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Digital Signal Processing of the Wideband External Pulse Recorded During Cuff Deflation: a New Way to Measure Blood Pressure

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***Abstract*—A new method of measuring blood pressure (BP) is presented. This technique involves automatic analysis of the wideband external pulse (WEP) recorded by a pressure sensor positioned over the brachial artery during standard BP cuff deflation. Three distinct components of this "K" or "WEP" signal can be defined: K1, K2, and K3 [1]. Each component has a different shape and "appearance/disappearance" property. K1 is a low frequency inaudible signal present with cuff pressure above systolic. The K2 signal appears at SP and disappears at DP (K2-algorithm) and can be used to measure BP. Using this property, the "K2-algorithm" has been shown to be more accurate than the auscultatory technique [1]. To implement an automatic measurement using the K2-algorithm, signal processing techniques are applied to K signals.**

I. Introduction

An elevated blood pressure (BP) is a major public health issue affecting approximately 1/3 of the American population (over 65 million people). Hypertension is a major risk factor for cardiovascular disease [2]. An accurate measure of blood pressure is essential to adequately evaluate and treat those at-risk. Even minor errors in measurement can misclassify millions of persons [3].

In 1969, Whitcher [4] was the first to emphasize that the signal recorded under a blood pressure cuff was a function of the frequency response characteristic of the sensor-amplifier used. Analysis of the "wideband external pulse" (WEP) signal is based on the ability of a pressure sensor (positioned over the brachial artery) to record inaudible frequencies (down to .1 Hz) during BP cuff deflation (Figure 1). Three distinct components of the WEP signal, called K1, K2 and K3, can be detected. K1 is a low frequency, inaudible signal which is present with cuff pressure (CP) above systolic pressure (SP). K2 is a triphasic signal appearing at SP and disappearing at diastolic pressure (DP) which approximately corresponds to the audible Korotkoff sound. K3 appears with cuff pressure between systolic and diastolic pressure and continues to be present below diastolic pressure.

The appearance/disappearance property of K2 signal was designated as the "K2 algorithm" and represents a new, objective noninvasive measurement of BP. The "K2 algorithm" is more accurate than the auscultatory technique, and may be especially useful in clinical situations in which the auscultatory technique does not work well [1]. Recording materials and methods have been described previously [1].

The K2 algorithm is a visual method of BP measurement. In order to produce an instrument based on this technique, an automatic way of detecting the appearance and disappearance of K2 must be developed. That is the purpose of this report.

II. Measuring BP Using an External Sensor

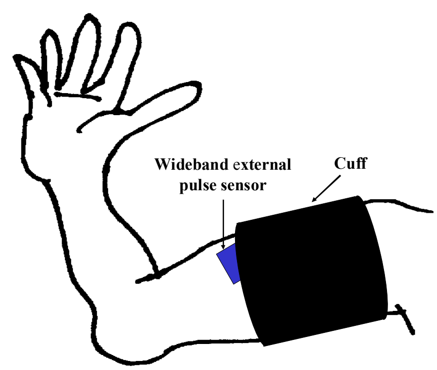

Fig. 1 Measuring BP using wideband external sensor during cuff deflation.

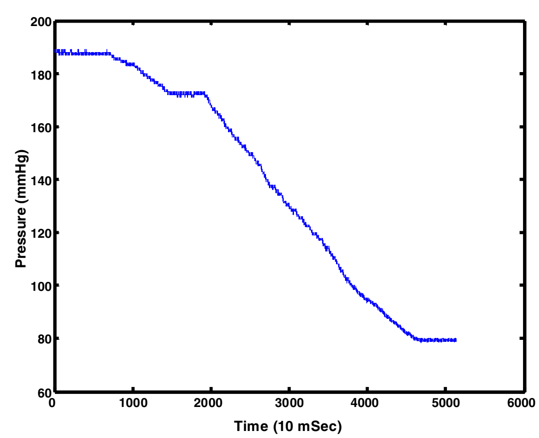

Fig 2. Cuff pressure (mmHg) vs. time

Figure 2 shows the cuff pressure (CP) being deflated while measuring BP. This is a relatively linear function of time. We inflate cuff pressure up to 180mmHg and deflate to below DP. Total duration of CP deflation from 180 to 80 mmHg is about 52 seconds.

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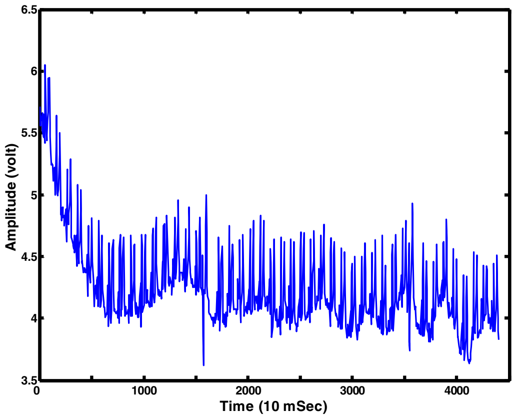

Fig. 3 Amplitude vs. time of pulse signal from ECG.

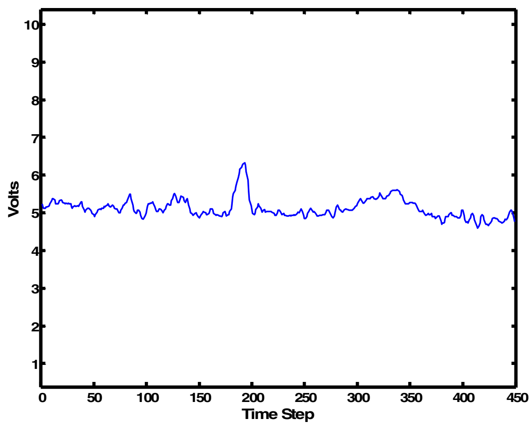

Fig. 4 a single ECG pulse (Time Step in mSec)

Figure 3 shows ECG signals coming from source; heart and figure 4 is single ECG pulse for one cardiac cycle. The amplitude of it is voltage and a cycle's period is about 1second.

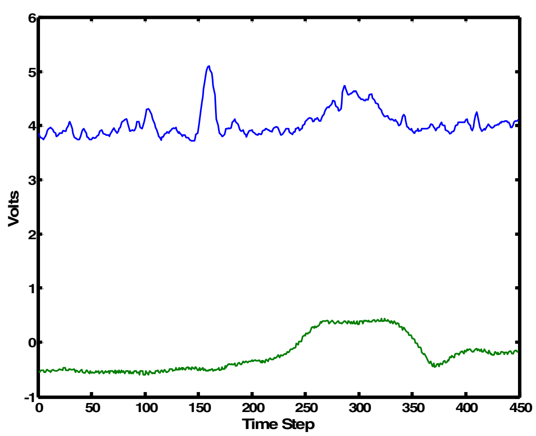

Fig. 5 Single ECG pulse and its corresponding K-Signal (Time Step in mSec)

Between a ECG pulse and its corresponding K-signal, there exists time delay shown in Figure 5, which is related to traveling time of the pulse wave from the heart to the WEP sensor. The K1 signal is seen here because the CP is greater than SP.

III. K-SIGNALS

In this section, we address K signals (i.e., WEP signals) measured with the wideband sensor during CP deflation in detail.

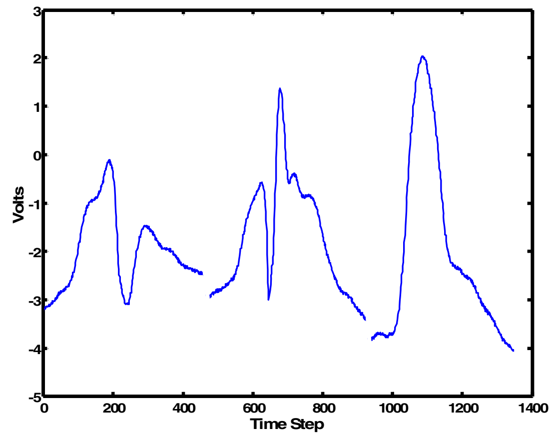

Fig. 6 K1, K1&K2, and K3 signals from left to right in mSec CP>SP, CP=<SP, and CP=<DP (Time Step in mSec)

TABLE 1. APPEARANCE/DISAPPEARANCE OF K SIGNALS.

CP	CP>SP	CP=SP	SP>CP>DP	CP=DP	DP>CP
K	K1	K1+K2	K1+K2+K3	K3	K3

As mentioned above and reference [1], K signals are divided into three different signals, K1, K2, and K3. In figure 6, three different signals shown: K1, K1+K2, and K3 are shown as examples. Table 1 explains relationship of K-signals to CP.

IV. DIFFERENTIATION OF K-SIGNALS

We approach one basic mathematical processing step; differentiation ($\frac{d}{dt}$) to analyze the K-signals. The purpose of differentiation is to find the gradient of the two adjacent data points depending on the step size where K2 is supposed to have a highest point.

In Matlab,

$$Y = \text{diff}(X) \quad (1)$$

$$Y = \text{diff}(X,n) \quad (2)$$

N represents *n*-th order differentiation. Y = diff(X) calculates differences between adjacent elements of X. If X is a vector, then diff(X) returns a vector, one element shorter than X, of differences between adjacent elements [6]:

$$[X(2)-X(1)\ X(3)-X(2)\ ...\ X(n)-X(n-1)] \quad (3)$$

If X is a matrix,diff(X) returns a matrix of row differences:

$$[X(2:m,:)-X(1:m-1,:)] \quad (4)$$

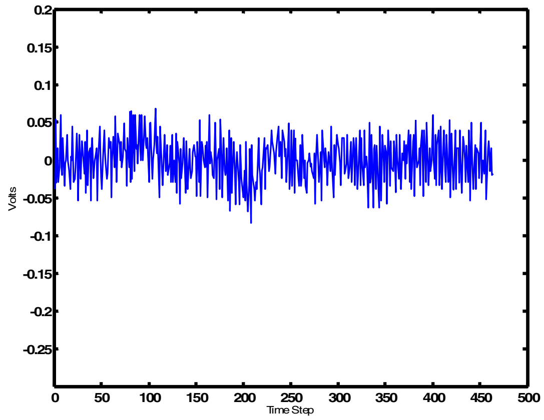

Fig. 7 Differentiated value of K1-signal (Time Step in mSec)

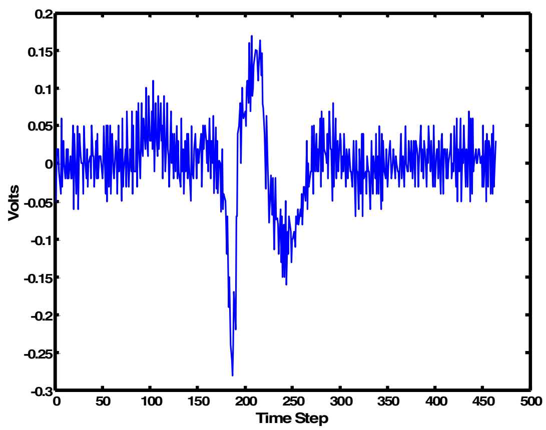

Fig. 8 Differentiated value of K2-signal (Time Step in mSec).

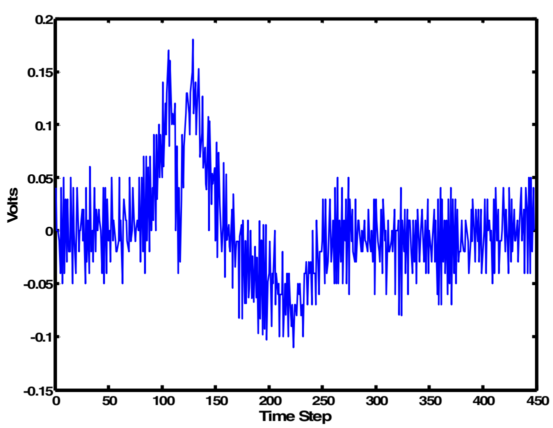

Fig. 9 Differentiated value of K3-signal (Time Step in mSec).

Figures 7, 8, and 9 show the differentiated values of K1, K1+K2, and K3 signals. Even though visually different shapes help us tell SP from DP, processed data are not sophisticated enough for implementing an automatic way of measuring BP. In the BP measurement, there are usually 40~50 pulses of each ECG and K-signals. In the next section, each differentiated K-signal will be processed with a user defined process called MINMAX.

V. MINMAX VALUE OF K-SIGNALS

MINMAX determined the minimum and the maximum values of any applied signal. In this particular application, MINMAX provides the minimum and maximum values of the differentiated K signal associated with a particular cardiac cycle.

With K representing the K signals and I representing the i-th cardiac pulse,

$$MAX_i = \max(\frac{d}{dt}K_i) \tag{5}$$

$$MIN_i = \min(\frac{d}{dt}K_i) \tag{6}$$

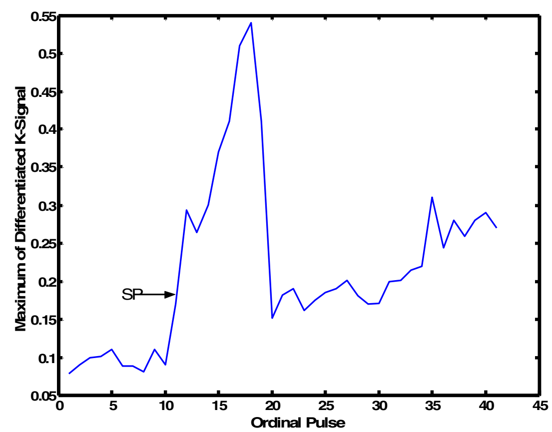

Fig. 10 An example: maximum value of whole differentiated values.

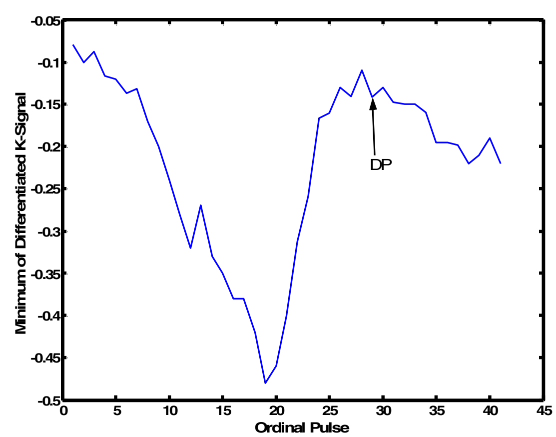

Fig. 11 An example: minimum value of whole differentiated values.

If we know the cardiac cycle, its corresponding differentiated K-signal and MINMAX processed signal, we can match SP with the maximum value and DP with the minimum value. As shown in Figure 10, the 11th pulse is matched with SP and its maximum value is approximately 0.17. Figure 11 shows that the DP is the 30th pulse and its value is -0.16.

VI. THRESHOLD FOR STANDARD

This algorithm was applied to the different subjects. Each subject represents a different data set. SP and DP of different data sets could be easily determined using different K2 signals an MINMAX values. This is shown in Figures 12 and 13.

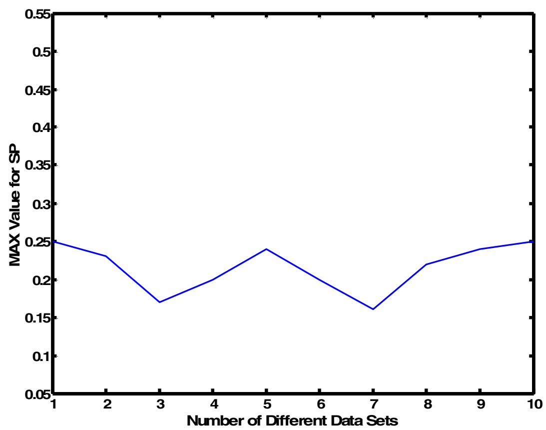

Fig. 12 Statistics: maximum values at its SP.

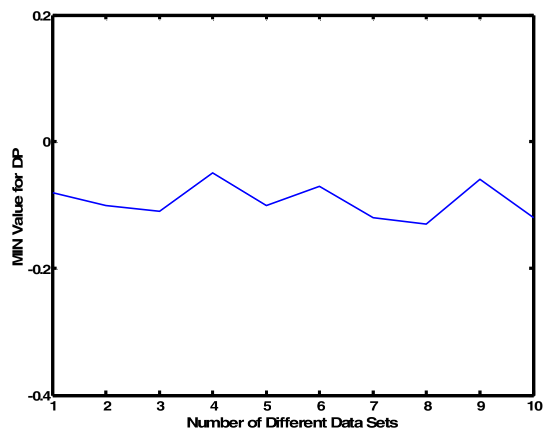

Fig. 13 Statistics: maximum values at its SP.

In Figure 12, maximum value for SP is in the range of 0.15 and 0.25, and for DP its value is between -0.05 and -0.15.

TABLE 2 THRESHOLD FOR SP.

BP	CP>SP	CP=SP	CP<SP	PEAK
MAX	↑	0.15~0.25	↑	→

TABLE 3 THRESHOLD FOR DP

BP	CP>SP	VALLEY	CP>SP	CP=DP	CP<DP
MIN	↓	→	↑	-0.05~ -0.15	→

Tables 2 and 3 refer to Figures 10 and 11. Arrows in these tables indicate the pattern of the data. The data can be increasing (↑), decreasing (↓) or reaching a peak (→) or valley (→). How to define and tune the threshold values is a critical issue. In this paper, we defined SP to be the first cardiac cycle in which the differentiated K signal fell into the threshold range (defined above). We defined DP to be the first decreasing MINMAX value of the differentiated K signals of the valley as seen in Figure 11.

VII. CONCLUSION

The "K2-algorithm," which has been shown to be more accurate than the auscultatory technique (using detection of Korotkoff sounds), is dependent on time-domain visual analysis of the WEP signal. In order to develop an instrument, an autoimatic way of determining the BP is necessary. In this paper, the authors suggest a new automatic BP measurement method using digital signal processing of the wideband "K-signal."

VIII. BLOCK DIAGRAM

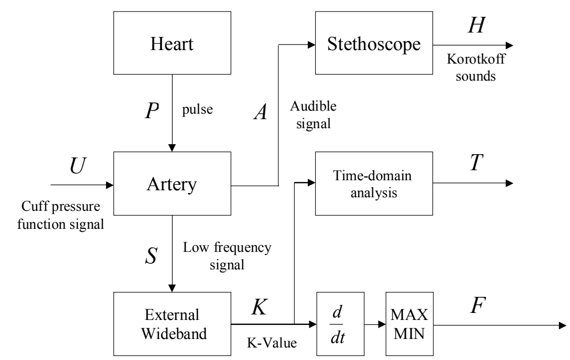

Fig. 14 Block diagram of measuring blood pressure.

P: Pulse signal from heart to artery.
U: Cuff pressure function of time t.
S: ECG Signal.
A: Audible sound signal.
H: Korotkoff sound signal.
T: unprocessed time domain signals.
K: K-Signals.
F: processed signals in a suggested method.

In Figure 14, we suggest a block diagram of detecting BP with wideband external pulse recording sensor and compare other methods: using audible sound and stethoscope.

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