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Electrocardiogram of a Silver Nanowire Based Dry Electrode: Quantitative Comparison With the Standard Ag/AgCl Gel Electrode

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ABSTRACT Novel dry electrodes have promoted the development of wearable electrocardiogram (ECG) that is collected in daily life to monitor the ambulatory activity of heart status. To evaluate the performance of a dry electrode, it is necessary to compare it with the commercial disposable silver/silver chloride (Ag/AgCl) gel electrode. In this paper, a silver nanowire (AgNW)-based dry electrode was fabricated for noninvasive and wearable ECG sensing. Signals from the AgNW electrode and the Ag/AgCl electrode were simultaneously collected in two conditions: sitting and walking. Signal quality was evaluated in terms of ECG morphology, R-peak to R-peak interval, and heart rate variability analysis. Quantitative comparisons showed that the AgNW electrode could collect acceptable ECG waveforms as the Ag/AgCl electrode in both the sitting and walking conditions. However, the baseline drift and waveform distortions existed in the AgNW electrode, likely due to electrode motion. If the skin-electrode contact is improved, the dry electrode can be a promising substitute for the Ag/AgCl electrode.

INDEX TERMS Dry electrode, ambulatory ECG, ECG discrepancy comparison, signal quality indices, heart rate variability analysis.

I. INTRODUCTION

The electrocardiogram (ECG) provides a graphical representation of the electrical activity of the myocardium during one cardiac cycle. It is characterized by a recurrent sequence of P-QRS-T waves and a conditional U wave. The observed characteristics of each ECG wave are clinically important in diagnostic decision for various cardiovascular diseases (CVD). Continuous monitoring of the routine ambulatory ECG is attracting more and more popularity due to the indispensable role in the prevention, early diagnosis and postoperative treatment of CVD, especially for the elderly people with heart problems [1].

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The disposable silver/silver chloride (Ag/AgCl) gel electrode is the most widely used in clinical practice. The adhesive used is beneficial to fix the electrode on skin and alleviate electrode sliding, leading to stable impedance between electrode and skin, along with the hydrogel layer that helps to reduce the impedance. However, the Ag/AgCl electrode is not ideal for daily ECG monitoring, due to drawbacks such as skin irritation caused by the adhesive, specific preparation before measurement and limitations related to the connecting cables [2]. The hydrogel layer that exists at the skin-electrode interface degrades with time as it dehydrates. This leads to loss of signal quality and increased motion artifacts and noise in the ECG. Moreover, the electrode needs to be carefully packaged to ensure prolonged retention of the hydrogel layer. Because of finite shelf life and electrode dehydration, these electrodes can only be used to record signals for a few hours at maximum.

For these reasons, dry electrodes have been developed in recent years expecting to substitute Ag/AgCl gel electrodes in applications of wearable ECG collection [3], [4]. Compared with gel electrodes, dry electrodes still have two main challenges to be settled: (1) dry electrode drops more easily from the skin than gel electrode owing to the lack of adhesive especially in walking condition, bringing about more serious skin-electrode noises [5], [6], (2) dry electrode has much higher skin-electrode impedance than gel electrode, which requires to design new type of ECG amplifier to match the input impedance [7], [8]. Hence, signals collected from dry electrodes are generally with lower quality especially in dynamic conditions.

To overcome these problems, researchers have tried to design feasible dry electrodes with the same diagnostic efficiency as Ag/AgCl electrodes for ambulatory ECG monitoring, such as nanowire electrode [9], [10], open-mesh electrode [11], micro-needle-based electrode [12] and polymeric dry electrode [13]. Meziane *et al.* [14] investigated three types of dry electrodes, stiff material, soft/flexible material and fabric dry electrodes, compared with gel electrode. The authors emphasized that motion artifacts and high skin-electrode contact impedance were two main challenges restricting the application of dry electrodes. To understand the impact of electrode movement, Cömert *et al.* [15] presented the simultaneous measurement of impedance at eight current frequencies during the application of controlled motion to the electrode under controlled force. Furthermore, in [16], a novel copper-meshed CB/PDMS electrode was developed to alleviate motion artifacts. The electrode could also be implemented in salt-water immersion environments. To reduce the impedance of dry electrode, researchers in [17] demonstrated a novel design for printed active electrodes on woven textiles, where the electrode structure was integrated with a buffer amplifier that converted high-impedance signals into low-impedance signals. The authors also verified that the proposed electrodes provided significantly improved performance compared to textile passive electrodes and had similar property to the Ag/AgCl electrodes.

Although many publications have demonstrated the effectiveness of novel electrodes for physiological signal collection, few of them emphasized the importance of signal difference from dry and gel electrode [18], [19]. Quantification of signal quality is essential because the purpose of developing new types of electrodes is the practical implementation. To the best of our knowledge, the current dry electrodes are still not able to collect ECG signals with comparable quality as the commercial Ag/AgCl electrodes, especially when patients are monitored in daily life with movement. Clarifying and comparing signal quality is necessary as it reflects the defects of dry electrodes in both material and structure, thus revealing the property of dry electrode [20], [21]. Meziane *et al.* [22] designed a spandex tank top with dry electrodes for continuous ECG recording. They experimentally validated findings with 12 men and 12 women by monitoring six types of movements in daily life while continuously recording their ECGs. Although signals were simultaneously collected, they did not quantify the difference between them. In [23], a novel type of dry electrode, which contained various additives for optimum conductivity, flexibility and ease of fabrication, was presented offering high user comfort. However, ECG signals were collected with subjects only in stationary state, which might be less persuasive if implemented in ambulatory ECG monitoring. The work of [21] took advantage of pencil lead as the raw material of ECG electrode and developed two types of dry electrodes: pencil lead solid electrode and pencil lead powder electrode for underwater ECG monitoring. By testing the heart rate variability (HRV), the authors claimed a high correlation between the ECG signals from the two types of dry electrodes and the commercially available Ag/AgCl electrodes. Nevertheless, all the signals were recorded for only 5 minutes, which might not characterize comprehensive cardiac status in long-term ambulatory ECG monitoring.

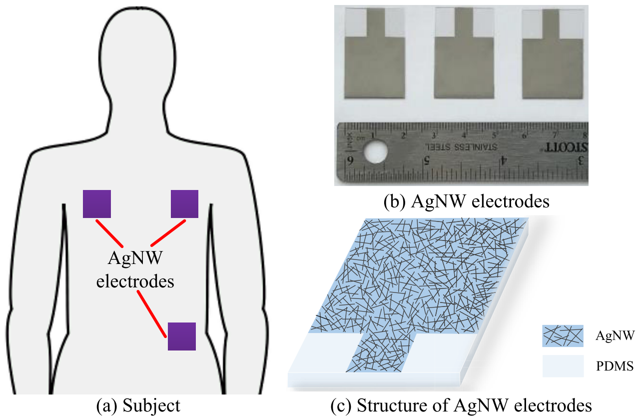

FIGURE 1. **Exterior and structure of AgNW electrodes. (a) Subject. (b) AgNW electrodes. (c) Structure of AgNW electrodes.**

The purpose of the present study is to compare the ECG signals collected from the conventional disposable Ag/AgCl gel electrode and the reusable silver nanowire (AgNW) dry electrode. The AgNW electrodes were tested and evaluated with subjects in sitting and walking conditions, simultaneously with the Ag/AgCl electrodes to ensure that the heart functioned in the same status. The signals were processed and the differences were characterized in both time and frequency domain. By comparing and quantifying the signal quality, this study revealed the temporal and spectral similarity of ambulatory ECG signals from the dry and the gel electrodes.

II. MATERIALS

The AgNW electrode, which is inlaid below the surface of an elastomeric substrate made of PDMS to achieve both flexibility and conductivity, is presented for noninvasive and wearable ECG sensing. Figure 1 displays the structure of AgNW electrodes used in this study. Polydimethylsiloxane (PDMS) (Sylgard 184, Dow Corning) precursor was prepared

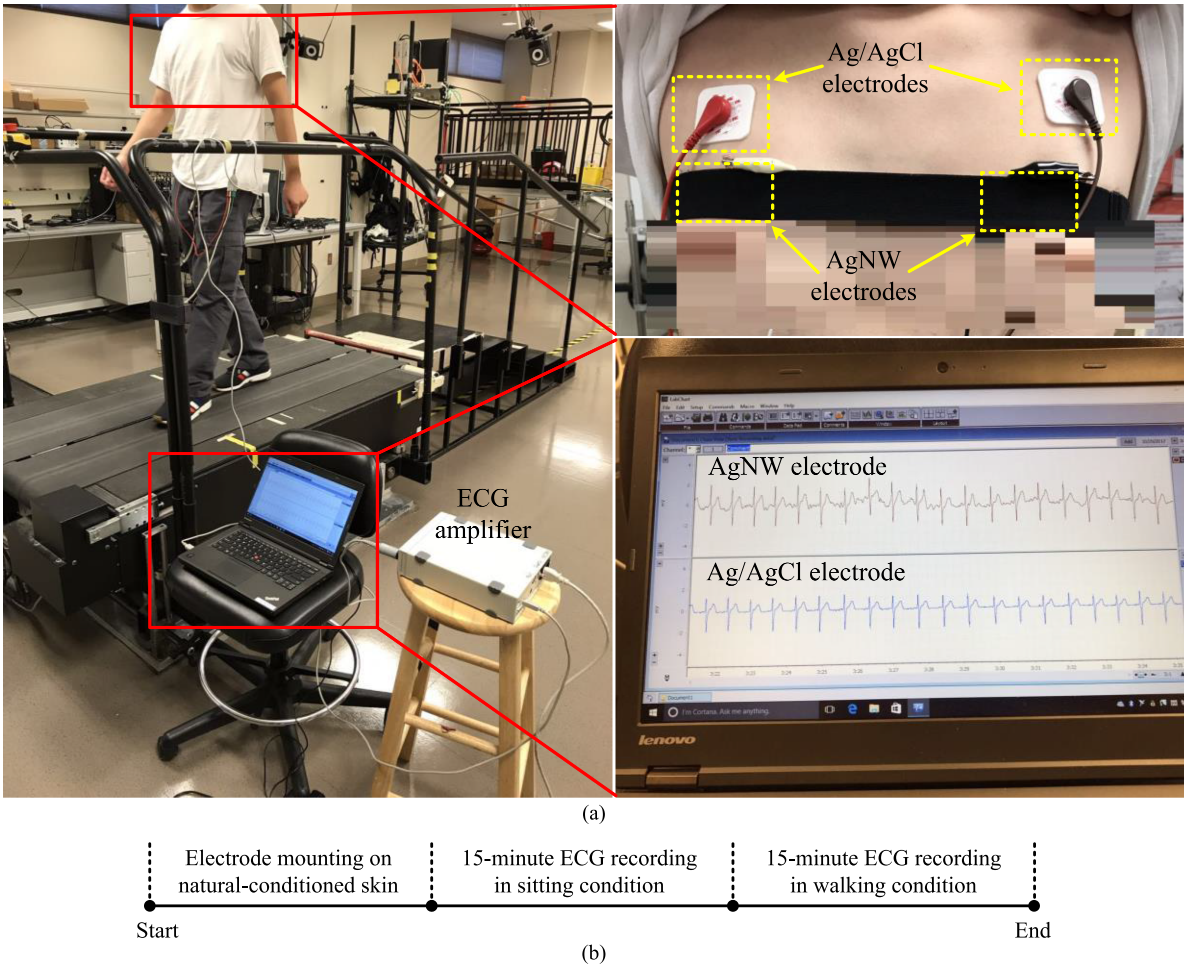

FIGURE 2. **(a) Electrode set-up, (b) ECG recording scheme.**

with a base to curing agent ratio of 10:1 in weight. The mixture was spin coated onto a silicon substrate, degassed in a vacuum chamber and cured at 60° for two hours. Cured PDMS was then cut into desired patterns to serve as the shadow masks for the electrodes. The AgNW/ethanol ink was drop cast into the grooves defined by the PDMS mask followed by evaporating the ethanol at 50°C on a hot plate. After peeling off the PDMS mask, PDMS precursor (based to curing agent ratio of 10:1 in weight) was coated on top of AgNW patterns, degassed and cured at 60°C for two hours. AgNW/PDMS composites were then interconnected using epoxy and copper wires. More details on the fabrication of the AgNW electrodes can be found in [10], [24], and [25].

III. EXPERIMENTAL DESIGNS

A. MEASUREMENT PROTOCAL

Experiments included 30 healthy volunteers with ages ranging from 25 to 31 (27.43 ± 1.99, mean ± standard deviation), with average weight 73.00 ± 2.65 kg and average height 170.71 ± 2.29 cm. The study protocol and data analysis were approved by the Institutional Review Board (IRB, protocol number 5891) at North Carolina State University (USA) and all the volunteers consented to be subjects for the experiments.

The PowerLab 26T (ADInstrument) was employed for simultaneous ECG acquisition using AgNW and Ag/AgCl electrode. The ECG signals were displayed and recorded by LabChart 7 software. Sampling rate of 400 Hz was adopted according to the Nyquist criterion and American Heart Association recommendation [26], [27]. For each measurement, skin was not specially prepared but in natural condition, and no filtration measurement was used during the sampling to obtain the original signal.

B. ELECTRODES SET-UP AND ECG RECORDING

Electrodes were distributed on the subject mimicking the 3-Lead ECG setup, as shown in Figure 2(a). Each pair of AgNW and Ag/AgCl electrodes was placed adjacently to each other on the subject's left chest and right chest, and combined with one Ag/AgCl electrode as bias signal on the left abdomen. The Ag/AgCl electrodes were mounted on the skin using the adhesives on the periphery of the electrodes. However, the AgNW electrodes did not possess such adhesives. Consequently, a chest strap having an elastic insertion was utilized to keep the AgNW electrode in place during the experiments. The length of the belt could be adjusted with hook and loop trap. We note that the AgNW and AgCl electrodes are mounted to the skin using different methods and possibly under different contact pressure, which could complicate the comparison of the signal qualities. While the adhesive is the most common way to mount the AgCl electrodes, a chest strap is the most common way to mount dry electrodes without adhesives like the AgNW electrodes used in this study. Therefore, in this study, the performances of the two types of electrodes were evaluated and compared in spite of the difference in the mounting methods, which is of more practical relevance.

The standard Lead I ECG signals were simultaneously recorded and compared with subjects in sitting and walking conditions; the signals were collected sequentially, as displayed in Figure 2(b). Subjects were asked to remain relaxed in sitting condition to collect 15-minute ECG recordings. Then, they were asked to walk on a treadmill, which was equipped with necessary shields to eliminate the electromagnetic interference from the motor, with a constant speed (2.88 km/h) to collect another set of 15-minute ECG signals. As a result, totally 30 groups of ECG signals (120 ECG recordings, each subject with 2 conditions ×2 electrodes) were collected. All the ECG recordings were qualified by signal quality indices (SQI) and HRV analysis to characterize the signal differences from the two electrodes.

C. PRE-PROCESSING OF ECG SIGNALS

The morphology of ECG cycles depends on the location of electrodes. Although the signals were collected simultaneously, there was an inter-electrode distance between each pair of gel and dry electrodes, resulting in different ECG amplitudes [28]. To balance the signals to the same magnitude, the amplitude ranges of the collected ECG signals were normalized to [0, 1] using Eq. (1), where X_{norm} and X_{ori} were normalized signal and the original signal, X_{max} and X_{min} were the maximum and minimum of the original signal. No filtration measurement was applied to the collected signals so that the SQI and HRV parameters could reveal the property of the original signals.

$$X_{norm} = \frac{X_{ori} - X_{min}}{X_{max} - X_{min}} \tag{1}$$

The QRS detection was performed on each signal individually using two open source QRS detector (wqrs and Pan-Tompkins [29]). The wqrs is based upon a length transform [30] and the Pan-Tompkins is based upon a search-back operation [31].

D. SIGNAL COMPARISON CRITERION

1) SQI PARAMETERS

Ten SQIs were extracted from the ECG waveform based on the published works [20].

1) bSQI: the percentage of beats detected by *wqrs* that are also detected by *Pan-Tompkins* method [32].
2) sSQI: the third moment (skewness) of the ECG signal [33].
3) kSQI: the fourth moment (kurtosis) of the ECG signal [32].
4) pSQI: the relative power in the QRS complex [32].

$$pSQI = \frac{\int_{5Hz}^{15Hz} P(f)df}{\int_{5Hz}^{40Hz} P(f)df} \tag{2}$$

5) basSQI: the relative power in the baseline [33].

$$basSQI = 1 - \frac{\int_{0Hz}^{1Hz} P(f)df}{\int_{0Hz}^{40Hz} P(f)df} \tag{3}$$

6) bsSQI: baseline drift in time domain [20].

$$bsSQI = \frac{1}{N}\sum_{i=1}^{N}(\frac{A_{Ri}}{A_{Bi}}) \tag{4}$$

where the A_{Ri} is the peak-to-peak amplitude of the ECG waveform around each QRS complex (from R−0.1s to R+0.1s, R is the QRS complex detected by Pan-Tompkins method [31]), A_{Bi} is the peak-to-peak amplitude of baseline around each QRS window (from R−1s to R+1s) [20], N is the number of the detected QRS complex in the analysis window. The baseline was extracted by the wavelet multi-resolution analysis (WMRA) [34], [35].

7) eSQI: the relative energy in the QRS complex [20].

$$eSQI = \frac{\sum_{i=1}^{N} E_{Ri}}{E_A} \tag{5}$$

where E_{Ri} is the energy of QRS complex, E_A is the energy of the ECG segment in the analysis window.

8) purSQI: signal purity of ECG [36].

$$purSQI = \frac{w_2^2(n)}{w_0(n)w_4(n)} \tag{6}$$

with w_n the nth-order spectral moment, it is defined as:

$$w_n = \int_{-\pi}^{\pi} w^n S_x(e^{jw})dw \tag{7}$$

where $S_x(e^{jw})$ represents the power spectrum. The spectral moment w_n can be estimated by the following derivatives:

$$w(n) \approx \frac{2\pi}{K}\sum_{i=0}^{K-1}[x^{(i/2)}(n)]^2 \tag{8}$$

$$x^{(1)}(n) = x(n) - x(n-1) \tag{9}$$

$$x^{(2)}(n) = x(n+1) - 2x(n) + x(n+1) \tag{10}$$

9) enSQI: the sample entropy of ECG waveform [37].
For a given length of template vector m, tolerance r and length of ECG waveform L, Sample entropy is the negative logarithm of the probability that if two sets of simultaneous data points of

TABLE 1. Sqi significance and assessment of high ecg quality.

SQI	Significance	Good quality
bSQI	An estimation of the level of QRS delineation	Close to 1 [39]
sSQI	A measure of the asymmetry of the probability distribution of ECG about its mean	Larger absolute value [38]
kSQI	A measure of how Gaussian-like a signal appears to be	Larger than 5 [39]
pSQI	Power intensity of QRS complex over noise	In [0.5, 0.8] [39]
basSQI	Power in the frequency band [0, 1] Hz, corresponding to the baseline drift	Close to 1 [33]
bsSQI	Amplitude ratio of QRS complex to baseline drift	Larger [20]
eSQI	Energy distribution of QRS complex	Close to 1 [20]
purSQI	A measure of how well the signal is delineated by a single frequency	Close to 1 [36, 40]
enSQI	A measure for assessing the complexity of ECG signal	Close to 0 [37, 41]
pcaSQI	A measure of redundancy in ECG signal	Close to 1 [38]

length m have distance smaller than r, two sets of simultaneous data points of length $m+1$ will also have distance smaller than r. Assuming the time-series ECG waveform $X = \{x_1, x_2, x_3, \ldots, x_N\}$ with length L such that the template vector $V_m(i) = \{x_i, x_{i+1}, x_{i+2}, \ldots, x_{i+m-1}\}$ of length m, and the distance function $d[X_m(i)], X_m(j)](i \neq j)$ represents the Euclidean distance. Then the enSQI can be defined as:

$$enSQI = SampEn(m, r, L) = -\ln \frac{A^m(r)}{B^m(r)} \quad (11)$$

where A is the number of template vector pairs having $d[X_{m+1}(i)], X_{m+1}(j)] < r$ of length $m+1$, B is the number of template vector pairs having$d[X_m(i)], X_m(j)] < r$ of length m.

10) pcaSQI: principle component analysis (PCA) of the ECG waveform [38].
A ratio containing the sum of the eigenvalues associated with the five principal components over the sum of all eigenvalues obtained by PCA, which is applied to the time-aligned QRS complex detected by the Pan-Tompkins method.

Table 1 lists the significance of each SQI parameter and the verification of a high-quality ECG signal. When evaluating the ECG quality, a sliding analysis window with a length of 15 seconds was applied, therefore, each ECG recording was divided into 60 segments and each segment will have its related results. Signals from AgNW electrode were also compared with those from Ag/AgCl electrode using t-test. Statistical significance is accepted at $p < 0.05$.

2) HRV PARAMETERS

HRV parameter is adopted as a quantitative performance measure since it reflects the changes in the dynamics of the autonomic nervous system, which contains sympathetic and parasympathetic components. HRV is also related to the CVD such as premature ventricular contractions (PVC) and premature atrial contractions (PAC) [21]. Temporal and spectral measures of HRV are considered in this study.

1) Temporal HRV
meanRR (ms): mean R-peak to R-peak (RR) interval.
SDNN (ms): standard deviation of all RR intervals.
RMSSD (ms): root mean square of the differences between adjacent RR intervals.
NN50: number of pairs of adjacent RR intervals differing by more than 50 ms in the entire ECG recording.
pNN50: the proportion of NN50 divided by total number of RR intervals.
2) Spectral HRV
LF (ms2): low frequency, power in frequency band from 0.04 Hz to 0.15 Hz.
HF (ms2): high frequency, power in frequency band from 0.15 Hz to 0.4 Hz.
ToP (ms2): total power in frequency band from 0.04 Hz to 0.4 Hz.
LF/HF ratio: low-frequency energy over high-frequency energy.

For frequency domain analysis, RR series derived from the whole 15-minute signal is analyzed using fast Fourier transform (FFT). FFT yields complexes spaced evenly along the frequency axis from zero to half of the sampling frequency. The sympathetic activity is associated with the LF frequency range while the parasympathetic activity is associated with the HF frequency range [42]. Thus, HRV derived from high-quality ECG signal should have more RR series energy concentrated in the frequency band from 0.04 Hz to 0.4 Hz [41]. In the presence of noise, errors in the detection of R-peaks will result in a distorted HRV, which would probably have a disordered distribution of energy in the different frequency bands and presumably contain increased energy in non-physiologically relevant bands.

3) CROSS-CORRELATION

The cross-correlation coefficient is employed to evaluate the consistency between two signals and quantify the signal similarity. The cross-correlation coefficient ρ of X and Y with

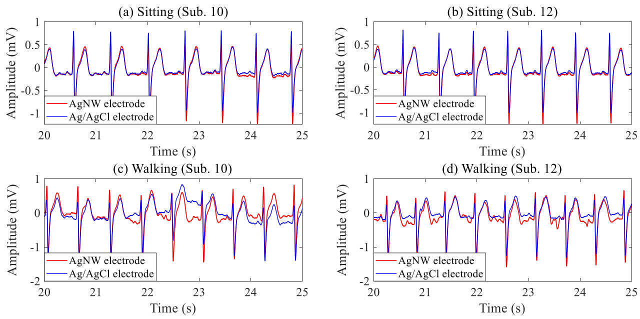

FIGURE 3. EC comparison between AgNW and Ag/AgCl electrodes.

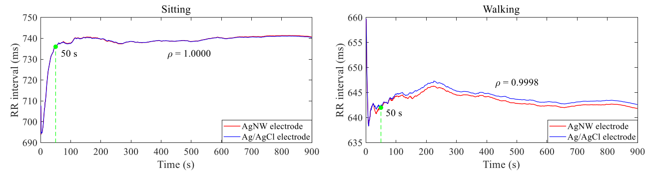

FIGURE 4. Correlation of RR intervals.

the same sample length L is defined as

$$\rho = \frac{\sum_{i=1}^{L} X_i \cdot Y_i}{\sqrt{\sum_{i=1}^{L} X_i^2 \cdot \sum_{i=1}^{L} Y_i^2}} \tag{12}$$

IV. EXPERIMENTAL RESULTS

A. ECG MORPHOLOGY

Figure 3 displayed 5-second ECG signals using the AgNW and Ag/AgCl electrodes with two subjects (Sub. 10 and 12) in sitting and walking conditions. In sitting condition, the AgNW electrode provided all the morphological features of ECG as the Ag/AgCl electrode for both subjects, although the QRS complex amplitude was slightly different. However, the waveform difference appeared in walking condition, which was mainly reflected in the waveform discrepancy due to the baseline drift. For Sub. 10, baseline drift in Ag/AgCl segment was more obvious, and for Sub. 12, the situation reversed. Nevertheless, segments from the two types of electrodes had the same heart rhythm. Despite some drawbacks of dry electrode such as likely movement, the AgNW electrode could still collect comparable ECG signal as the Ag/AgCl electrode even in ambulatory condition.

B. RR INTERVALS

Figure 4 showed the average RR intervals derived from the collected signals. The results clearly demonstrated a high RR interval correlation between AgNW and Ag/AgCl signals. In sitting condition, the correlation of RR interval was $\rho = 1.0000$, the average RR intervals were 738.4 ms and 738.5 ms respectively for AgNW and Ag/AgCl electrodes. The interval droped quickly and then increased drastically in the first 50 s, after this point, it remained stable at a constant level of approximate 740.0 ms. Similarly, the RR interval also showed high consistency ($\rho = 0.9998$) in walking condition, the averages were 644.1 ms and 643.4 ms respectively for the two electrodes. However, it dropped drastically at the beginning and then rose slightly to a stable level within the first 50 s. Finally, it remained unchanged with an average amplitude of about 645.0 ms. In the presence of RR interval, it could be believed that the AgNW electrode was able to achieve comparable heart rate estimation as the Ag/AgCl electrode.

Different from the RR interval in sitting condition, there was a small gap of approximately 2.0 ms between the AgNW and Ag/AgCl RR intervals in walking condition. This could be explained that some R-peaks were incorrectly detected due to waveform distortion caused by electrode motion. For the same signal period, algorithm might detect all the R-peaks accurately for high-quality signal but fail to achieve this for low-quality signal. If R-peaks were missed or non-R-peaks were recognized as R-peaks, the RR intervals would change correspondingly, resulting in discrepancy in RR series.

By comparing the waveforms and RR intervals from the two types of electrodes, it could be concluded that signals from AgNW and Ag/AgCl electrodes were slightly different in waveform but strongly correlated in RR series. Consequently, there should be distinct discrepancies of the evaluation indices related to signal morphology, such as sSQI, kSQI, basSQI and bsSQI. Accordingly, evaluation indices related to RR interval, such as HRV parameters, should be highly consistent.

C. SQI PARAMETERS

The detailed SQI results were summarized in Appendix Table 1-6. In general, significant statistical differences ($p < 0.05$) were identified for most of the subjects and SQI parameters in both sitting and walking conditions. More specifically, 6 SQI parameters, i.e. sSQI, kSQI, pSQI, bsSQI, eSQI and purSQI, were found to be statistically different for all the subjects in sitting condition, and 5 SQI parameters, i.e. pSQI, basSQI, eSQI, purSQI and enSQI, were found to be statistically different for all the subjects in walking condition.

All the segments of each signal were further analyzed using SQI for detailed quality information. According to the criterions in Table 1, segments from each ECG recording were evaluated and the quantities of high-quality segments for each subject were counted. As mentioned in Section 3.4.1, each ECG recording was divided into 60 segments, as a result, each subject was evaluated to have at most 60 high-quality segments for each electrode signal. Based on this operation, two points should be noted about the statistical difference. On one hand, although most SQI parameters have shown significant statistical differences, the p-value did not necessarily represent that there must be one high-quality segment with one low-quality segment at the same period for each subject. For instance, if the pSQI values of two segments were both located in [0.5, 0.8], then both of the two segments

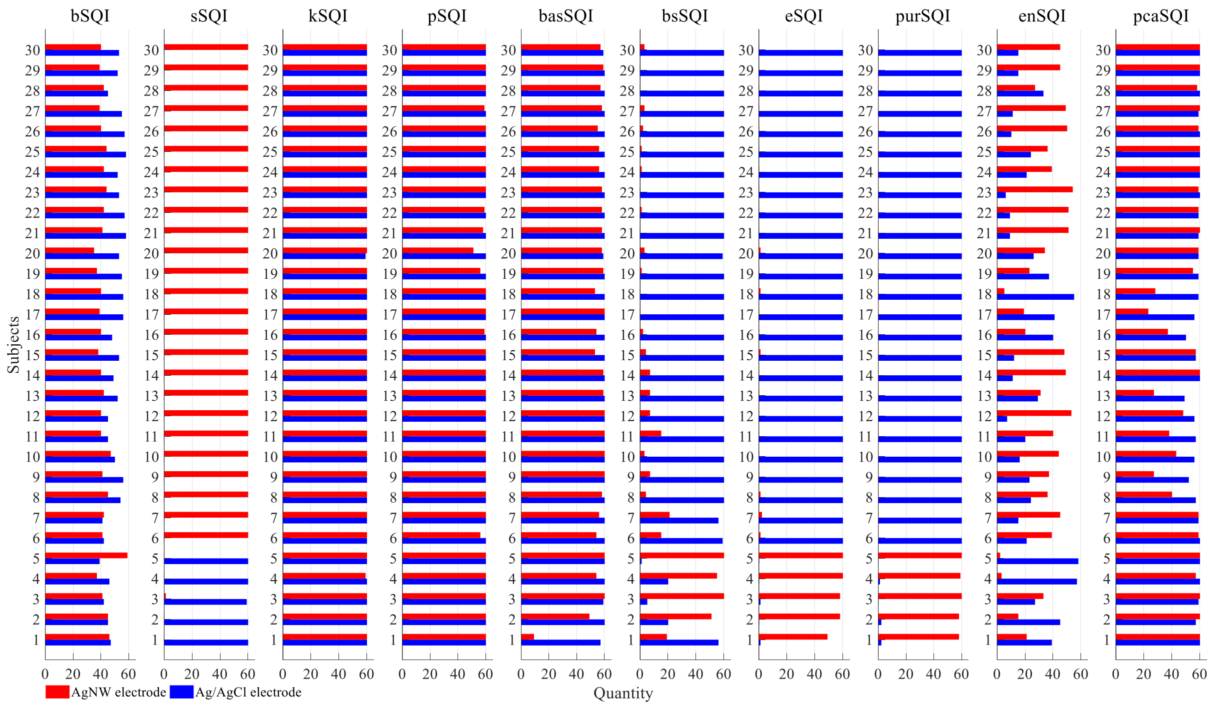

FIGURE 5. Quantity comparison of high-quality segments for each subject in sitting condition.

were regarded to have high quality with respect to pSQI. Similarly, if neither segment was located in [0.5, 0.8], then both segments were regarded to have low quality with respect to pSQI. On the other, for some SQI parameters that were statistically different, segments at the same period might also be estimated to have high quality. For instance, kSQI values were statistically different in sitting condition, however, all the recordings could be evaluated to have high quality, because kSQI values of all the segments were larger than 5.

The statistical results in sitting condition were displayed in Figure 5. As can be seen, there were totally three better SQI parameters, i.e., kSQI, pSQI and basSQI, for both AgNW and Ag/AgCl signals, almost all the signal segments were identified to have high quality with respect to the three parameters. Meanwhile, AgNW signals have claimed better quality results than Ag/AgCl signals in terms of sSQI and enSQI. For sSQI, 25 subjects have achieved 60 high-quality segments when using AgNW electrode, and only 5 subjects have achieved 60 high-quality segments when using Ag/AgCl electrode. However, the results were opposite for eSQI and purSQI. As to enSQI, although none of the subjects realized 60 high-quality segments, 20 subjects had more high-quality segments when using AgNW electrode compared to Ag/AgCl electrode. On the contrary, 28 subjects had more high-quality segments when using Ag/AgCl electrode compared to AgNW electrode for bSQI. Besides, bsSQI and pcaSQI also demonstrated better quality of Ag/AgCl signals. In summary, there were totally 5 better SQI parameters achieved for the AgNW electrode, and 8 better SQI parameters achieved for the Ag/AgCl electrode.

Figure 6 displayed the statistical results of high-quality segments in walking condition. Different from the sitting condition, only pSQI had all subjects achieved 60 high-quality segments for AgNW electrode, and no SQI parameter had all subjects achieved 60 high-quality segments for Ag/AgCl electrode. There were only two SQI parameters, i.e., eSQI and purSQI, indicating more high-quality segments when using AgNW electrode compared to Ag/AgCl electrode, by contrast, for Ag/AgCl electrode, more high-quality segments were identified by all the SQI parameters except pSQI, eSQI and purSQI. Consequently, totally 3 better SQI parameters were achieved for the AgNW electrode, and 7 better SQI parameters achieved for the Ag/AgCl electrode.

Generally, in sitting condition, AgNW electrode was able to produce ECG signal with comparable SQI parameters as Ag/AgCl electrode, but in walking condition, some parameters of AgNW electrode became worse than the Ag/AgCl electrode. The results illustrated that Ag/AgCl electrode had better property in ECG signal collection even in dynamic condition. Anyway, advantages of AgNW electrode could still be discovered from some SQI parameters. For instance, the QRS complex of AgNW signal was more distinct and could be more easily detected by different R-peak detection algorithms (bSQI), The QRS complex of AgNW signal was highly peaked (kSQI) and most of the ECG energy was concentrated in frequency band from 0 Hz to 40 Hz (pSQI). Besides, the information contained in the AgNW signal was significantly useful with less useless information and redundancy (pcaSQI).

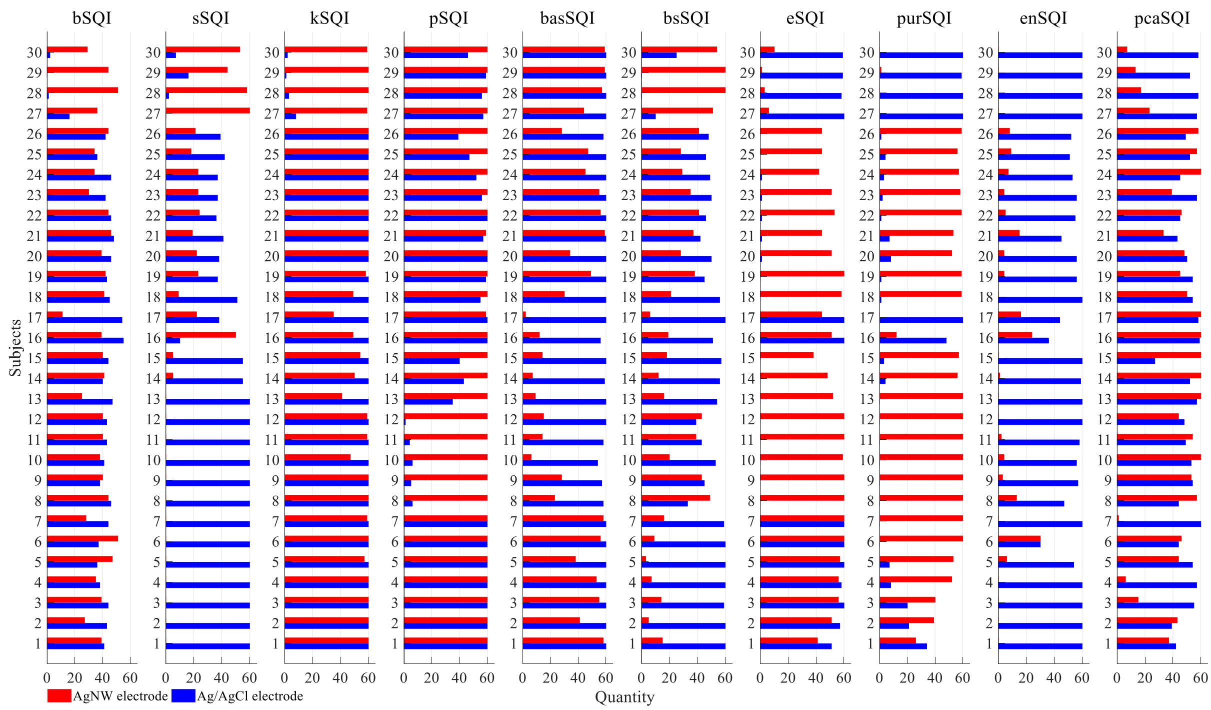

FIGURE 6. Quantity comparison of high-quality segments for each subject in walking condition.

Particularly, the AgNW signal had worse basSQI and bsSQI than the Ag/AgCl signal in both sitting and walking conditions. Almost all the subjects achieved more than 50 high-quality segments with respect to basSQI and bsSQI for Ag/AgCl electrode, as to AgNW electrode, only basSQI in sitting condition achieved comparable high-quality segments with Ag/AgCl electrode. The results meant that the baseline drift of AgNW signal was more significantly reflected than that of Ag/AgCl electrode. This was consistent with the fact that dry electrode moved more easily than gel electrode due to the lack of adhesive, causing baseline drift and even waveform distortion.

D. HRV PARAMETERS

Figure 7 displayed the average FFT amplitudes of RR series. The spectral distributions have shown excellent matches in both sitting ($\rho = 1.0000$) and walking ($\rho = 1.0000$) conditions, and most energy concentrated in frequency band below 0.4 Hz, especially in LF and HF components. Although contaminated by baseline drift and motion artifacts, the high correlation illustrated that the RR series from AgNW signal could be clearly delineated. If R-peaks were clearly identified, frequency distribution could be appropriately reflected according to the RR series.

The HRV results were displayed in Figure 8(a) (the detailed HRV results were summarized in Appendix Table 7-10). As can be seen, HRV parameters changed significantly with respect to different subjects. Nevertheless, for both sitting and waking conditions, each HRV parameter from AgNW signal was highly correlated with that from Ag/AgCl signal

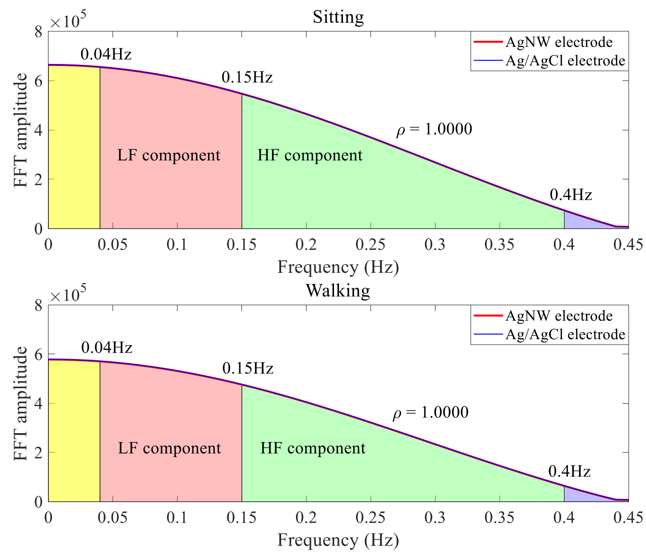

FIGURE 7. Comparison of FFT based HRV power spectra.

with little disparity, and the temporal and spectral parameters were comparable between AgNW and Ag/AgCl signals, which proved high correspondence with the consistency of RR series. Although the AgNW signal was prone to be affected by baseline drift due to electrode motion, the results demonstrated that the AgNW electrode was able to collect ECG signals with small RR variation [42], however, if not firmly fitted, AgNW electrode still needed to be improved to prevent movement on skin.

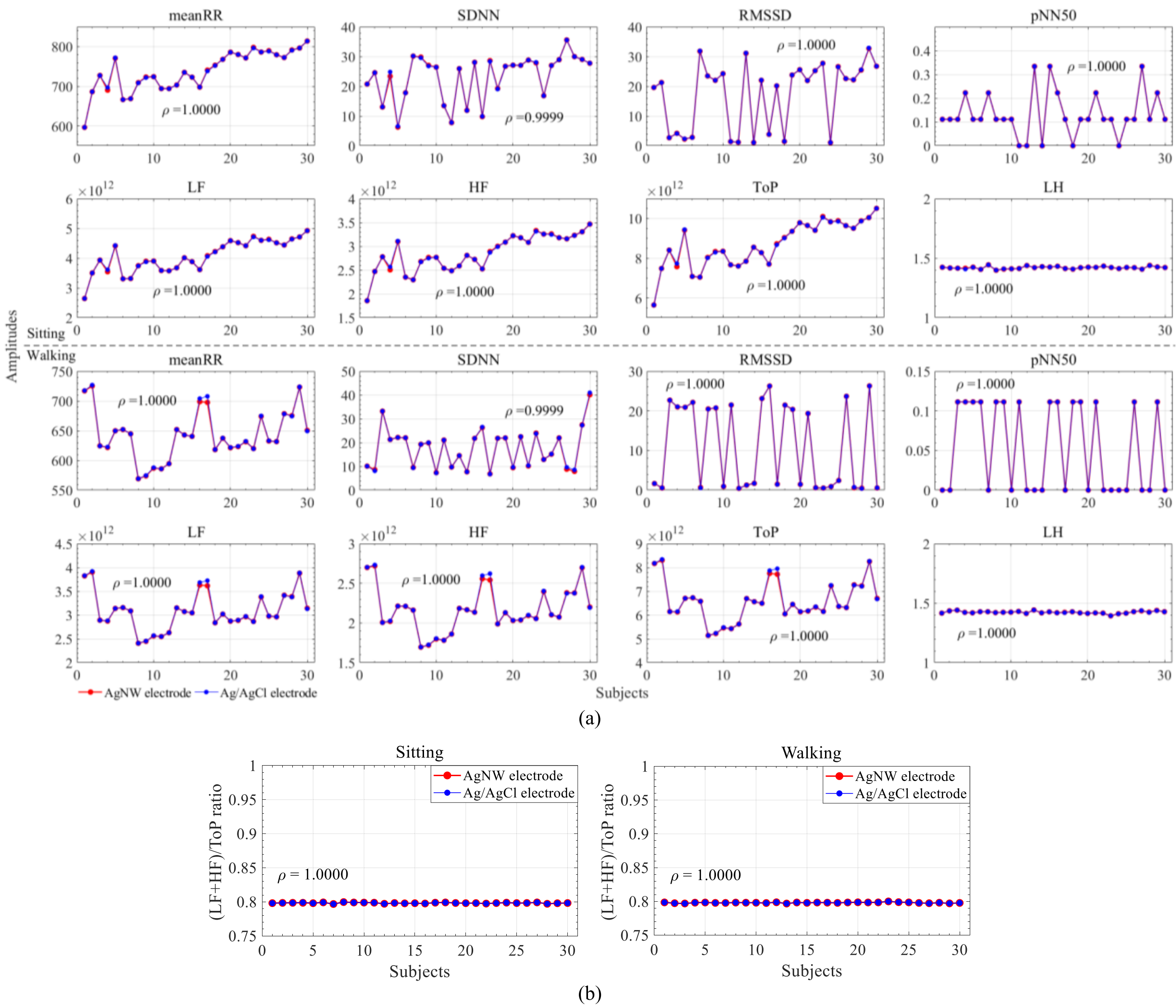

FIGURE 8. **Comparison of (a) HRV parameters and (b) LF and HF over ToP ratios.**

Regarding the spectral quality measures of HRV, the energy ratio was calculated by (LF+HF)/ToP, as displayed in Figure 8(b). Similar to the HRV parameters, the ratios were strongly correlated in both sitting and walking conditions, and all subjects have shown higher energy ratios (∼0.8). Definitely, AgNW electrode was able to collect ECG signals provided with more RR series energy concentrated in frequency band from 0.04 Hz to 0.4 Hz.

V. DISCUSSIONS

The present study attempted to compare quantitatively two types of biopotential electrodes: the reusable flexible AgNW dry electrode and the disposable commercial Ag/AgCl gel electrode. Heart activities and body potential may change in different periods, and the collected ECG signals may also have morphological variations. Consequently, synchronous ECG collection was carried out with the two types of electrodes placed adjacently. However, signal amplitudes differed slightly due to the distance between the two electrodes. To this end, all the signals were normalized to the same magnitude. In such a way, morphological changes could be minimized. Besides, signals were not further filtered after they were collected, because none of the filtration measures would have equal effect to the signal quality.

Quantification of the performance comparison of AgNW and Ag/AgCl electrode was achieved by using SQI and HRV analysis. The most critical problem restricting the development of dry electrode in clinical applications is the skin-electrode contact, which initially results in higher impedance and is more susceptibility to motion artifacts. The AgNW electrode presented good electrical characteristics, it was provided with better adhesion compared to the fabric electrode that could partly reduce the movement of electrode on skin. Actually, the AgNW electrode still needed to be fixed via some measures such as using elastic strap.

Although the AgNW signal could have comparable waveform and RR series as the Ag/AgCl electrode, the SQI parameters, especially the basSQI and bsSQI, revealed that the AgNW electrode was more susceptible to motion artifacts than Ag/AgCl electrode due to the method of attachment to the skin. As the motions became more serious, the electrode shifts across the skin more drastically, resulting in baseline drift and waveform distortion on the amplified signal. Accordingly, improving the contact between electrode and skin is a key measure to reduce the magnitude of motion noises. However, some SQI parameters demonstrated that AgNW electrode was able to collect better signal than Ag/AgCl electrode, such as sSQI and enSQI in sitting condition, eSQI and purSQI in walking condition.

Previous study has confirmed that HRV analysis represents a unique, noninvasive tool for achieving a more precise assessment of autonomic function in both the experimental and clinical settings [42]. Available research has also indicated that the significance of HF component is far better understood than the LF component. The situation with respect to LF spectral is more complicated as it is modulated by sympathetic and parasympathetic outflows. Consequently, the LF component is deficient in precise delineation of the sympathetic activation. In this study, AgNW electrode had comparable LF and HF components as Ag/AgCl electrode in both sitting and walking conditions. The results suggested that the AgNW electrode could be considered as a substitute for the Ag/AgCl electrode if the information of RR series in frequency band from 0.04 Hz to 0.4 Hz needed to be further explored.

For clinical applications, the Ag/AgCl electrode is convenient in terms of the excellent attachment to skin. The signal collected is of high quality for both monitoring and diagnostic purposes. Without the above advantages, dry electrode is currently not a practical sensor in clinical use. However, dry electrode may be suitable for situations where the patients have sensitive, allergic, damaged or burned skin. It may also be employed for neonatal skin or ambulatory monitoring situations. On the other hand, the signal quality of the AgNW electrodes can be further improved after proper adhesives are integrated to such electrodes.

It should be noted that the quality metrics employed in this study are just a recommendation and unlikely to be the optimal set of quality indicators. It may also require changes according to different patient populations or ECG collection devices. Nevertheless, the general framework described in this study should be sufficiently flexible for the utilization of arbitrary number of quality metrics. Based on a given situation, the most appropriate parameters can be selected.

VI. CONCLUSIONS

Static and ambulatory ECG signals were collected simultaneously by using AgNW and Ag/AgCl electrodes, the signals were quantitatively analyzed and evaluated in terms of SQI parameters and HRV analysis to explore the signal quality discrepancy, thus demonstrating the property of AgNW electrode compared to Ag/AgCl electrode. SQI results indicated that morphological features of all the signals could be clearly delineated. The AgNW electrode achieved 5 better SQI parameters in contrast with 8 better SQI parameters of the Ag/AgCl electrode in sitting condition. However, in walking condition, there were only 3 better SQI parameters realized for AgNW electrode, along with 7 better SQI parameters of Ag/AgCl electrode. Additionally, basSQI and bsSQI showed that the baseline drift and motion artifacts were still serious problems limiting the clinical application of AgNW electrode. HRV analysis indicated that all the HRV parameters from AgNW electrode were highly correlated with those from Ag/AgCl electrode. The AgNW electrode could have most of the RR series energy concentrated in frequency band from 0.04 Hz to 0.4 Hz, and the LF and HF components were strongly correlated with those deduced from Ag/AgCl electrode. Although much effort still needs to be taken for innovation at the skin-electrode contact level, dry electrode may be a promising substitute for commercial Ag/AgCl electrode in clinical applications.

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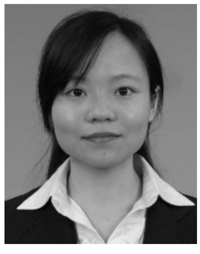

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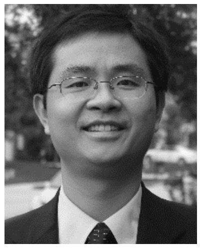

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