

# Unipolar Cardiac Leads Between History and Science



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**Abstract** The surface electrocardiography (ECG) uses a virtual reference point to measure the potential of chest electrodes. This reference potential is known as *Wilson central terminal (WCT)* and is assumed negligible (near zero) in amplitude. Consequently, the precordial leads have been named as the *unipolar leads*. Although this assumption was found incorrect immediately after this reference potential was introduced, it was difficult to measure its real amplitude. We recently introduced a 15-lead electrocardiography device that can record the traditional ECG leads in combination with the raw potential of limbs and chest electrodes directly referred to the circuit grounding. Consequently, we are able to record the potential of the raw chest electrodes, which we named as *true unipolar chest leads*. The aim of this study is to have

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a clear understanding of the WCT potential and its influence on the chest leads. Our records show that the true unipolar leads may be more sensitive for detecting cardiac diseases in the left anterior descending coronary artery in patients with non-ST elevation reported on chest leads.

**Keywords** Electrocardiography · Wilson central terminal · Unipolar leads · Limb potential · Left anterior descending · Electrocardiography database

## 1 Introduction

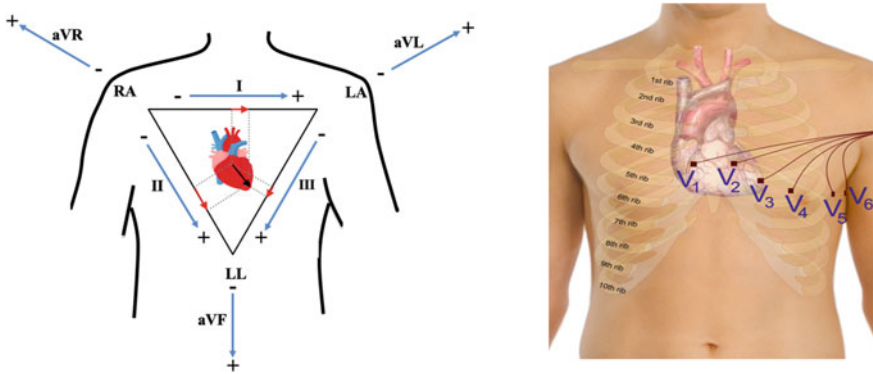
The heart impresses an electrical current that flows from the heart through the limbs, which can be used for examining the cardiac function [1, 2]. First, Waller used two electrodes on the body and found changes in electrometer by heartbeat [3, 4]. He applied electrodes on limbs to show the electrical activity of the heart. However, Einthoven made a major breakthrough in Electrocardiography by using the string galvanometer in 1901 [4]. He used a silver-coated quartz filament (or string) in a strong magnetic field to measure the strength and direction of the *current* of the heart [5]. The string was moved in the magnetic field when the current of the heart moved through it [5]. The Einthoven's device was very bulky and far from the hospital, hence, he used the telephone wire to receive the patients' heart impulse from the hospital [2, 5]. Later, Einthoven introduced the mathematics relations between three limb leads, which has been known as *Einthoven Triangle* hypothesis [6]. The vertices of the Einthoven Triangle are electrodes placed on the right hand, left hand, and left leg which are used to measure the limb leads, known as the lead I, lead II, and lead III [4, 6]. In this theory, the human body is characterized as a two dimensional, homogeneous conductor and part of infinity with the heart located in the centroid of the triangle [2, 4].

$$\begin{aligned}\text{Lead I} &= \Phi_L - \Phi_R \\ \text{Lead II} &= \Phi_F - \Phi_R \\ \text{Lead III} &= \Phi_F - \Phi_L\end{aligned}\tag{1}$$

As the three limb leads to construct a closed loop (Fig. 1), the Kirchhoff's voltage law can show the relationship between the limbs (Eq. 2) [2].

$$I + III = II\tag{2}$$

Although some researchers suggested a different system to record the heart activity [2, 3, 7], only the Einthoven limb leads had clinically used for three decades [2, 5, 8]. Wilson highlighted the fact that the limb electrodes are far from the heart, and introduced the *unipolar lead* concept [5, 8–10]. In *Wilson hypothesis*, the electrical activity of the heart can be measured by the potential difference between six exploring



**Fig. 1** Twelve lead electrocardiography

electrodes on the chest and an *indifferent electrode* of zero potential, which is known as Wilson Central Terminal (WCT) [10]. These six leads are designated as unipolar precordial leads (V1:V6) as he assumed the WCT amplitude is equal to zero [2, 10]. The Wilson Central Terminal is measured by the average potential of the right arm ( $\Phi_R$ ), left arm ( $\Phi_L$ ) and left leg ( $\Phi_F$ ) [9, 10].

$$\Phi_{WCT} = \frac{1}{3}(\Phi_L + \Phi_R + \Phi_F) \tag{3}$$

$$V_1 : V_6 = \Phi_{V1} : \Phi_{V6} - \Phi_{WCT} \tag{4}$$

Wilson also proposed to use three unipolar limb leads (VR, VL, and VF), which were measured by the difference potential of limbs' electrode and the WCT reference point [10].

$$\begin{aligned} VL &= \Phi_L - \Phi_{WCT} \\ VR &= \Phi_R - \Phi_{WCT} \\ VF &= \Phi_F - \Phi_{WCT} \end{aligned} \tag{5}$$

Because the three unipolar limb leads had a small amplitude, Goldberger [11] modified the WCT to increase these leads' amplitude by 50%. The new leads are measured as the potential difference between each limb potential and the average of the other two limb potentials. These leads are known as augmented leads and named as aVR, aVL, and aVF [11].

$$\begin{aligned} aVL &= \Phi_L - \frac{1}{2}(\Phi_R + \Phi_F) \\ aVR &= \Phi_R - \frac{1}{2}(\Phi_L + \Phi_F) \end{aligned}$$

$$aVF = \Phi_F - \frac{1}{2}(\Phi_R + \Phi_L) \quad (6)$$

The augmented leads were suggested in 1942 finalizing the development of the ECG lead system. The current ECG lead system consists of three Einthoven limb leads, three augmented leads, and six precordial leads (Fig. 1) [4].

Currently, Electrocardiography is the most wide-spread non-invasive tool for diagnosis of cardiac diseases, currently in use in every clinical center. However, some of the aforementioned fundamental ECG hypotheses have been challenged either during the development of the Electrocardiography [1901–1942], or afterward. Therefore, we discuss two of these fundamental ECG hypotheses: the Einthoven equilateral Triangle hypothesis, and the Wilson hypothesis in order to make a tangible picture of the Wilson central terminal and its influence on the precordial leads.

### 1.1 Wilson Central Terminal

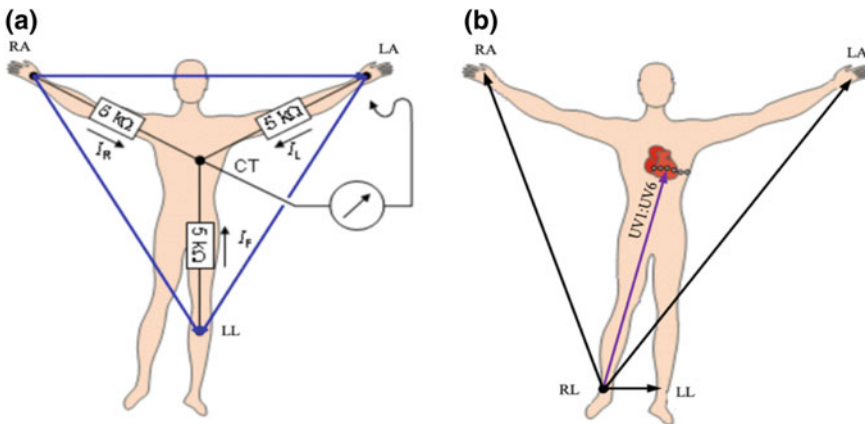
Wilson hypothesized that a neutral reference point of the human body could be measured by averaging the limb potentials. This reference point was introduced having null amplitude, being steady, and locating in the center of the Einthoven triangle [10]. The potential in the infinite medium has a null amplitude, which could be considered as the ideal reference point. In physics, we can only measure the potential difference between two points. However, we can have the potential of one point in case the second point is located in the far distance (infinity) from the first [12]. Thus, Wilson used three large resistors through which a negligible current would pass (based on Ohm's law), and consequently, he was able to measure the limbs' potential (Fig. 2, panel a) [10]. This assumption was found incorrect and absorbed immediate interests among researchers to measure this systematic error in the Electrocardiography. The proposed methods can be categorized into three different perspectives.

In the first approach, the human body is immersed in large homogeneous conductor to measure the potential difference between the WCT and the assumed zero potential (the water itself). In 1938, Eckey and Frohlich immersed a human body into a full bathtub and determined the WCT amplitude to be into a range of 0.2–0.3 [mV] [13]. A year later, Burger conducted the same experiment and immersed five men into a bathtub filled by water and reported the WCT amplitude was 0.26 mV [14]. In 1946, Wilson submerged a human in the Lake Michigan and found that the average absolute amplitude of the WCT could be as large as 0.15 mV [9]. Dolgin repeated the same experiment with different adjustments and confirmed the previous finding [15]. In 1954, Bayley et al. and Bayley and Kinard encased the body of volunteers inside a metal structure and immersed it in water for the duration of the recording [16, 17]. They determined that the WCT is not steady and its amplitude could be as large as 0.4 of Einthoven's leads during the cardiac cycle [16–18]. Thus, they used three rheostats to adjust the weights of the three WCT components in order

to minimize the WCT amplitude [17]. The legitimacy of the first approach was undermined by a variety of factors, including the effect of water pressure on ECG recording and degree of the conductivity of surrounding water [19]. Additionally, the zero potential of surrounding water [9, 20] and the widespread use of this method [21] have been questioned.

In the second approach, the *zero potential* of the human body was measured using numerical methods [2, 22–24] or surface potential mapping [25–27]. In these methods, the zero potential is not exactly aligned with the WCT definition; however, they referred to it as Wilson Center Terminal. The numerical methods are developed based on the theory that the summation of the electrical potential at the body surface should be zero [2]. Miyamoto et al. used 128 electrodes placed on the thorax and averaged their potential to estimate the amplitude of the human reference point. They reported the average value of the WCT as  $-0.169$  mV in 10 normal volunteers, and  $-0.051$  mV in all 60 subjects including controls and patients [19, 25, 26, ].

In a third approach, the potential of the right arm left arm and left leg directly measured using the right leg as a reference point (Fig. 2, panel b) [28]. We recently developed a new Electrocardiography device that can measure nine unipolar leads including three limbs’ potential and six true unipolar limb leads, in addition to 12 lead ECG [28–32, 33, 28]. Our results confirm the previous findings that the WCT is not steady and null, and we found out the WCT amplitude could exceed the amplitude of lead II (up to 247% of lead II).



**Fig. 2** Traditional approach (panel a) in comparison with our approach (panel b) to measure the WCT. In our approach, the limb potential and unipolar chest lead are measured with respect to the right leg

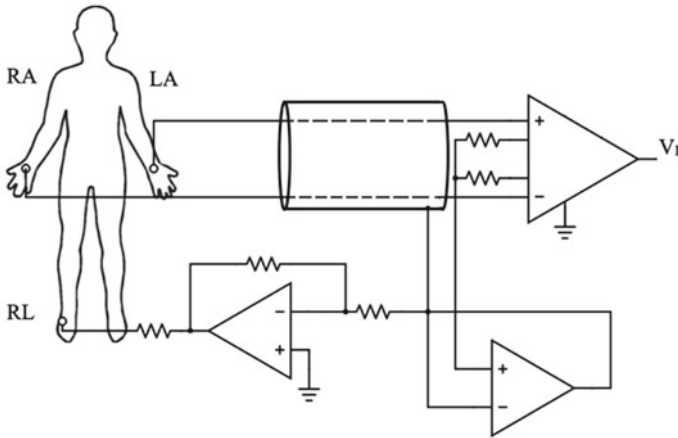


Fig. 3 ECG amplifier using right leg driver (lead I)

## 2 True Unipolar ECG Recording Device

Our ECG device is designed to record traditional ECG signals in addition to the nine true unipolar leads including three limb potentials and six unipolar chest leads. The true unipolar leads are the raw biopotential measured from the exploring electrodes directly referred to the *right leg* (RL). Although the right leg was not included in the original ECG montage, it was added as necessary return grounding for voltage amplifier as well as a way to reduce the interference from external electric fields [33]. Reduction of interference from external electrical fields is usually achieved with a technique known as a *driven right leg* or *right leg driver*, which usually implies an injection of a small current into the body (via the right leg electrode) and measuring amplifier circuits (via their reference terminal). In some specific biopotentials applications, the right leg driver is avoided using a technique known as voltage reference bootstrap that might result in an advantage to reduce common noise capture [2, 4, 33].

Driven right leg circuitries (DRLs) are widely used for the majority of the designs. Using the DRL increases patient safety because the human body is not directly grounded [4, 33, 34]. Figure 3 shows an example of the DRL application. As can be seen, the human body is driven by a measure of the common mode signal at the measuring electrodes while the amplifier is directly grounded. The technical documentation of the INA118 can be found in [35].

Our hardware system is developed around the INA116 instrumentation amplifier [36] from Texas Instruments (Burr-Brown series). This chip has typically a bias current of the only handful of femto-Amperes, and it incorporates a specialized guard ring amplifier which is primarily used to preserve the signal to noise ratio (SNR). The guard ring amplifier is used to measure the WCT components, as it generates a replica of the input signal [28, 29, 31, 32, 37, ]. Therefore, the WCT components' voltages are directly measured by using the guard buffer of the limb electrodes. The

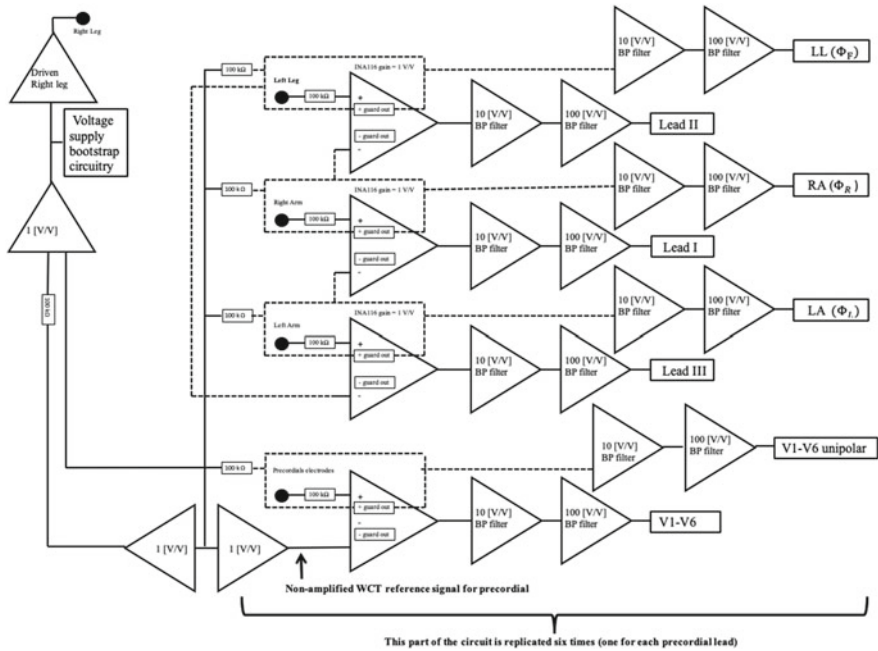


Fig. 4 Block diagram of the employed hardware (adapted from [28])

INA116 chips have a gain set of 1 V/V; two AC coupled active non-inverting low pass filters with gains of 10 V/V and 100 V/V are used to provide the required gain and bandpass filtering.

To ensure that the SNR of the measured signals is sufficient, specialized grounding circuitry is designed utilizing a combination of the right leg circuitry and a modified voltage bootstrap circuitry [9, 29, 37–39]. The non-amplified average of the measurement electrodes is directly inputted to the driven right leg circuitry, which is designed to drive 20  $\mu$ A [40–42].

This circuitry is battery powered, and the necessary analogue to digital conversion and data logging is operated by the BIOADC [43], which samples data with a 16-bit over a range of  $\pm 5$  V with a sampling rate of 800 Hz. The BIODAC is directly (galvanically insulated USB HUB) connected to a battery-powered laptop, and it comprises an anti-aliasing low-pass filter operating at the Nyquist frequency. Finally, a specialized importing script including a zero-phase lag 50th order bandpass filter (0.05–150 Hz), a zero-phase lag 50th order 50 Hz and harmonics notch IIR filters are used to normalize the frequency components to the diagnostic ECG bandwidth of the acquired signal. Complete details can be found in our recent publication [28] (Fig. 4).

### 3 True Unipolar Leads

We are able to record the three Einthoven unipolar limb lead (the voltage of right arm, left arm, and left leg) and six true unipolar precordial leads for the first time. We have recorded data from more than 100 patients at the Campbelltown hospital (NSW) over two years (2016–2018). All the patients volunteered for this study and gave written consent (this study was approved by the Ethics Committee of the South West Sydney Health District on 23rd September 2015 with the protocol number HREC/15/LPOOL/302). Some recordings have been removed from the dataset due to poor signal to noise ratio or because of abrupt interruption of the recording (emergency or patient being transferred to another department for an intervention/procedure). The published dataset<sup>1</sup> [44] contains 92 patients (27 were female) with an average age of 65.23 years and a standard deviation of 12.12 years. The majority of the patients had a history of cardiac disease and were admitted to the hospital from the emergency department because of difficulties in breathing and/or chest pain.

#### 3.1 Einthoven Unipolar Limb Lead

We are able to measure the amplitude of Wilson Central Terminal by averaging the voltage of Einthoven limbs. In this part, we are trying to answer the question of *what is the Wilson Central Terminal?* We investigate the legitimacy of two hypotheses:

1. *The WCT is null and steady during the cardiac cycle.*
2. *The WCT and aVF are inversely proportional.*

The first hypothesis is the Wilson assumption to measure the precordial leads, which has been proved incorrect by many researchers. However, their approaches were cumbersome, usually having a small test case population, and more importantly, their validity has been questioned [9, 20, 21]. The second hypothesis assumes that the left leg potential has the smallest amplitude among the Einthoven limb potentials, as it has the longest distance from the heart. Hence, considering the assumption that the left leg has near zero amplitude ( $\Phi_F \cong 0$ ), the WCT can obtain using the right arm, and left arm. Consequently, WCT and aVF are inversely proportional.

$$\begin{aligned} \Phi_{WCT} &= \frac{1}{3}(\Phi_R + \Phi_L) \xrightarrow{\text{yields}} \Phi_{WCT} = -\frac{2}{3}aVF \\ aVF &= -\frac{1}{2}(\Phi_R + \Phi_L) \end{aligned} \quad (6)$$

To assess the credibility of these two theories, we calculated the average peak to peak amplitude of three beats for all patients. In Fig. 5, We report the relative amplitude of the WCT, RA, LA, and LL with respect to lead II. As it is shown in

<sup>1</sup>Our dataset name is WCTECGdb, and was published in the Physionet website (<https://alpha.physionet.org/content/wctecgdb/>).



Fig. 5 (panel a), the minimum, maximum and average amplitude of the WCT in relation to lead II among all 92 patients are 0.11, 2.47, and 0.78 respectively. The left arm expected to have a higher potential than the right arm, as it is closer to the heart (Fig. 5 panels b, c). The left arm with respect to lead II has an average of 1.61 (within range of [0.038 6.41]), while right arm average is 0.88 (within range of [0.01 2.79]) for all 92 patients. Figure 5 (panel d) demonstrates the amplitude of the left leg with respect to lead II. Although the left leg has a small amplitude in comparison with the right and left arms' potentials, it does not have zero amplitude. The left leg potential in relation to lead II is in the range of [0.007 1.78] with an average of 0.22 for all patients.

Our recording shows that the WCT does not have a small amplitude and has ECG lead characteristics such as p-wave or QRS complex. The WCT has neutral (Figs. 6 and 8), negative (Fig. 7), or positive (Fig. 9) deflection during the cardiac cycle. Figure 6 is an example of the WCT with a large amplitude. The WCT signal is as large as 2.41 of lead II, and it exhibits all the characteristics of the ECG trace.

Figure 7 is an example of WCT with negative deflection. The left arm, right arm, and left leg show ECG features. Furthermore, the left leg has relatively small potential in comparison with the right arm and left arm.

As it can be referred from Eq. 6, the WCT and aVF are highly correlated in case the left leg potential has near zero amplitude. It can be understood from Fig. 5 (panel d) that the left leg has a small amplitude for most of the patients, however, it also has a relatively big amplitude for some patients. Figures 8 and 9 are an example of the WCT and aVF lead having a low and high correlation. As can be seen in these figures, the RA, LA, and LL signals have ECG characteristics. Figure 8, shows a low correlation between the aVF lead and the WCT signal, as the LL amplitude is as large as 0.22 of lead II. In contrast, the LL has a negligible amplitude in Fig. 9, consequently the WCT and the aVF lead are highly correlated.

### ***3.2 True Unipolar Precordial Leads***

The true unipolar leads and precordial leads are referred to like the same concept in the literature. However, it has been known that this terminology is incorrect. The precordial leads initially represent the difference potential between the electrodes placed on the chest and the WCT. Since Wilson assumed the WCT is null, the precordial leads have been referred to as unipolar leads. However, our ECG device is able to record the potential of electrodes placed on the chest without using the WCT signal [29–32]. Therefore, we recorded the traditional precordial leads (V1:V6) and what we address as the true unipolar leads (UV1:UV6) at the same time for all patients.

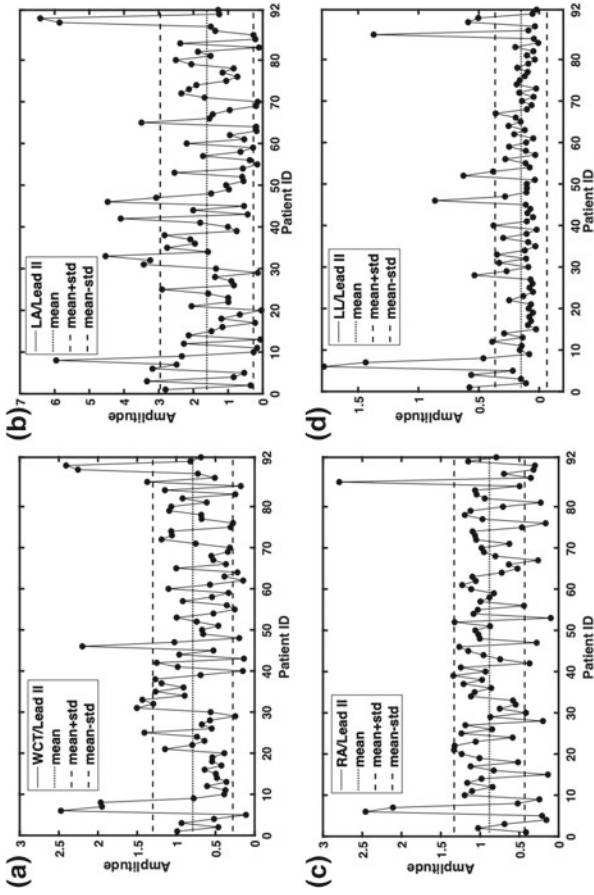
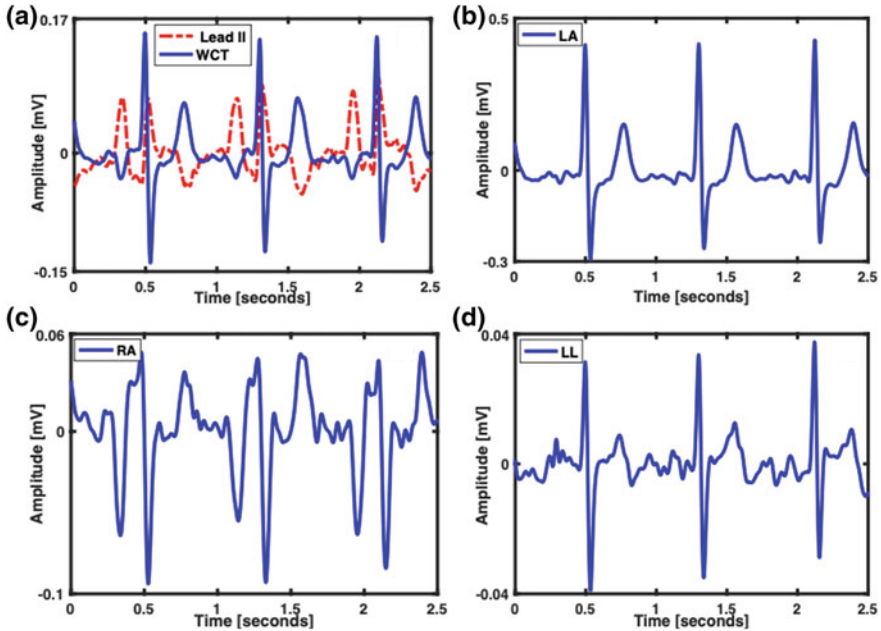


Fig. 5 The amplitude of the WCT, right arm, left arm and left leg with respect with Lead II

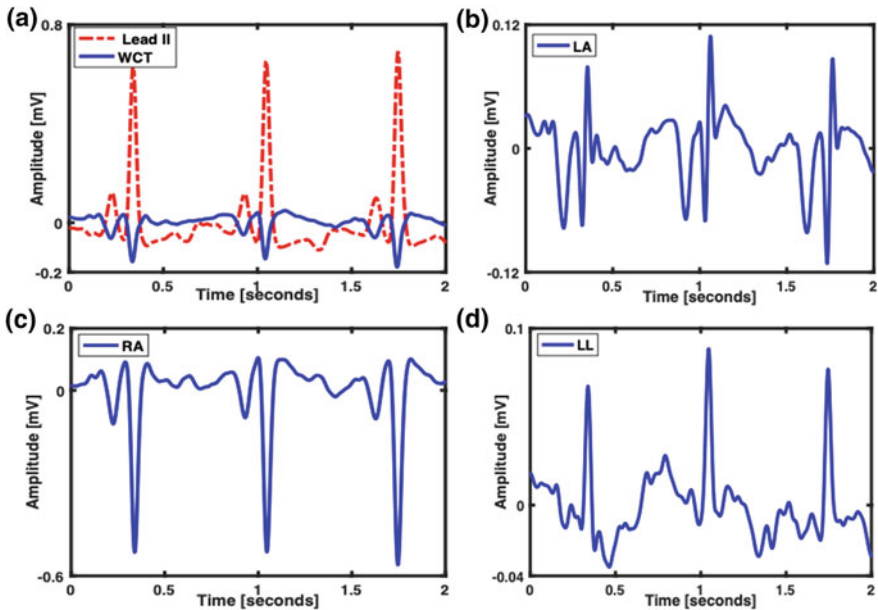


**Fig. 6** Example of neutral WCT. The WCT is 2.41 of lead II amplitude (average); the recording is from a 80-year-old male patient admitted from the emergency department with NSTEMI diagnosis

Our recording shows that the WCT is highly individual and has medically relevant amplitude, which impacts the precordial leads' shape and resulting to lose important information in the precordial leads.

We investigated the clinical features of true unipolar leads in comparison with precordial leads for all 92 patients. In this paper, we selected four patients from the WCTECGdb [44] with Non-ST Elevation Myocardial Infarction (NSTEMI) diagnosis to show the influence of the WCT on precordial leads. Our records show that the unipolar ECG may be more sensitive for detecting disease in the left anterior descending (LAD) coronary artery in patients presenting with NSTEMI. We are currently recording more data to show the validity of this hypotheses. As the WCT has no effect on the limb leads and augmented leads, we do not include them in the Figs. 10, 11, 12 and 13.

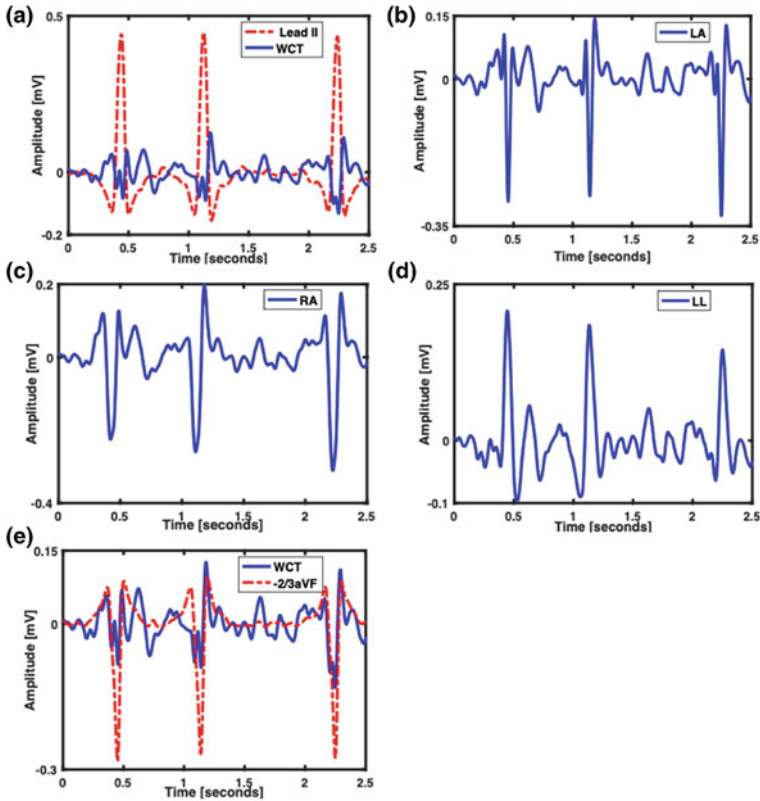
- Patient75: He presented with a non-ST segment elevation myocardial infarction. In this type of myocardial infarction, the mechanism of injury is subendocardial myocardial infarction. As it can be referred from Fig. 10 (panel a), the t-waves are biphasic in leads V2:V4, while they are inverted in leads UV1:UV6. Consequently, the unipolar ECG may be more sensitive at detecting this type of injury than the standard ECG. As the only difference between unipolar chest lead, and precordial



**Fig. 7** Example of negative WCT. The WCT is 0.32 of lead II amplitude (average); the recording is from a 54-year-old male patient admitted from the emergency department with ischemic cardiomyopathy diagnosis

lead is the WCT signal (Eq. 4), the influence of the WCT on UV1 can be clearly seen in Fig. 10 (panel b).

- Patient46: His angiography showed focal severe mid LAD stenosis, which supplied a large collateral to a distal dominant right coronary artery (the native right coronary artery being completely occluded). The patient subsequently underwent coronary artery bypass surgery. As can be seen in Fig. 11, the true unipolar leads show loss of clear T waves, which is suggestive of ischemia.
- Patient85: His angiography showed proximal to mid LAD stenosis, which was subsequently stented (after optical coherent tomography (OCT) imaging). As seen in Fig. 12, the true unipolar leads show more markedly biphasic T waves UV1:UV3. In other words, biphasic T waves in VU1–UV3 typically suggest proximal LAD disease which is known as Wellens Syndrome. This was not apparent on the precordial leads but was predictive of the underlying culprit lesion.
- Patient66: His angiography showed focal severe stenosis in distal RCA and proximal large diagonal branch stenosis of the LAD (both of which were stented). As it can be referred from Fig. 13, the true unipolar leads show T wave inversion UV4:UV6 consistent with diagonal branch territory problem/ischemia.

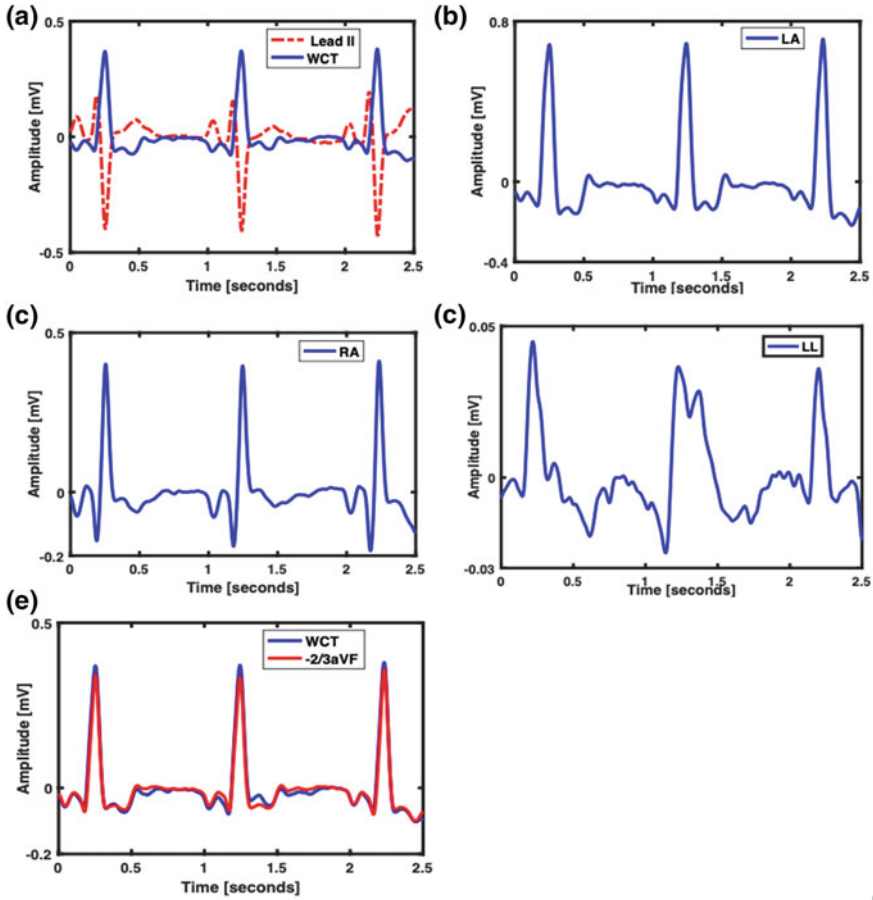


**Fig. 8** Example of neutral WCT that mutates into positive and neutral. There is low a correlation (45%) between the WCT and aVF lead. The LL amplitude is as large as 0.22 of lead II

### 4 The WCT Location

In theory, the WCT is located in the centroid of the Einthoven triangle. However, research conducted in 2005 shows that many cardiologists do not have a clear understanding of unipolar leads and the WCT concept [45]. As mentioned earlier, although there was an initial wave of interest working on the fault in the WCT assumption after Wilson hypothesized its concept, this error has been widely accepted, and the topic received scant research attention. Furthermore, there is no consensus understanding of the Einthoven triangle, as its edges have been considered differently in the literature. Hence, a clear view of the Einthoven triangle hypothesis may lead to a more precise answer to the question, *where is Wilson central terminal?*

Einthoven assumed the human body is two-dimensional conducting homogeneous medium with the shape of a triangle. The heart is regarded as a single dipole in the center of the triangle. The dipole changes its magnitude and direction in every moment, which causes it to change its electrical field. Considering these assumptions,



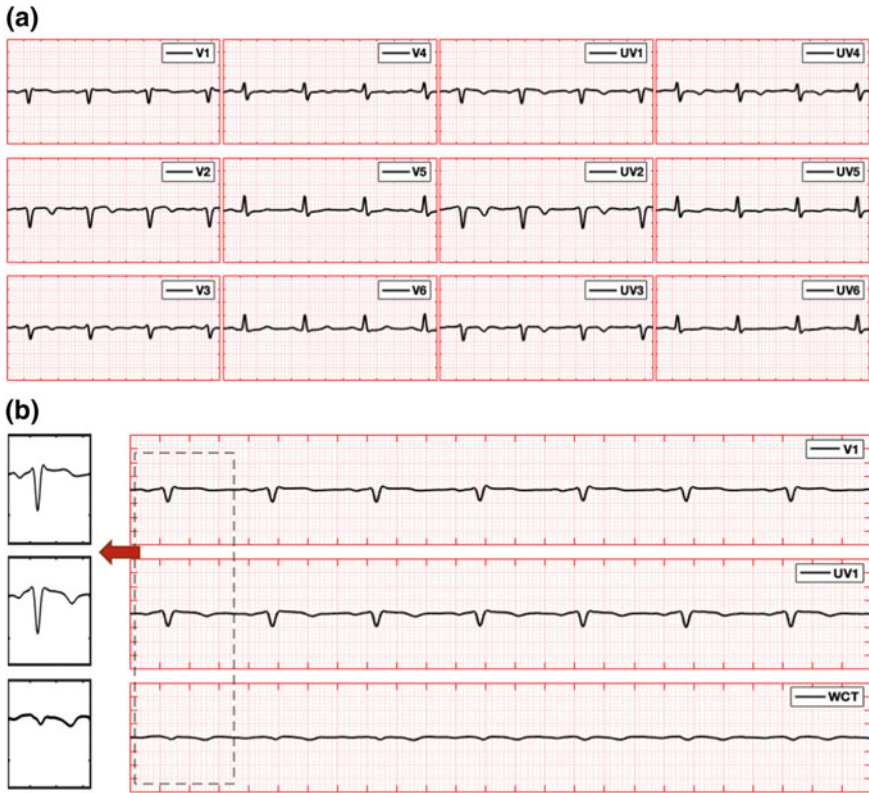
**Fig. 9** Example of positive WCT with small LL amplitude (0.032 of Lead II). The WCT and aVF are highly correlated (98%) as the amplitude of WCT is negligible

the potential of every point in the body measured by Eq. 7 [1], which  $\Phi$  is the potential of a single current dipole  $\vec{p}$  (with strength  $p$ ) in infinite homogenous medium with a conductivity of ( $\sigma$ ):

$$\Phi = \frac{1}{4\pi\sigma} \frac{p \cos \theta}{R^2} + c \tag{7}$$

$R$  is the length of the vector  $\vec{R}$  directed from dipole source location to the target point, and  $\theta$  is the angle between vectors  $\vec{p}$  and  $\vec{R}$ .

As Goldberger discussed [46], the distance between the limb electrodes and the dipole are equivalent; therefore the difference between the limb potential amplitudes is only dependent to angles  $\theta_1, \theta_2(\theta_1 + 120)$  and  $\theta_3(\theta_1 + 240)$ . It could be easily



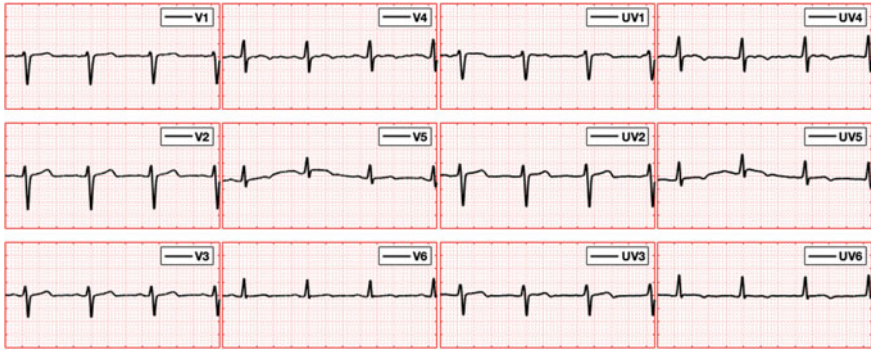
**Fig. 10** Panel a: comparison of unipolar chest lead (UV1:UV6) with precordial leads (V1:V6). Panel b: the influence of the WCT on V1; top panel is standard V1 precordial; middle is true unipolar UV1; bottom panel is the WCT signal. The t-wave is inverted in UV1. Recorded from 70 years old male, admitted to a hospital for NSTEMI (patient75)



**Fig. 11** Comparison of unipolar chest lead (UV1:UV6) with precordial leads (V1:V6). Recorded from 69 years old male, admitted to a hospital for NSTEMI (patient46)

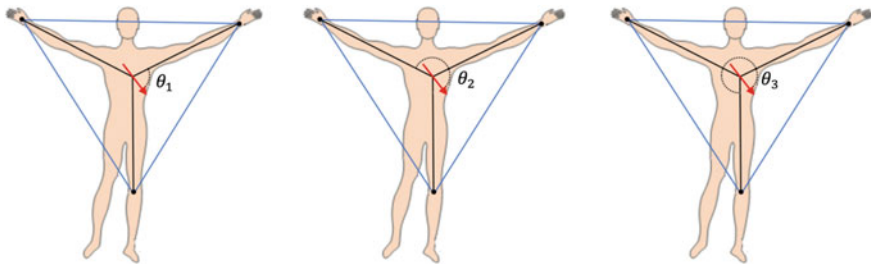


**Fig. 12** Comparison of unipolar chest lead (UV1:UV6) with precordial leads (V1:V6). Recorded from 52 years old male, admitted to a hospital for NSTEMI (patient85)



**Fig. 13** Comparison of unipolar chest lead (UV1:UV6) with precordial leads (V1:V6). Recorded from 41 years old male, admitted to a hospital for NSTEMI (patient66)

shown that for every direction of the heart vector, the sum of the limb potential is equal to zero [46] (Fig. 14).



**Fig. 14** Einthoven assumed the potential of each limb only depends on the angle between  $\vec{p}$  and  $\vec{R}$  vectors



The geometrical position of the limb electrodes shaped the Einthoven triangle [46–48, ]. Wilson assumed the symmetrical orientation of the heart vector with respect to the electrodes on the limbs [17] and hypothesized that the potential of the dipole (heart) is equal to zero and calculated by the average of the Einthoven limb potentials. Although the Einthoven hypothesis is the major breakthrough in electrocardiography, it has been known his assumptions are oversimplifying the human body, and the heart activity. The same argument can be made for the Wilson hypothesis.

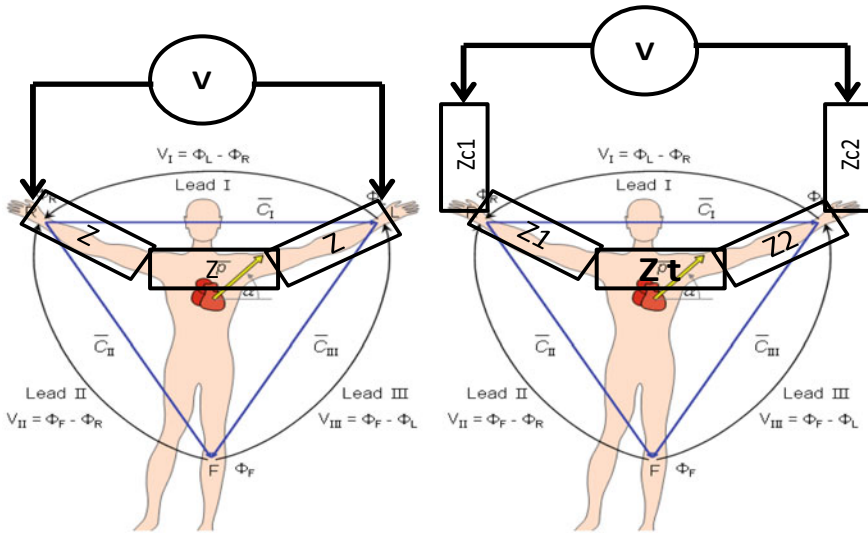
The WCT located in the centroid of Einthoven triangle, represents the potential of the single dipole, and its potential is equal to zero in case three electrodes are placed in the same distance from the heart, and all Einthoven assumptions are correct.

However, as it can be referred from Eq. 7, in case the imaginary line between limb electrodes do not build up the equilateral triangle, the limb potentials depend on the  $R$  amplitude and the angle ( $\theta$ ). Consequently, the centroid of the triangle cannot represent the dipole anymore. Furthermore, the other assumptions (the electrical activity of the heart is a single dipole located in the center of the body, and the human body is a homogeneous conductor) are ill-posed models of the human body [46].

In some literature, there is also a misunderstanding between geometrical space and electrical space. As an example, in the standard surface ECG representation, it is possible to see that limb leads are the edges of the Einthoven triangle, this can be easily shown incorrectly. The Einthoven law (Eq. 2) contradicts the fact that equilateral triangle edges are in the same length, and more importantly, three limb leads could only construct a triangle (not equilateral) for less than 50% of the cardiac cycle [49].

## 5 Discussion

Originally, the heart was theorized to act as a current source, and the electrocardiography model measured bio-currents using a very sensitive galvanometer (string galvanometer). As there is no obvious current pathway that includes the heart when the instrument is connected between the two legs and the right leg is the most distant limb from the heart, Einthoven did not include the right leg in the cardiac conduction model. In other words, ECG recordings were intended as a measure of the net current impressed by the heart circulating into an external circuit closed by the measurement instrument. Therefore, it was possible for Wilson to complete the transformation from the equilateral triangle (Einthoven's triangle) to the equivalent star circuit (originating the augmented leads) when he faced the problem of finding a reference for precordials. In theory, if each of the Einthoven leads measures the net current impressed by the heart between the two limbs, averaging all the electrodes



**Fig. 15** Ideal measurement of lead I versus real measurement of lead I. Left panel shows an idealized measurement of lead I as voltage; right panel refers to real measurements of lead I in which includes contact impedances ( $Z_{c1}$  and  $Z_{c2}$ ) and variable impedance of torso ( $Z_t$ )

together should give the best approximation of the point of origin, the neutral point of the cardiac electrical activity.

Impractical use of current measurement devices and the link between current and voltage resulted in the replacement of all ECG current measurements with voltage, neglecting that measuring voltage instead of current requires dealing with the different impedances of body sections. In fact, each lead is interpreted as the voltage drop across a composed resistance (impedance, as a matter of fact) due to the net current impressed by the heart to the points of measurement based on Ohm’s law (Voltage = Resistance \* Current). For example, lead I (Fig. 15) can be interpreted as the drop of voltage across the sum of the contact impedance at both electrodes that includes the impedance of the two arms and the impedance of the chest across the shoulders that changes with respiration.

Of course, current and voltage measurements are perfectly interchangeable if the body is simply considered as a homogeneous volume conductor (constant resistance) with the limb electrodes placed at equal distance with no or negligible contact impedance. However, in real life recording the contact impedance imbalance between the ECG electrodes is often not verified. Additionally, the limb leads are measured across different sections of the chest, which are different in shape, and their resistance changes with respiration and body posture resulting in adding a frequency-dependent delay and a phase difference between voltage and current. The modified phase relationship between voltage and current may also affect the limbs’ potential and consequently, the WCT. Moreover, as the voltage potential difference between the reference point (RL) and the other limb electrodes are used to measure the RA, LA, and LL

potentials, different body and contact impedances may impose different delays upon the limb potentials resulting in an unpredictable alteration of WCT [29, 32].

Based on the Einthoven theory, if the limb electrodes placed on the same distance from the heart, the WCT presents the potential of the dipole. However, it is not the case in practice. The WCT amplitude is highly dependent on where the limb electrodes are placed (Eq. 7). Hence, it is obvious not to have a negligible amplitude in averaging the limbs' potential. On the other hand, the location of the limb electrodes influences the shape and amplitude of precordial leads [50]. As our device uses the right leg as a reference point to measure the potential of the electrodes on the chest, the WCT variation does not affect the true unipolar leads. On the other hand, the true unipolar leads are robust and independent from the limb electrodes' displacement.

## 6 Conclusion

The electrocardiography is the most common tool in the diagnosis of cardiac diseases. In this paper, we discussed two important hypotheses proposed by Einthoven and Wilson, which shapes the currently in use electrocardiography tool. It has been known that these two theories simplify heart activity, and do not provide a precise model for the human body. However, no one can measure the influence of these false assumptions on the leads. As our ECG device can record the potential of the Einthoven limb electrodes and chest electrodes, we were able to show the impact of the WCT on precordial leads. Furthermore, we depicted a clear picture of the WCT concept by answering the questions *what is the Wilson central terminal?* and *where is the Wilson central terminal?* Our records show that the WCT is not null, and it has ECG features such as p-wave and QRS complex with clinically relevant amplitude (as high as 2.47 of lead II). We also compared the limb potential amplitudes. Our records show that the left arm has a high amplitude as it is closer to the heart, and the left leg has a small amplitude for most of the patients. However, the left leg potential is not negligible for all the patients, and its amplitude with respect to lead II is in a range of [0.007 1.78] and with an average of 0.22 for all patients.

We used two terminologies to address the chest leads, first, precordial leads (V1:V6) referring to the current approach used for recording the chest leads, second, the true unipolar leads (UV1:UV6) addressing our approach used for recording the chest electrodes' potential. We show that the WCT signal is clinically relevant, and has an impact on precordial leads' shape and amplitude. Our preliminary results show that the true unipolar leads may be more sensitive for detecting cardiac diseases in the left anterior descending coronary artery in patients with NSTEMI.

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