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Application Note 215: Cardiac Output Measurement—Using NICO100C and LEAD130

NOTE: This app note references **LEAD130 four-clip cardiac output lead** and **EL506 strip electrodes**, which have been discontinued. The recommended replacement is EL500 spot electrodes x8 + LEAD1100C x8 + CBL204 Y-adapter x4 + MEC110C extension.

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 NICO100C module can be used to measure Z(t) and dZ/dt directly. In the case of Cardiac Output, delta Z is empirically determined to be:

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

Where:

T = Systolic [LVET] ejection time (seconds)
$dZ/dt_{(max)}$ = 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/dt is:

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

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 x HR

Where:

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

The NICO100C is designed to record the parameters associated with CO measurements. The NICO100C 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 NICO100C measures both impedance magnitude and dZ/dt simultaneously. The NICO100C 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

NICO100C as follows:

Magnitude Range:	5 Ohms/volt
LP-Magnitude:	100 Hz
HP-Magnitude:	DC
Frequency Select:	50 kHz
Channel Select:	Channels 1 - 9

ECG100 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/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 NICO100C 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

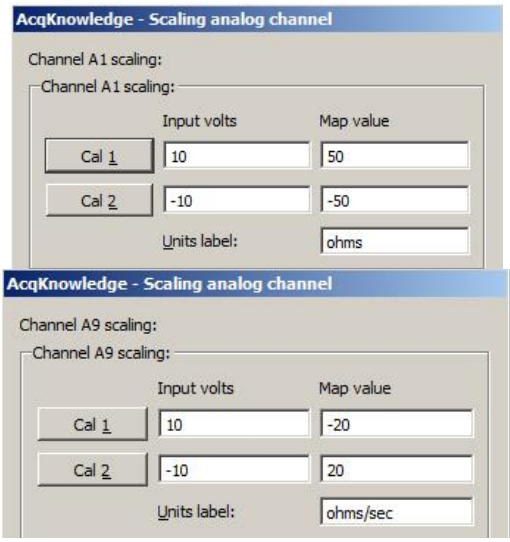
Do not connect the GROUND pin of the TSD108 to the DA100C module when using this transducer with the EBI100C module. Doing so will cause inaccurate impedance measures, because the TSD108 contact surface is tied to isolated ground. An alternative is to insulate the TSD108 from the skin surface by using a latex balloon or some other non-conductive barrier. If this latter procedure is followed, the GROUND pin may be attached to the DA100C module.

*Acq*Knowledge *Setup*

Setup Acquisition as follows:

Sample Rate: 1000 Hz

Setup Channels as follows:



Analog Channels: Acquired Channels:1, 2, 3, 9:

Channel **A1**: Z(t) from NICO100C module, with Scaling set as follows, (using NICO100C range of 5 Ohms/volt):

Channel **A2**: ECG collected from ECG100 module

Channel **A3**: Heart Sounds collected from TSD108 and DA100C module

Channel **A9**: dZ/dt from NICO100C module, with Scaling set as follows:

Calculation channels:

Channel **C0**: Bandpass filter of Channel A3 (Heart Sound) at 40 ï 60 Hz, Q = 0.707
This selective filter picks out the sounds created by heart valves.

Channel **C1**: Peak maximum, via Rate, source is Channel A9 (dZ/dt).
Result is $dZ/dt_{(max)}$ determined cycle by cycle.

Channel **C2**: BPM, via Rate, source is Channel **A2 (ECG)**. This Rate calculation determines the cycle by cycle BPM of the ECG signal on Channel 2.

The following two channels were created during post-processing, but they could easily have been calculated online.

Channel **4**: Calculate Stroke Volume using the Expression Evaluator:

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

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

$$CO = SV \times HR$$

Subject Setup

1. Connect four EL506 disposable strip electrodes to the subject as shown below.
2. Connect the LEAD130 (MECEBI1) as follows:

Color	Lead	EL506 Position
white	I+	Neck, top
red	V+	Neck, bottom
green	V-	Back, top
black	I-	back, bottom

3. Measure the distance ñLò(in centimeters) as the vertical distance between the upper and lower sets of voltage sensing electrodes.

Other connections for CO measurement include ECG electrode leads (use 2 EL503 electrodes on the chest) and the TSD108 heart sounds microphone to the DA100C differential amplifier. The ECG leads should be set as follows (no ground required):

Color	Lead	EL503 Position
white	vin -	right side of chest
red	vin +	left side of chest

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).

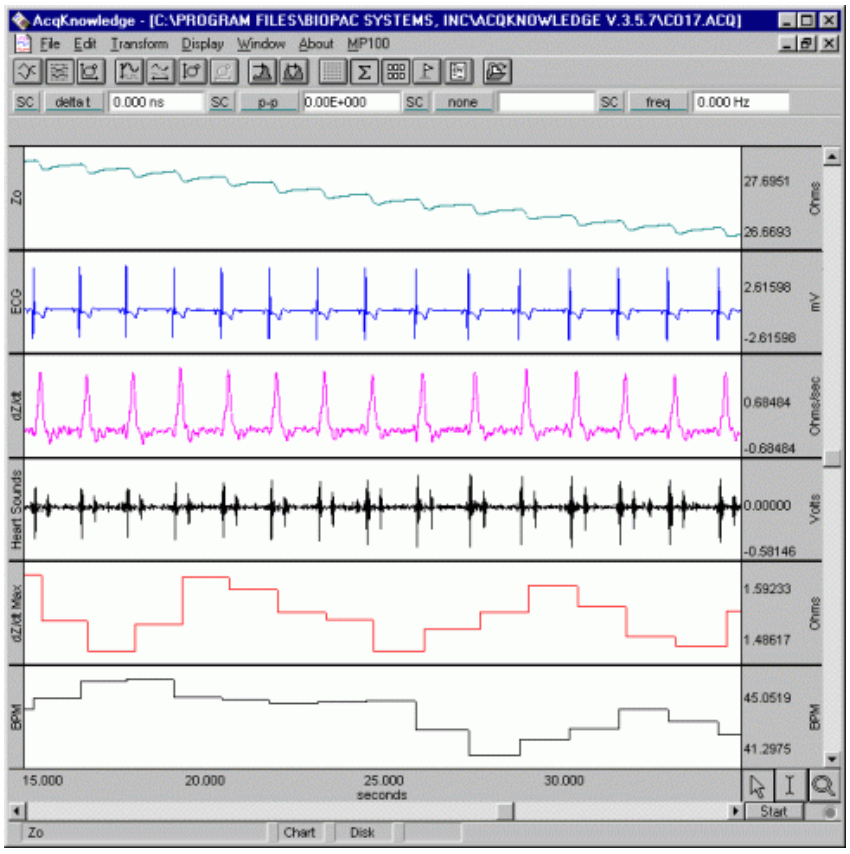
In practice, there are many methods for the determination of (T). All of these methods are somewhat ambiguous, when one attempts to extract (T) from specific points on a waveform, whether using the phonocardiogram or the dZ/dt waveform itself, or in concert with the electrocardiogram.

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 is extremely important to match the electrode configuration of the original equipment set-up.

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

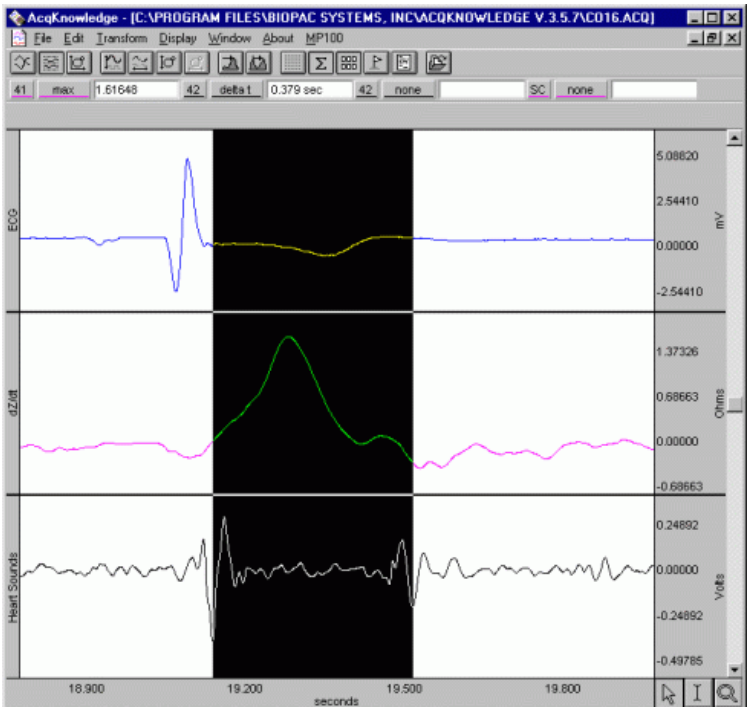


dZ/dt$_{(max)}$ is shown fifth from top and is being determined on a cycle by cycle basis from the raw **dZ/dt** waveform shown third from top.

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)

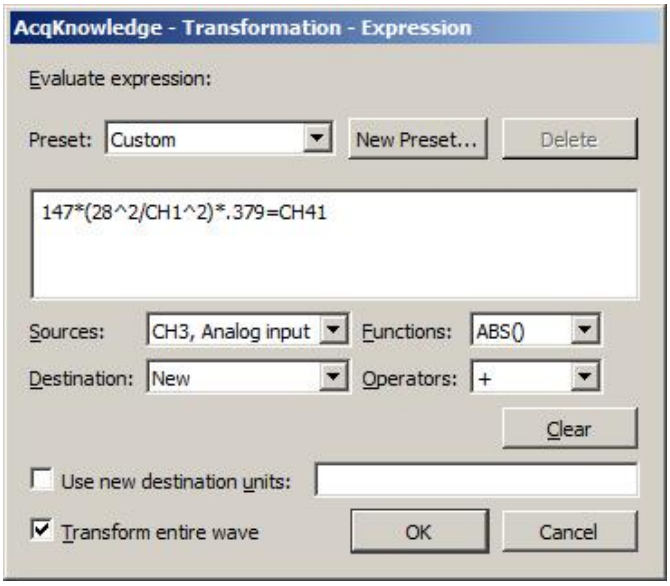
1. Sweep the Acq*Knowledge* cursor to bridge from peak to peak in the filtered (40-60 Hz) heart sounds graph. The delta t shown (0.379 seconds) indicates the time from aortic valve opening to closing.

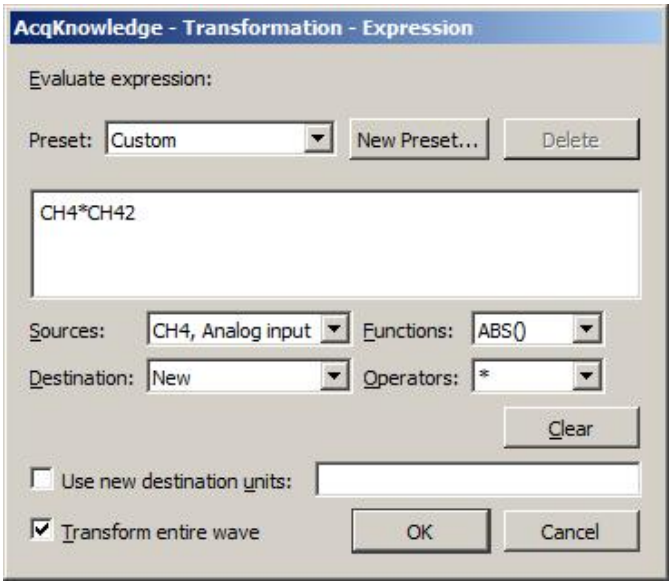


2. Use the Expression evaluator (under the Transform menu) to calculate stroke volume.

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

R = 147 ohms x·cm (constant)
L = 28 cm (as measured above)
Zo = Ch1
T = .379 s (derived from LVET above)
$dZ/dt_{(max)}$ = Ch41 (cycle by cycle peak maximum)





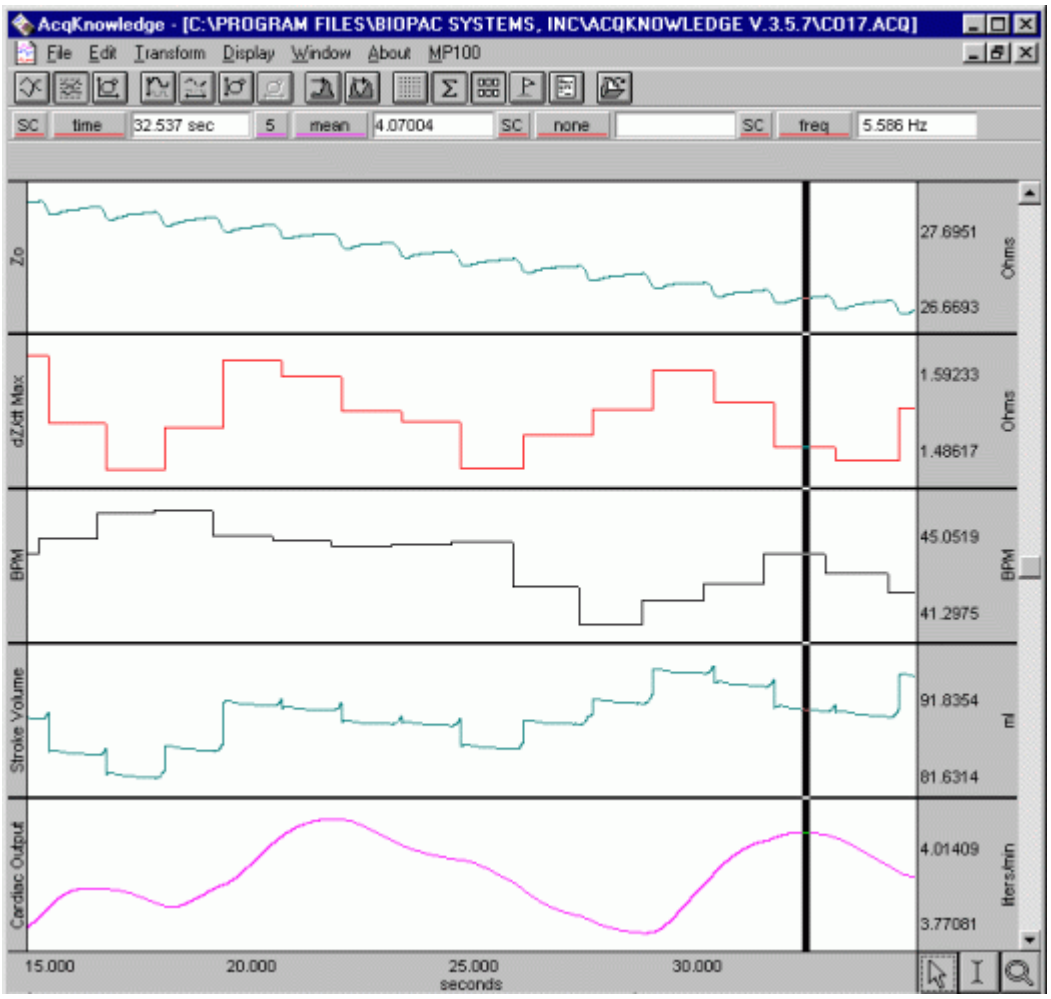
3. Use the Expression evaluator to calculate Cardiac Output, where CH 4 = SV and CH 42 = HR.

$$CO = SV \times HR$$

4. For smoothed results, filter the Cardiac Output signal with an IIR filter set to 0.2 Hz high pass and a Q of 0.707.

5. To normalize for liters/minute, instead of ml/minute, divide the CO signal by 1000.

In the following graph, the Cardiac Output is 4.07 liters/min at 32.537 seconds into the recording. Note that the Stroke Volume varies between 80 and 95 ml (blood ejected from heart) for each beat during the time period shown.



Cardiac Output is 4.07 liters/min at 32.537 seconds into the recording. Note that the Stroke Volume varies between 80 and 95 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/dt	Impedance Change	0.8 ï 2.5 ohms/sec
T	Ventricular Ejection Time	0.25 ï 0.35 seconds
PEP	Pre-ejection Period	0.05 ï 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/ m² (indexed to body surface area)