Precordial electrocardiographic recording and QT measurement from a novel wearable ring device

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BACKGROUND The availability of portable and wearable electrocardiographic (ECG) devices has increased secondary to technological development. Single-lead ECG recordings have been shown to reliably detect and characterize cardiac rhythms such as atrial fibrillation. Acquisition of precordial electrodes for full 12-lead ECG reconstruction from bipolar recordings is complicated by the absence of a body ground/Wilson central terminal electrode. The extent of difference between standard precordial leads and those from a wearable bipolar ECG recorder has not been characterized.

OBJECTIVE The purpose of this study was to characterize the precordial ECG lead set from sequential bipolar recordings from an ECG ring wearable device.

METHODS In 70 patients who wore an ECG device on a right-hand finger, sequential precordial leads (CR1–CR6) were obtained along with chest electrodes (V1–V6). During acquisition of the modified precordial lead CR6, a full standardized 12-lead ECG capture was obtained. Signal quality was assessed using automated analysis software, and correlation values between the ring-derived ECG precordial leads and standard ECG leads were compared with regard to QRS duration, QT width, and RR interval.

RESULTS High concordance in the morphologies of precordial ECG leads obtained in a standard fashion and those recorded through an ECG ring was observed. Morphologic alignment improved with increasing laterality of the precordial lead with chest to right arm ring recording (CR5, CR6) compared with anterior chest leads to right arm (CR1, CR2). Segmental measurements of QRS duration and QT segment were well aligned and of high correlation.

CONCLUSION Wearable ring-based ECG technology is capable of high-fidelity recordings of precordial leads for nonsimultaneous reconstruction of complete ECG sets. These recordings correlate highly with surface-obtained QRS and QT duration measurements and have significant implications for clinical applications. Uninterpretable tracings were primarily due to electrode noise from poor electrode contact.

KEYWORDS Antiarrhythmic monitoring; Arrhythmia; Electrocardiogram; Ischemia; QRS widening; QT prolongation; Wearable technology

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Introduction

Consumer-targeted wearable electrocardiographic (ECG) devices have the potential to facilitate earlier diagnoses and potentially improve outcomes through identification of coronary artery disease and cardiac arrhythmias.[1] The first generation of wearable devices has functionality primarily limited to diagnosing arrhythmic events, such as atrial fibrillation. Early research on the detection of atrial fibrillation with consumer wearable devices has shown that they are capable of reliable identification and characterization of arrhythmias.[2]

Most cardiovascular disease in developed nations are caused by coronary artery disease, which affects more than 15 million patients in the United States alone. The next generation of wearable devices aims to generate more extensive ECG projections to identify and potentially localize myocardial injury. Use of the right or left arm for precordial bipolar lead generation in a convenient wearable form factor may offer a viable solution for the detection of ischemia-/infarction-related events.

Two differences between intermittent bipolar recordings and surface ECGs are the lack of simultaneity due to sequential lead acquisition and the lack of any central "ground" reference. Chest precordial leads typically are referenced to this ground or, in the typical absence of a dedicated grounding, an "electrical average" of all limbs. The lack of this body ground or Wilson central terminal (WCT) lead in wearable devices may lead to morphologic mismatch compared to true precordial leads because the derived precordial leads are referenced to other body parts. The presence of

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KEY FINDINGS

- Wearable electrocardiogram (ECG) technology has been miniaturized to allow high-fidelity recording from a ring form factor.
- A bipolar ECG ring is able to measure QRS and QT durations of the ECG with high precision and accuracy from modified precordial measurements.
- Surface reconstruction of a full 12-lead ECG from the wearable ECG ring is possible. Alterations in precordial morphology are present because of the nature of bipolar recording and filtration artifacts.
- Automated analysis and abnormality detections from the modified recording sets may be feasible in the future.

"body ground" also decreases electrode and environmental noise, as common-mode noise signals may be noted through the recording leads and effectively canceled from the recording.

Previous studies have examined the morphology and relation of bipolar chest recordings referenced to upper arm limb electrodes,[3,4] annotating these nonstandard precordial leads as CR/L1-CR/L6, as opposed to "unipolar" V1-V6 leads that are referenced to the WCT. Previous analysis has shown concordance of CR1-CR6 with traditional precordial leads V1-V6 for ST-segment analysis and QT measurement.[3,5,6]

In this study, precordial leads from a novel wearable ECG ring were obtained and compared to the precordial leads of a standard 12-lead ECG.

Methods

All aspects of the study were approved by an independent institutional review board. One hundred five patients were recruited sequentially on study days in an outpatient interventional cardiology clinic. Inclusion criteria were age 18–85 years. Exclusion criteria included presence of pacemaker, or rapidly changing or unstable ECG over the 30-second recording period, such as intermittent atrial tachycardia. Additional exclusion criteria included movement disorder such as Parkinsonian tremor or inability to wear a ring on a finger and obtain an ECG in standard fashion. No patients

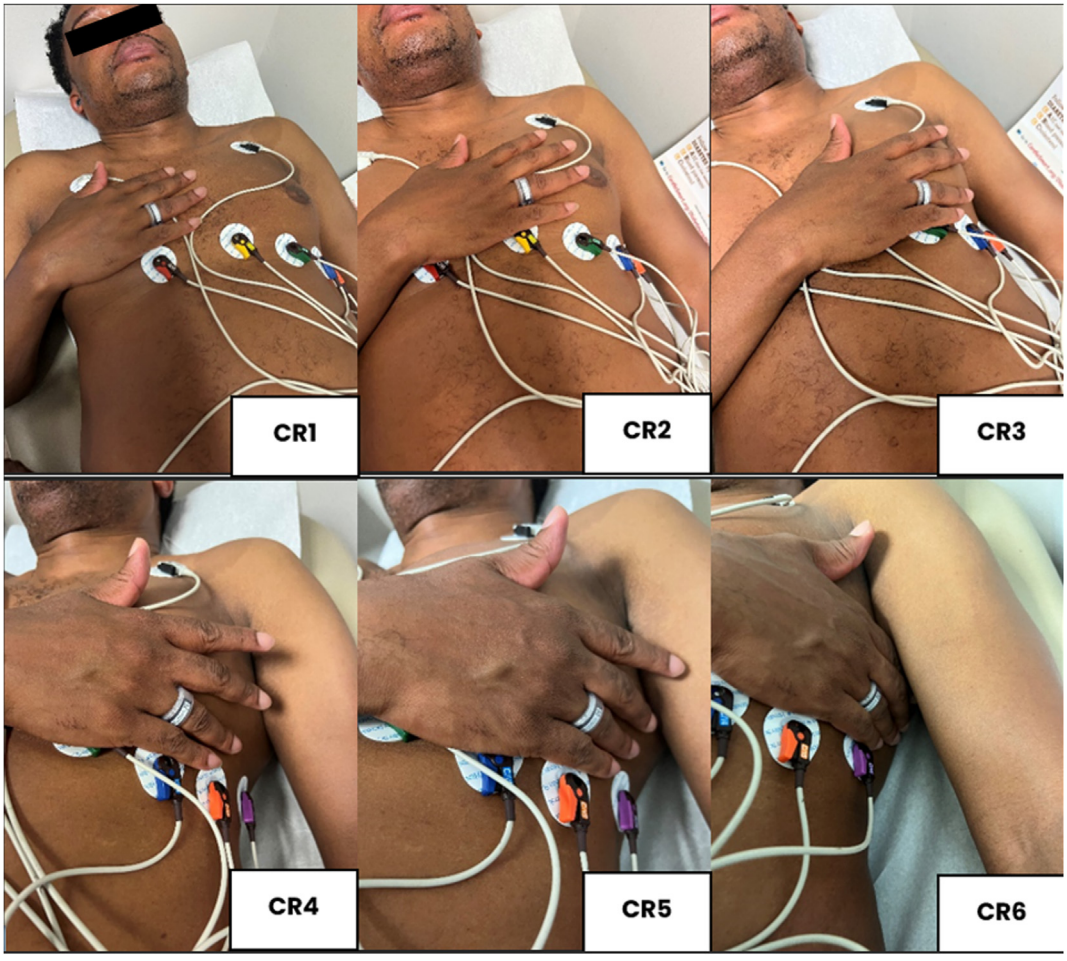

Figure 1 Modified chest precordial lead acquisition.

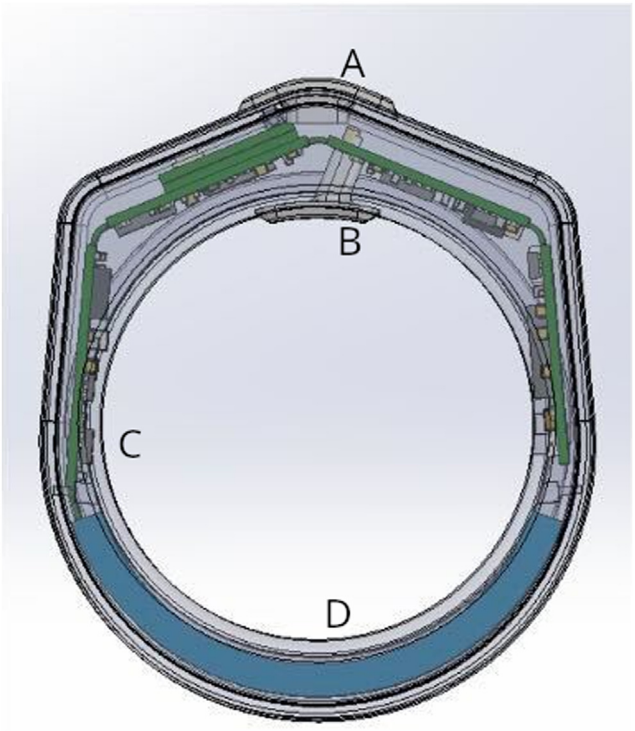

Figure 2 Electrocardiogram ring diagram. A = outer electrode; B = inner electrode; C = photoplethysmograph opening adjacent to circuit board; D = battery.

were excluded because of movement disorders or inability to wear the ring.

ECG recording rings (Everbeat, Potomac, MD) available ranged from United States/Canada sizes 8–13 in whole integer increments. Patients wore an appropriately sized ring on the index or ring finger of the right hand, allowing for a comfortable fit. Patients with ring size <8 or >13 were excluded. The right index (first) finger was used as the preferred site for all patients. If a more size-matched fit was obtained on the ring finger or if the patient preferred, the ring (fourth) finger was recommended.

Formal informed consent was obtained from all patients by a research assistant separate from the patient's clinical team. The research reported adhered to the guidelines of the Helsinki Declaration as revised in 2013.

After the patient viewed a tablet-based video instruction animation, recordings were made for 30 seconds in an asynchronous sequential fashion for each precordial ring lead location. The final 10 seconds of each 30-second ring recording was used for data analysis. Precordial recordings were obtained via the ring touching the skin of chest locations corresponding to V1-V6 areas, immediately superior to the standard full 12-lead tab electrode locations (Figure 1). Per convention, these were categorized as CR1-CR6. Patients followed on-screen application (app) prompts for positioning the ring.

Table 1 Correlation values between standard 12-lead precordial and modified (CRx) precordial ring single-lead electrocardiogram for segments

Segment for R^2 alignment	V1	V2	V3	V4	V5	V6
No. of patients	65	70	67	68	66	65
RR	.93	.92	.95	.92	.92	.92
QRS	.82	.86	.95	.94	.96	.92
QT	.80	.90	.93	.90	.91	.90

The ring structure consisted of a circuit board, battery, photoplethysmographic light emitting diode, and outer electrode and inner electrodes (Figure 2). Ring recordings were performed with 16-bit quantization at a sampling rate of 512 Hz . The outer electrode of the ECG ring was clearly visible and on the palmar side of the outside surface of the ring, and an inner electrode was located adjacent and facing the inner side of the ring, such that holding compression between these measurement electrodes tends to improve skin contact. There was no additional postrecording filtration, and the digitizer had effective bandwidth of 0.1–100 Hz. Bipolar/limb lead recordings could be obtained by touching the outer palmer electrode to the opposite hand or left leg.

A standard diagnostic 12-lead ECG was obtained with adhesive electrodes in standard positions using a GE MAC 5500 (General Electric Healthcare, Chicago, IL). The surface ECG was acquired simultaneously with CR6 ring acquisition, thus allowing direct alignment of cardiac complexes. All other ring recordings were asynchronous. Diagnostic surface ECG settings were used (bandwidth 0.05–100 Hz).

Signal quality was assessed using automated analysis software (PulseAI, Belfast, United Kingdom), and correlation was determined between ring ECG precordial leads and standard precordial ECG leads with automated measurement of QRS duration, QT width, and RR interval. If the PulseAI suite was not able to obtain sufficient signal-to-noise ratio to produce measurement, the recording was discarded and not counted toward the recording total, resulting in different numbers for final number of measurements (Table 1). Direct correlation was performed with Bland-Altman analysis to evaluate concordance and bias. Leads with unacceptable noise levels that prevented algorithmic interpretation were not included in analysis but were noted.

Results

Of the total 150 patients who were eligible for the study, 105 agreed to participate, and 70 completed the study. Fifty-two patients were male (74%), and median age was 61 $\pm$ 7 years (range 21–84 years). Thirty-five patients were unable to obtain 5 or more ring-based precordial lead recordings suitable for automated analysis because of either difficulty in holding the posture required and ensuring electrode contact without muscle or other artifact or inability to follow tablet-based app instructions. The adhesive electrode-based surface ECG was successful in all 70 patients who completed the ring-based precordial recording set. Of these 70 patients, 42 (60%) wore the device on the index finger; the remaining patients wore the device on the fourth finger.

For the patients with complete recording sets, individual tracings with a single unreadable ring-based ECG lead

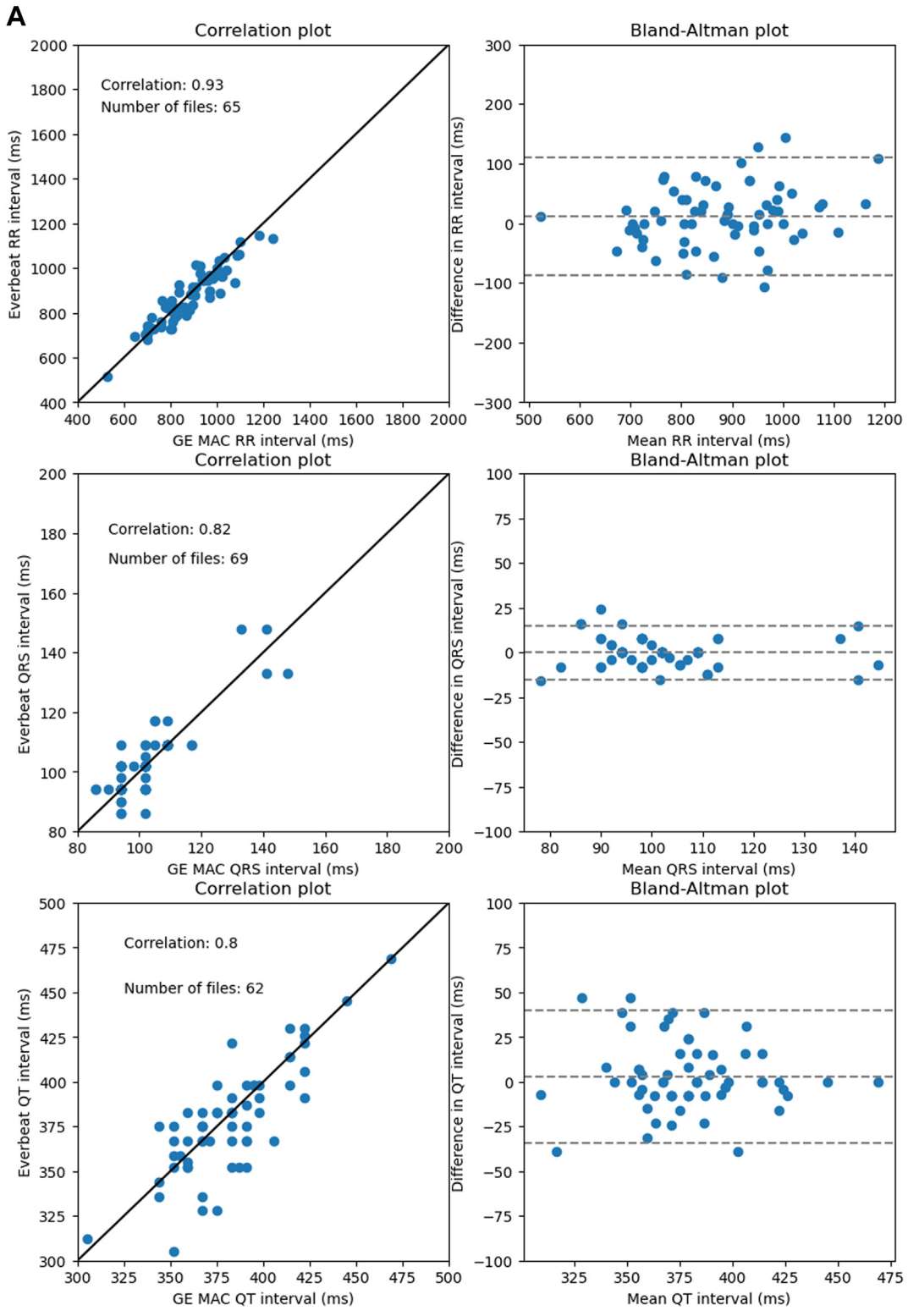

Figure 3 R^2 and Bland-Altman correlation plots between single-lead and corresponding ring-based electrocardiographic recordings for leads V1 and V5. **A:** V1-CR1 correlation. **B:** V5-CR5 correlation.

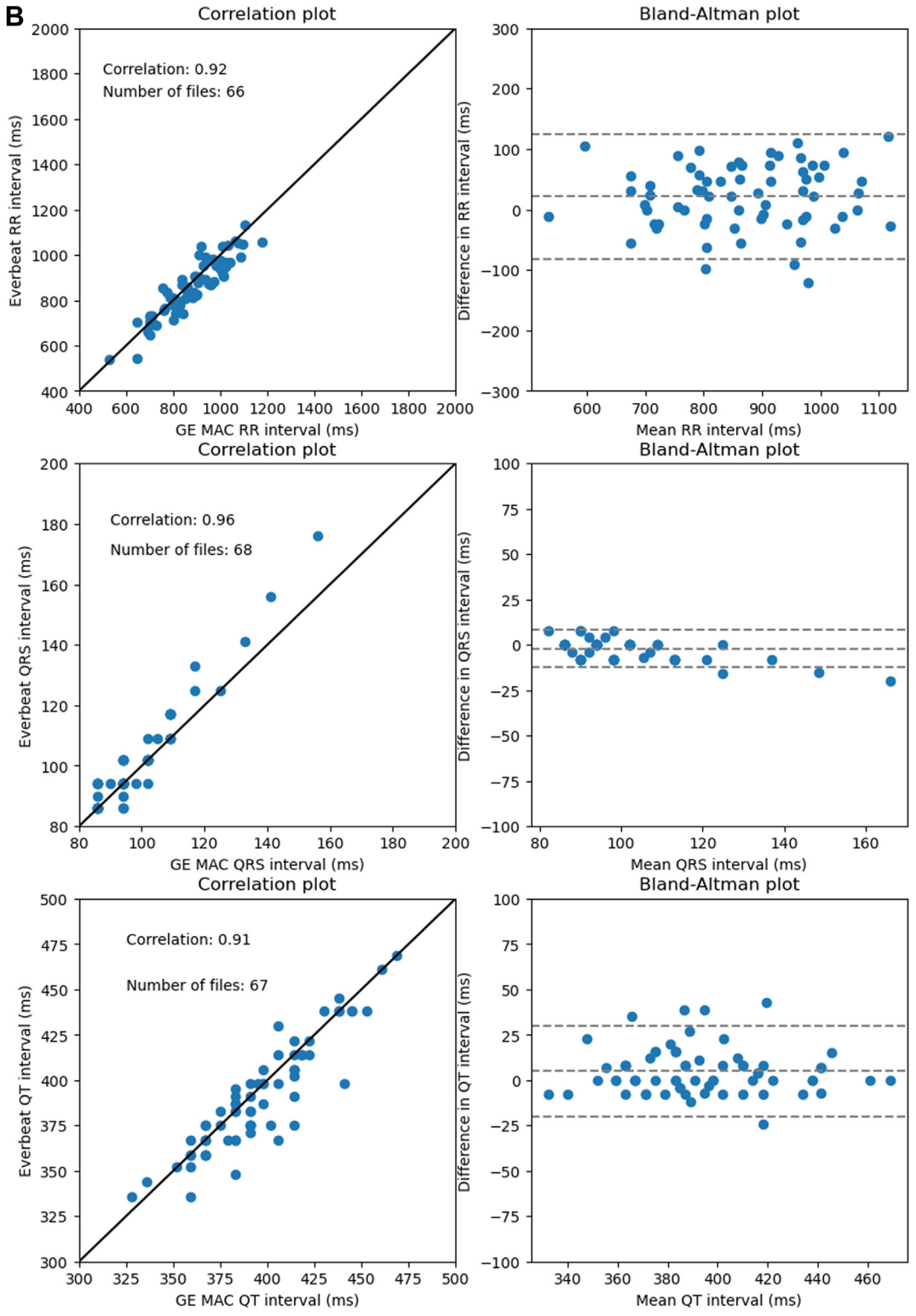

Figure 3 continued

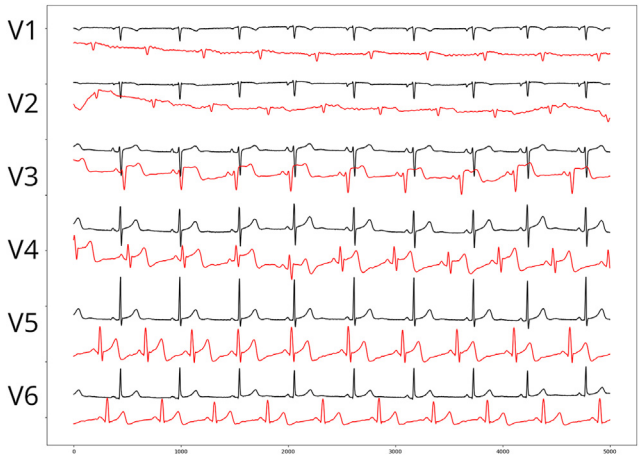

Figure 4 Representative tracings of simultaneous, standard precordial electrocardiographic leads and nonsequential ring-based precordial leads. The simultaneous 12-lead precordial lead set (V1-V6) *(black)* is displayed immediately above the corresponding nonsimultaneous ring-based precordial lead set (CR1-CR6) *(red)*. Time is given in milliseconds.

recording or with marked noise greater than the signal were discarded on a lead-by-lead basis. Of the 70 recordings obtained, between 65 and 70 ($\mu = 67$) noise-free tracings per precordial lead were used for the final analysis (Table 1). The most common reasons for exclusion of a single lead set were intermittent electrode contact giving "electrode chatter" noise and marked movement artifact giving noise over the recording period, resulting in insufficient signal-to-noise ratio for analysis.

Segmental analysis

A comparison of CR1-CR6 and V1-V6 measurements of RR, QRS, and QT intervals is given in Table 1. Overall, the correlation between RR intervals ranged from 0.92–0.95 for all leads, reflecting a high degree of reliability for QRS identification and measurement of heart rate and intervals using the wearable ring ECG. The correlation between QRS duration ranged from 0.82–0.96, and between QT interval measurements ranged from 0.80–0.93. Lateral precordial lead sets had a higher correlation with the surface unipolar precordial leads for all measurements.

Correlation and Bland-Altman plots for RR interval, QRS duration, and QT-segment length for leads CR1 vs V1 and for CR5 vs V5 demonstrated no significant QT bias (Figure 3). A representative ring tracing and 12-lead precordial dataset are shown in Figure 4. Due to rapid deflection of the QRS and the filtration limits (0.1-Hz high-pass filtration vs diagnostic-quality 0.05 HPF, which preserves "DC offset" values), there is alteration of the J point and ST offset compared to the diagnostic ECG.

Discussion

This study demonstrates that high-quality asynchronous precordial leads can be obtained from a finger-worn wearable ECG ring through dry electrode contact with the patient's chest. The modified chest leads (CR1-C6) have high morphologic alignment with standard unipolar chest leads (V1-V6) and improve with increased laterality (V5-V6).

Improved morphologic concordance with lateral chest electrodes is expected based on the relationship between the bipolar recording locations relative to where the body ground would be located. With increasing laterality of the chest, the right arm is in alignment with the body ground, whereas in septal precordial leads the WCT would be aligned with or posterior to the heart, and the right arm would give a significantly more rightward effective ground.

Despite differences in morphology, there is excellent QRS and QT concordance with $R^2 > 0.90$ for ring-based measurement between CR3-CR6 and V3-V6, indicating that these leads are attractive candidates for clinical-grade, at-home QT monitoring. No significant under- or overestimation bias was observed.

Study limitations

Limitations of the study include the relatively small number of patients and the substantial number of patients who were not able to capture a full precordial CR lead set solely with app-based instruction. In-person assistance or tablet-based UI assist with graded pedagogy (start with acquiring 1 lead and give feedback regarding contact and noise) may be important for obtaining improved results. Although the QRS and QT durations were demonstrated to be well correlated, direct ST-segment offset and morphology would not be well correlated with diagnostic ECG (Figure 4), in a similar fashion to the alteration in ST-segment morphology observed when filtered recordings such as telemetry ECG are used. This filtration is required to suppress wandering baseline and noise and to improve usability of the recording. However, because the morphologic changes are predictable, changes from the baseline QRST morphology may be considered for advanced or automated analysis in the future.

Conclusion

ECGs reconstructed from a wearable ECG ring produce highly accurate measurements of RR intervals and QRS and QT durations, and have generally favorable morphologic comparison to traditionally acquired full simultaneously recorded 12-lead ECG precordial leads. Lateral precordial CR leads are more morphologically aligned with 12-lead precordial tracings due to the aligned projection of the opposite hand with the absent central electrode. As wearable ring form factor ECGs become more refined and technologically enabled, the clinical application for early detection of cardiovascular disease could be of significant value in decreasing the time to recognition of atrial fibrillation, in detection of repolarization abnormalities, and in identification of arrhythmic events. If ring-based ECG leads are shown to be accurate and stable over time, automated recognition of changes of QRST morphology indicative of coronary disease or ischemic events may be possible.

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Disclosures
Dr G. Stuart Mendenhall, Dr Matthew Jones, and Greg Eoyang hold equity in Grektek Holdings, Inc. (dba Everbeat), which plans to manufacture a wearable ring that is capable of single-lead ECG recordings. Dr Alan Kennedy holds equity in PulseAI, which uses AI techniques for electrocardiographic interpretation. Dr Charles Pollack and Dr Steven H. Silber are on the Advisory Board of Grektek.

Authorship
All authors attest they meet the current ICMJE criteria for authorship.

Patient Consent
Formal informed consent was obtained from all patients by a research assistant separate from the patient's clinical team.

Ethics Statement
The research reported adhered to the guidelines of the Helsinki Declaration as revised in 2013.

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