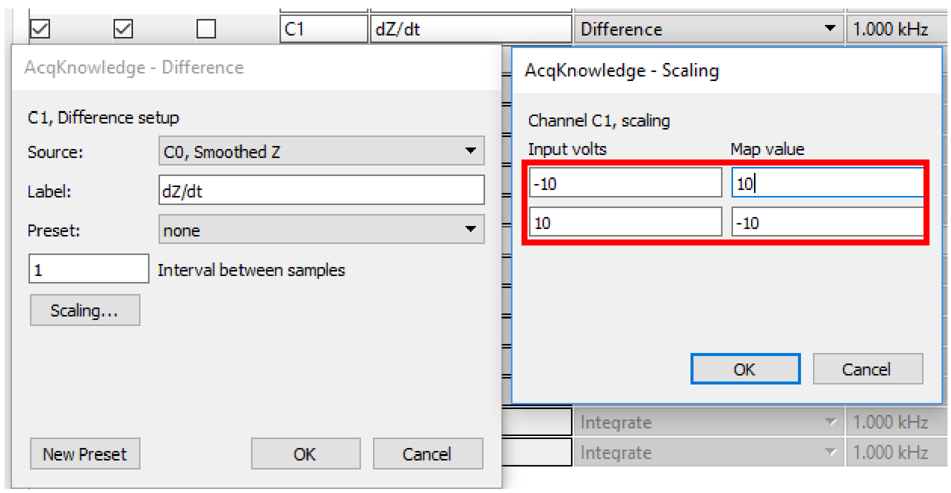
Channel **2**: ECG collected from ECG100C module

Channel **3**: Heart Sounds collected from TSD108 and DA100C module

Calculation channels:

Channel **C40**: Lowpass filter of Analog Channel 1 10 Hz, Q = 0.707 This filter on Z(t) cleans up any residual noise on the Z(t) waveform prior to differentiating. This filter is optional, depending on signal quality.

Channel **C41**: One sample difference of CO. This calculation performs a derivative on Z(t), resulting in dZ(t)/dt. This signal must be inverted before continuing. An easy way to do this is to click “Setup > Scaling” and reverse the signs of the numbers in one of the two columns (see below).



Channel **C42**: Bandpass filter of Analog Channel 3 at 40-60 Hz, Q= 0.707. This selective filter picks out the sounds created by heart valves.

Channel **C43**: Peak maximum, via Rate, source is C1. C1 result is $dZ(t)/dt_{(max)}$. This Rate calculation determines the cycle by cycle peak maximum

Channel **C48**: BPM, via Rate, determination on Analog Channel 2**.** This Rate calculation determines the cycle by cycle BPM of the ECG signal on Analog Channel 2.

The following two channels were created during post-processing.

Channel **4**: Calculate Stroke Volume using Transform > Expression:

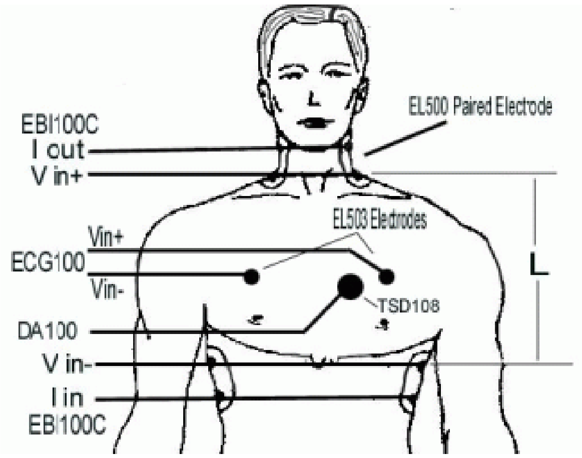
$$SV = R \times (L^2/Zo^2) \times T \times dZ(t)/dt_{(max)}$$

Channel **5**: Calculate Cardiac Output using the Transform Expression:

$$CO = SV \times HR$$

When using the EBI to measure CO use four of the CBL204 Touchproof “Y” electrode lead adapters and eight of the LEAD110 electrode leads connected to EL500 paired disposable electrodes.

As shown in the following diagram, the two top neck electrodes are connected to the “I Out” on the EBI100C. The bottom torso electrodes are connected to the “I In” on the EBI100C. The inner (upper and lower) sets of voltage sensing electrodes are connected to Vin+ and Vin- respectively.

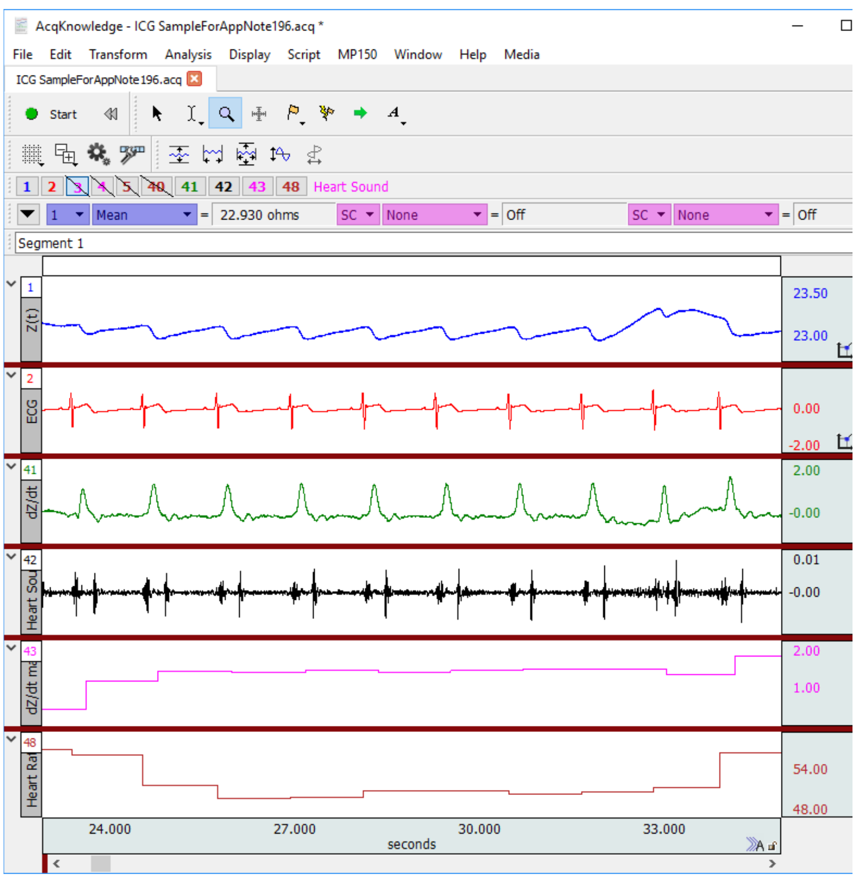


The distance “L” (measured in centimeters), is the vertical distance between the upper and lower sets of voltage sensing electrodes

Other connections for CO measurement include ECG electrode leads (shown by the EL503 electrodes) and the TSD108 heart sounds microphone to the DA100 differential amplifier. The TSD108 may require relocation to optimally detect the opening and closing of the aortic valve, for positive definition of the Left Ventricular Ejection Time (T).

In practice. There are many methods for the determination of (T). All of these methods are somewhat ambiguous, when one attempts to extract (T) from specific points on a waveform, whether using the phonocardiogram or the dZ(t)/dt waveform itself, or in concert with the electrocardiogram.

Following is data collected from a subject using the referenced setup procedure.

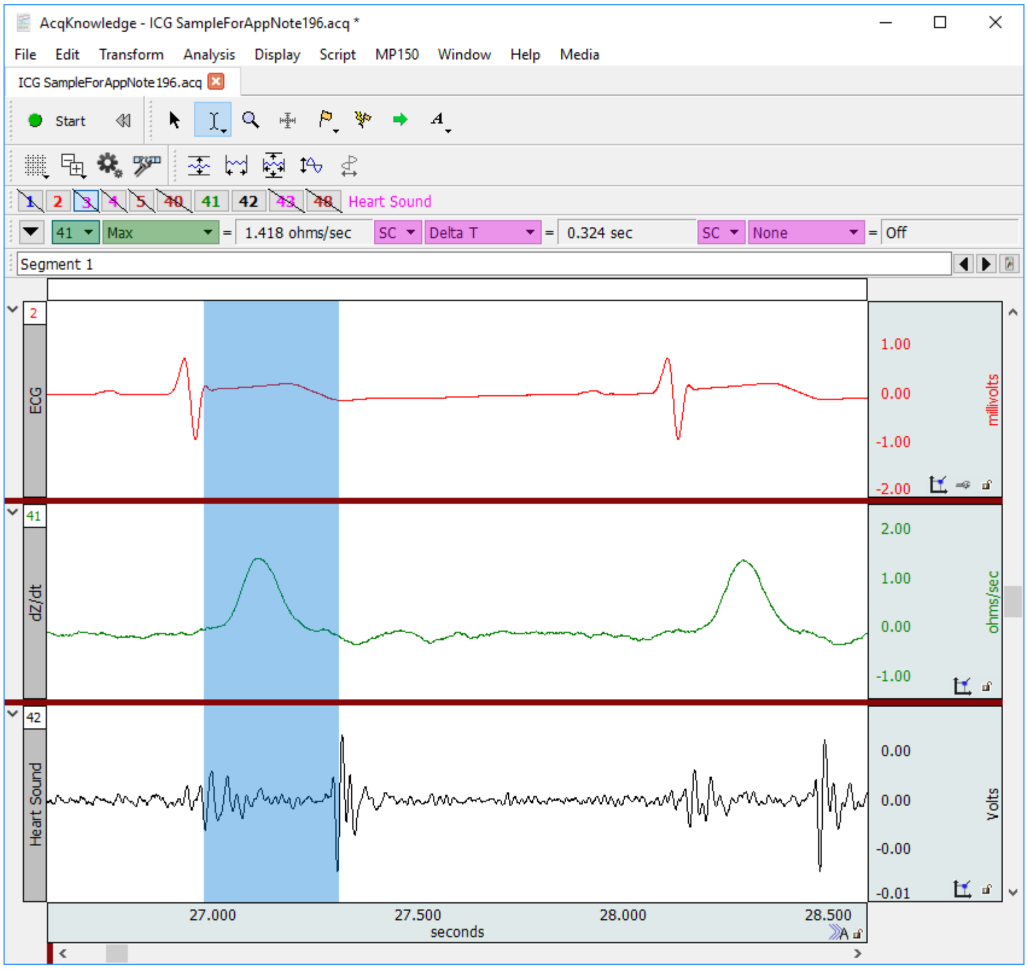


dZ(t)/dt$_{(max)}$ is shown fifth from top and is being determined on a cycle by cycle basis from the raw **dZ(t)/dt** waveform shown third from top.

Similarly, the heart rate in **BPM** shown at bottom is being derived from the raw **ECG** waveform in Channel 1, shown second from top.

Measuring Left Ventricular Ejection Time (T)

Sweep the Acq*Knowledge* cursor to bridge from peak to peak in the filtered (40-60 Hz) heart sounds graph. The delta t shown (0.324 seconds) indicates the time from aortic valve opening to closing.



IMPORTANT NOTE

Cardiac Output measures are relative and sensitive to electrode type, number and location. For example, band electrodes will generate different results than spot electrodes. By using two spot electrodes (for each lead/subject contact), results will more closely approximate band electrodes, than when using a single spot electrode for each lead/subject contact. By the same token, four spot electrodes (symmetrically circularly distributed for each lead/subject contact) will even more precisely emulate band electrode results.

If only relative measures of Cardiac Output are required, then single spot electrodes may be used for each lead/subject contact. If absolute measures of Cardiac Output are required, then it's extremely important to match the electrode configuration of the original equipment set-up.

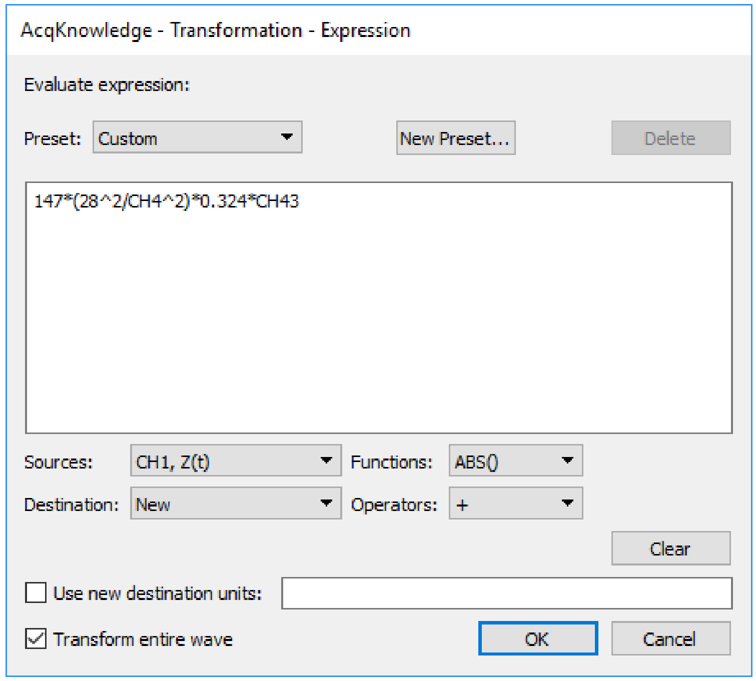
Stroke Volume

Offline Calculation Equation:

$$SV = R \times (L^2/Zo^2) \times T \times dZ(t)/dt_{(max)}$$

Where

R = 147 ohms x·cm (constant)
L = 28 cm (as measured above)
Zo = 28^2/CH40^2
T = .324 s (derived from LVET above)
$dZ(t)/dt_{(max)}$ = Ch43 (cycle by cycle peak max)



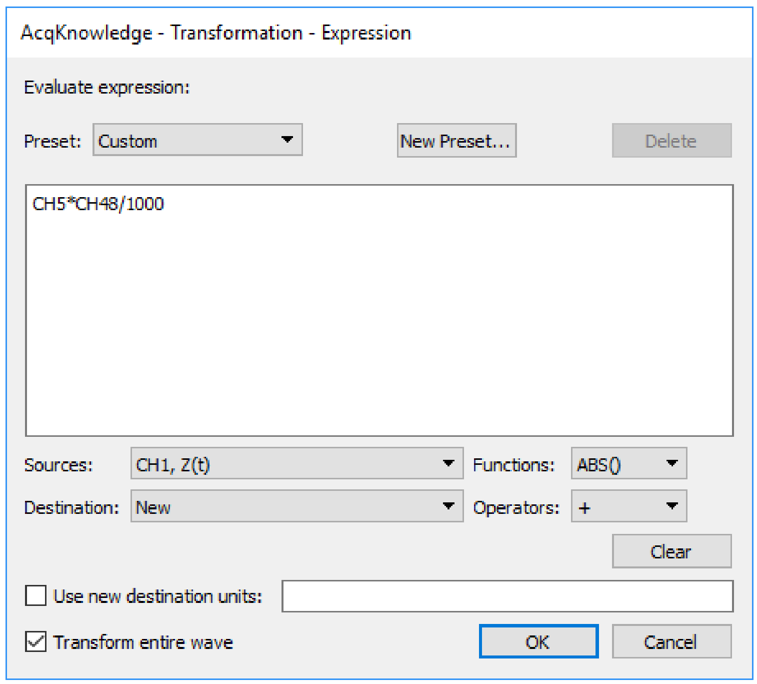
Cardiac Output

Now Calculate:

CO = SV x HR

CH5 = SV

C48= HR



1. For smoothed results, filter the Cardiac Output signal with an IIR filter set to 0.2 Hz low pass and a Q of 0.707.
2. To normalize for liters/minute, instead of ml/minute, divide the CO signal by 1000.

In the following graph, the Cardiac Output is 5.288 liters/min at 598.500 seconds into the recording. Note that the Stroke Volume varies between 72 and 114 ml (blood ejected from heart) for each beat during the time period shown.

Cardiac Output Related Statistics

Compiled from: *Impedance Cardiography: A Noninvasive Way to Monitor Hemodynamics*
Dimensions of Critical Care Nursing, Vol. 19, No. 3, May/June 2000

Zo	Base Thoracic Impedance	Males: 20-30 ohms, Females 25-35 ohms
dZ(t)/dt	Impedance Change	0.8 – 2.5 ohms/sec
T	Ventricular Ejection Time	0.25 – 0.35 seconds
PEP	Pre-ejection Period	0.05 – 0.12 seconds
SV	Stroke Volume	60-100 ml/beat
CO	Cardiac Output	4-8 liters/minute
CI	Cardiac Index	2.5-4.5 liters/min/ m^2 (indexed to body surface area)