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Non-Invasive Assessment of Cardiac Contractility on a Weighing Scale

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Abstract— **Myocardial contractility, the intrinsic ability of the heart muscle to produce force, has been difficult to quantify non-invasively. Pre-ejection-period (PEP), the time the ventricles spend in isovolumetric contraction, is widely accepted as a way to measure contractility. This work presents a way by which the ballistocardiogram—a readily accessible non-invasive cardiovascular signal—can be used in tandem with the electrocardiogram to obtain a parameter highly correlated to PEP and thus to myocardial contractility. This parameter is the delay from the electrocardiogram R-wave to the peak (the J-wave) of the ballistocardiogram. In this work, we showed that this delay, the RJ interval, was correlated to PEP ($r^2 = 0.75$) for 709 heartbeats across 4 subjects, with a slope of 1.11, and a y-intercept of 151 ms. This suggests that the RJ interval can be used in place of the PEP for a reliable, practical, and non-invasive assessment of myocardial contractility.**

I. INTRODUCTION

In 2005, L.H. Opie succinctly described myocardial contractility: "[it] is the inherent capacity of the myocardium to contract independently of changes in the preload or afterload. Whatever the problems of measuring it, contractility remains an essential corner concept to separate the effects of a primary change in loading conditions from an intrinsic change in the force of contraction" [1]. The difficulty in measuring contractility arises from the fact that ultimately, this intrinsic "effectiveness" of the heart muscle comes down to one main parameter: intracellular calcium. While excellent *in vitro* work has been done in directly correlating calcium concentration to force produced by a single or few myofibrils [2], correlating calcium levels in the whole heart to overall myocardial force is much more difficult.

Instead of calcium concentration, clinicians have a few, mainly invasive, methods to assess contractility. One method, the maximum derivative of left ventricular pressure with respect to time, has been shown to be highly indicative of contractility [3], but can only be obtained invasively using a pressure catheter. Another method, which involves looking at one of a few systolic time intervals [4], has the advantage that some of these time intervals can be obtained non-invasively. One in particular, the pre-ejection period (PEP) has been shown to be strongly indicative of contractility, and can be measured non-invasively by impedance cardiography (ICG) [5]. As shown in figure 1, the PEP is measured from the Q-wave of the ECG to the B-wave of the ICG (dz/dt). Intuitively, the PEP is often described as the duration of ventricular isovolumetric contraction.

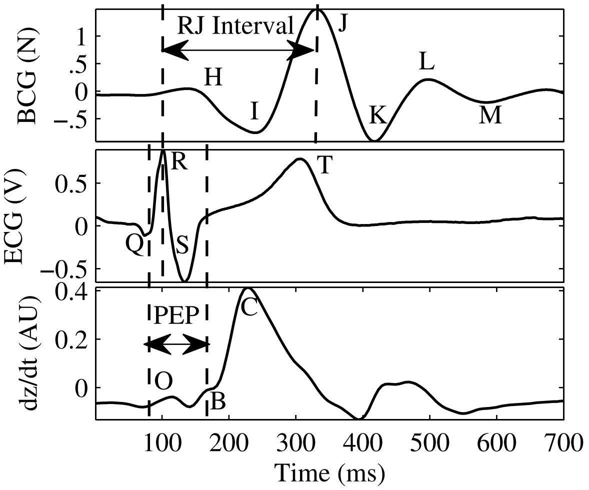

Fig. 1. Ensemble average ECG, BCG, and ICG. RJ interval and PEP are depicted.

In this work, we show how another non-invasive cardiovascular signal, the ballistocardiogram (BCG), can be used to assess contractility. The ballistocardiogram, the time varying component of a person's body weight as the body experiences a reaction force to the cardiac ejection of blood, is highly representative of the mechanical output of the heart [6]. The J-wave of the BCG signal, representing the maximum impulse exerted by the cardiovascular system on the body, is thought to occur just after isovolumetric contraction, as the blood rushes from the left ventricle into the aortic arch [6]. We hypothesized that the time interval between the R-wave of the ECG and the J-wave of the BCG, the RJ interval, is correlated to the PEP and thus can be used as an assessment of myocardial contractility. This interval is also depicted in figure 1.

To test our hypothesis, we obtained a BCG by having subjects stand on a bathroom scale. As described in previous work [7], the time varying body weight change is detected by the strain gauges in the scale. The results shown in this work are not specific to the bathroom scale method—supine and seated BCG methods could also be employed. The Valsalva maneuver was used as a non-invasive way to modulate contractility [8], thus providing us with a range of RJ intervals and PEPs across which correlation could be tested. Details of the measurement techniques and experimental setup appear in Methods below.

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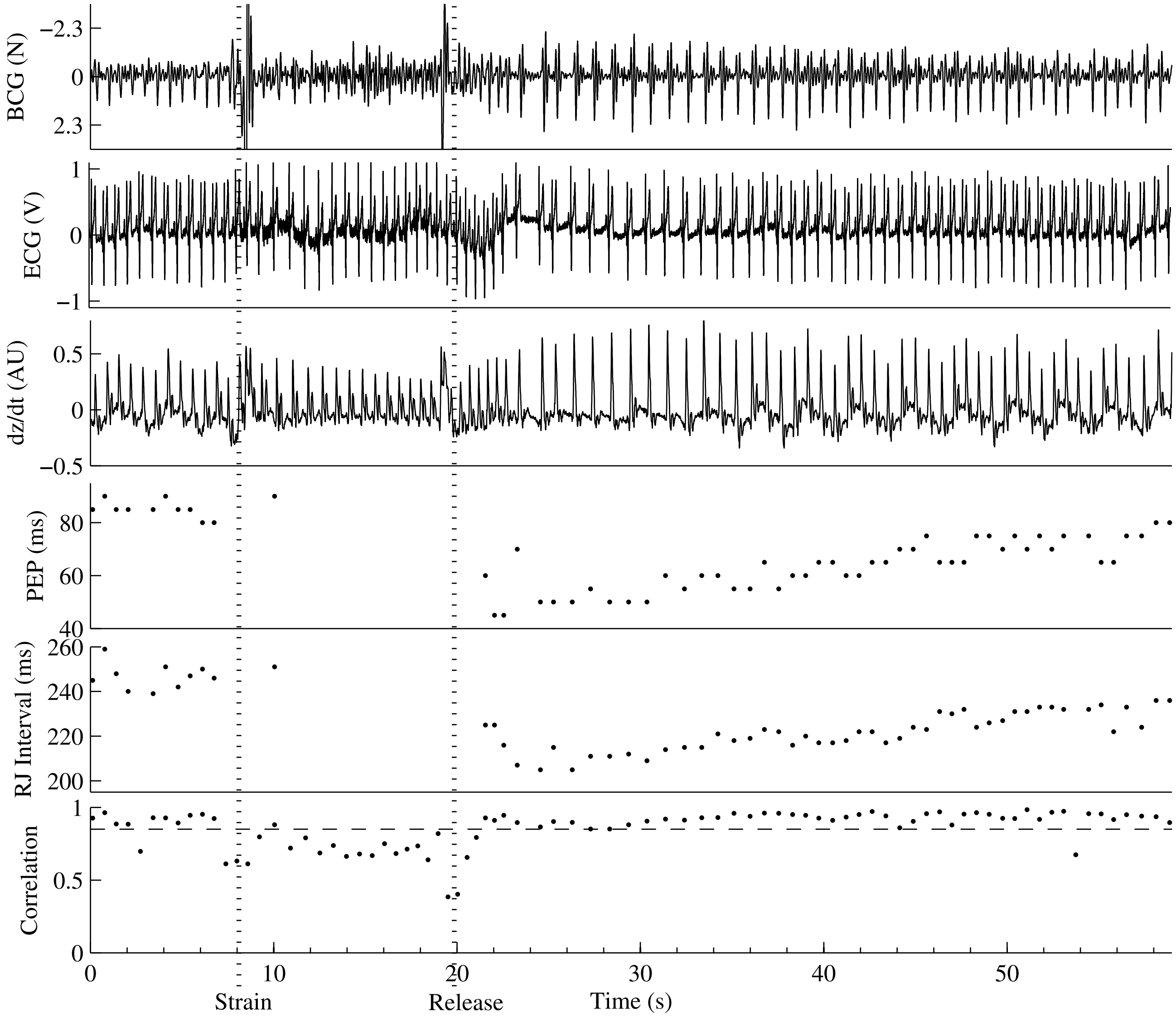

Fig. 2. The top three panels show sample a BCG, ECG, and ICG from subject 1. The next two panels show time series of the PEP and RJ interval. Note the blank space in these time series during the strain of the Valsalva, when either the BCG or ICG was too noisy to obtain a valid reading. This is depicted in the final time series, which is the cross-correlation of the BCG ensemble average with each BCG beat. Beats whose correlation was less than 0.85 (the horizontal dashed line) were automatically discarded.

However the BCG is recorded, we maintain that acquiring it is far less burdensome than acquiring an ICG. Typical ICG systems are quite costly and require eight electrodes to be placed on the body in a precise manner, necessitating a trained professional to be present not only during placement but during use to insure that all electrodes remain in place. The BCG, while it is far from providing the diagnostic breadth of the ICG, is very low cost, requires no electrodes, and can be acquired "passively" by a chair or bed. This practicality largely motivated this study.

II. METHODS

A. Experimental Setup

Four male subjects (see table I) participated in this Stanford IRB approved trial (Protocol 6503). Each subject was instructed to stand as still as possible upon the scale for sixty seconds as all the signals were recorded. Each subject was then instructed to perform the Valsalva maneuver. After the strain period of the Valsalva, which was for as long as the subject felt comfortable (about 10-15 seconds), each subject was again instructed to stand as still as possible for about two minutes as they recovered from the strain. The following subsections give more details about electrode placement and the recording process.

B. BCG Measurement System

The BCG measurement platform was the same as that described in previous work [7]. Briefly, a home bathroom scale (BC-534, Tanita, Tokyo, Japan) was modified with custom circuit which recorded the BCG as a force on the strain gauges in the scale. The BCG output from this circuit

TABLE I

CORRELATION SUMMARY

Subject	Age	Ht. (cm)	Wt. (kg)	r^2	Slope	y-intercept
1	22	165	61	0.78	0.907	165
2	37	182	70	0.66	1.06	151
3	26	175	63	0.79	1.11	155
4	24	178	77	0.76	0.74	174

was sampled by a National Instruments data acquisition card (16-bits, ±5V, 1kHz sample rate). An ECG, obtained using a similar custom circuit described in [7], was also acquired simultaneously by the same data acquisition system. Three ECG electrodes were placed on the subject in standard Lead II configuration.

C. ICG Measurement System

A commercially available impedance cardiograph (Niccomo, Medis GmbH, Ilmenau, Germany) was used to record the ICG signal. This particular model automatically determines the PEP for each beat, and records this information along with both a raw ICG signal as well as an ECG. It is important to note that the Niccomo has a time resolution of five milliseconds, that is, the PEP given is a multiple of 5 ms.

Per the system instructions, eight electrodes were placed on the subject. Four electrodes were placed along the sides of the neck, two on each side, separated vertically by 3 cm. The remaining four were placed along the sides of the torso, two on each side. The first on each side was placed lateral to the xiphisternum, with the other placed 3 cm below it.

D. Synchronization of Recordings

From the above, the reader will note that two ECGs were recorded simultaneously—one sampled by our own data acquisition system and the other sampled by the Niccomo. Motion artifact was intentionally introduced to the start and end of both ECGs by having the operator tap five times on one electrode of each recording system. This intentional motion artifact allowed us to synchronize the time base of each recording system.

E. Digital Signal Processing and Feature Extraction

The ECG from our circuit was digitally band-passed from 10 Hz to 30 Hz to isolate the R-waves, which were then detected using a simple thresholding algorithm. The timing of these R-waves was used to divide the BCG signal up into beats, each beginning 100 ms prior to the R-wave and ending 600 ms after. These beats were ensemble averaged, obtaining the best estimate of a BCG beat. This 700 ms long "best estimate beat" was cross correlated with each of the BCG beats segmented earlier. Prior to cross-correlation, the beats were normalized such that the first tap of their autocorrelation function was unity, as described in [9].

Those beats that had less than a 0.85 cross-correlation maximum were deemed unacceptable for J-wave extraction. During the strain period of the Valsalva maneuver, most subjects found it difficult to stand still on the scale, resulting in a noisy BCG during that period. This 0.85 correlation threshold was necessary to avoid BCG beats that were corrupted by the motion artifact during strain. This threshold value was the same across all subjects, and was chosen conservatively by manual examination of the data.

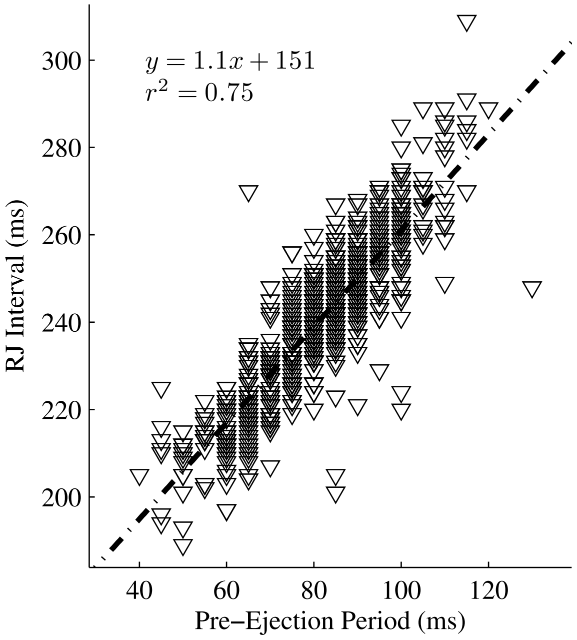

Fig. 3. RJ interval vs. PEP for 709 beats total across 4 subjects.

The maximum value of each beat that surpassed the threshold was taken to be the J-wave peak. The difference in time index between the J wave and the R wave for each beat was the RJ interval for that beat. The reader should note that once a threshold was selected, this was an entirely data-driven process—the RJ interval was only considered valid for beats that were well correlated to the ensemble average.

Since the time base of the BCG signal was synchronized to that of the Niccomo as described earlier, the PEP values recorded by the Niccomo could easily be matched to the RJ interval recorded at the exact same heartbeat. The Niccomo automatically rejects noisy beats and thus could not provide a PEP for all of the beats for which we had an RJ interval (and vice versa). Thus, only the beats in which both the Niccomo and our system had a measurement were considered. As the results show, in recordings of only a few minutes in duration, many hundreds of beats met this criteria.

III. RESULTS

A. Example Time Traces

Example ECG, BCG, and ICG time traces are shown in figure 2 to demonstrate the general trends observed from the four subjects. A time-series plot of the PEP and RJ interval is also shown. Finally, the bottom panel shows a time-series of the cross-correlation between the BCG ensemble average and each BCG beat. The reader should note that, as mentioned in section II-E, the correlation dips significantly below the 0.85 threshold during the strain period of the Valsalva, contributing to most of the missed beats whose RJ intervals could not be matched to PEPs recorded from the Niccomo.

B. Correlation of PEP and RJ Interval

Figure 3 depicts the correlation in PEP and RJ interval for every beat from all subjects that both a PEP and RJ interval could be obtained. Across all 4 subjects, values from 709 beats were correlated. The reader should note the 5 ms quantization of PEP due to the limitations of the Niccomo discussed earlier.

Table I summarizes the correlation coefficients, slopes, and *y*-intercepts of this same data, but separated by subject.

IV. DISCUSSION AND FUTURE WORK

The results strongly support our hypothesis: the PEP is well correlated to the RJ interval. This suggests that the ballistocardiogram can be used to interrogate the contractile state of the heart. Since it is entirely non-invasive and only requires a simple ECG showing the R-waves, we believe the RJ interval based measurement to be one of the most versatile methods available for determining contractility.

Three final points stand out most from the results. First, it would appear as if the 5 ms quantization introduced by the Niccomo is artificially limiting the correlation. This is readily seen in figure 3, where points are heavily "bunched" along the *x*-axis. Future work will focus on using a custom ICG system (or interpolating the Niccomo signal) to achieve a higher time resolution PEP to more closely match the resolution achieved by the RJ interval.

Second, the strain phase, typically associated with longer PEPs, was underrepresented in the correlation analysis due to the higher noise and the associated difficulty of extracting reliable RJ intervals. Despite this, the RJ interval shows a remarkable correlation within the observed range, and future work will focus on using more robust extraction methods and alternate, non-standing methods of acquiring the BCG.

The final point of interest is that the RJ interval, while strongly correlated to PEP, is over 100 ms longer, leading to the non-zero *y*-intercept in figure 3. This is likely due to the mechanical delay introduced by the body and the scale. It's interesting that the *y*-intercepts decrease monotonically with age. While a higher *N* is needed for statistical significance, this suggests that perhaps the changing compliance of the aorta with age decreases the propagation time of the impulse to the feet. The slope, however, remains close to unity, suggesting that this delay is constant for each person and can readily be accounted for. Future work will characterize this delay, perhaps relating it to physical and demographic parameters. Finally, the *N* of four subjects will certainly be increased to enhance the significance of all the above results.

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