ECG-based Indices of Physical Activity

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Abstract

Inter-subject comparisons of heart rate variability (HRV) require that physical activity levels be matched between subjects, to minimize the confounding effects of intra-subject variability in HRV measurements. HRV studies based on standard ECG recordings are hindered by these effects. The current study investigated methods for finding periods of minimum physical activity based on the ECG alone. This paper describes an "activity index" (based on mean heart rate, total power of the observed heart rate signal, and a heart rate "stationarity index"), and presents an algorithm for locating periods of minimum activity by tracking this activity index. The algorithm was tested using a set of 35 ECG recordings for which an independent activity indicator was available. The algorithm consistently selected periods of minimum activity in agreement with the independent activity indicator. No discrepancies were noted in any of the 35 cases.

Introduction

Most short- and medium-term (up to one hour) measurements of heart rate variability are themselves highly variable over time. This intra-subject variability limits the value of inter-subject comparisons of these measurements, unless periods of comparable physical activity can be matched. With the goal of being able to make such comparisons in the absence of independent activity data, this study investigated methods for finding periods of minimum activity based on the ECG alone. Such periods are well-suited for HRV comparisons, since minimum activity levels are usually comparable even when maximum or average activity levels are not. Independent of these considerations, inter-beat intervals (hence HRV measurements derived from them) are usually measured most accurately during the noise-free ECG segments that occur most often during periods of minimum activity.

Heart rate

Many definitions of heart rate are possible. This study makes use of both *instantaneous* heart rate, $H(t)$, and *mean* heart rate, $\overline{H}_N(t)$, as defined below.

Given the sequence of beat arrival times R_n, where n denotes the beat number, a uniformly sampled instantaneous heart rate signal may be defined as

$$H(t) = \frac{1}{2k\Delta t}\left(\frac{R_i-(t-k\Delta t)}{R_i-R_{i-1}} + (j-i) - \frac{R_j-(t+k\Delta t)}{R_j-R_{j-1}}\right) \tag{1}$$

where Δt is the desired sampling interval for $H(t)$, k is a smoothing parameter, and i and j have been chosen such that

$$\begin{aligned} R_{i-1} &\le t-k\Delta t < R_i \\ R_{j-1} &< t+k\Delta t \le R_j \end{aligned} \tag{2}$$

The middle term $(j-i)$ in equation (1) thus represents one more than the number of complete interbeat intervals within a window of width $2k\Delta t$ centered on t; the first term is the fraction of the previous interval within the window, and the last term is the fraction of the final interval that falls outside the window. From the instantaneous rate $H(t)$, we derive the mean heart rate:

$$\overline{H}_N(t) = \frac{1}{2N}\sum_{n=-N}^{N-1} H(t+n\Delta t) \tag{3}$$

In the present study, $\Delta t = 0.5$ seconds, $k = 1$, and $N = 300$ (i.e., mean heart rate is determined over a period of $2N\Delta t = 5$ minutes).

Correlates of physical activity in the ECG

Among the candidates for inclusion in an ECG-based activity index are:

- mean heart rate
- total power of the observed heart rate signal
- "stationarity" of the heart rate signal
- ectopic beat rate
- ST segment deviation
- QT interval
- noise content of the ECG

Mean heart rate is the most obvious of these, since it responds directly to changes in the level of physical activity. Many other factors influence mean heart rate, however, so that mean heart rate in isolation is inadequate as an index of activity. It should be noted that systematic detector errors can occasionally result in erroneous measurements of mean heart rate; this observation alone suggests the need for additional components in an activity index.

The total power measurement is strongly influenced by QRS detector errors, which affect virtually all HRV measurements. These errors include not only missed or extra detections, but also mismeasured fiducial points. Any of these errors is most likely to occur when the ECG is noise-corrupted, which in turn is most likely to occur when the subject is relatively active. The inclusion of total power in an activity index is thus motivated primarily by the need to account for imperfect signal processing rather than any intrinsic property of the signal source. In this study, total power is defined as

$$P(t) = \frac{1}{2N} \sum_{n=-N}^{N-1} \left(H(t + n\Delta t) - \overline{H}_N(t) \right)^2 \qquad (4)$$

where N, $H(t)$, Δt, and $\overline{H}_N(t)$ are defined as above.

"Stationarity" of the heart rate signal refers to the likelihood that a trend is present during the window of observation; such a trend is likely to be associated with a change in activity level. For this study, a simple index of stationarity is defined as

$$S(t) = \left| \overline{H}_{N/2}(t - \frac{N}{2}\Delta t) - \overline{H}_{N/2}(t + \frac{N}{2}\Delta t) \right| \qquad (5)$$

where N and Δt are defined as above, and $\overline{H}_{N/2}(t)$ is the mean heart rate over a window only half the length of that in equation (3).

Although changes in ectopic beat rate, ST deviation, and QT interval are often associated with activity, no such changes are observable during the normal activities of many subjects, reducing the value of these indices for the purposes of this study. Similarly, although an increase in the noise content of the ECG is strong evidence for an increase in the level of physical activity, the absence of significant noise may simply indicate good practice in electrode application.

More significantly, it is possible to derive mean heart rate, total power, and stationarity from an RR interval sequence without reference to the original ECG. An activity index based on these three measures may be obtained easily from the computer-readable RR interval files produced by many modern ECG analyzers. The other measures are not always available, and when they are provided tend to be less reliable than are RR interval measurements. For these reasons, the present study focussed on an activity index based on mean heart rate, total power, and stationarity only.

Derivation of the activity index

We may transform any sequence of interbeat intervals into an instantaneous heart rate signal $H(t)$, and derive a corresponding trajectory in the 3-d space defined by $\overline{H}_N(t)$, $P(t)$, and $S(t)$ (Figure 1). In general, one would expect to find that all three variables increase with activity, and that the times of minimum activity would occur when the trajectory most closely approaches the point indicated in Figure 1 as the "ideal resting ECG". This point, $\{H_r, P_r, S_r\}$, does not coincide with the origin, since extremely low mean heart rate measurements are likely to be erroneous; for this reason, it has been placed at $H_r = 40$ beats per minute (bpm), with $P_r = S_r = 0$. An activity index may be defined as the Euclidean distance of the trajectory from the "ideal resting ECG":

$$A(t) = c + \sqrt{a_1(\overline{H}_N(t) - H_r)^2 + a_2 S(t)^2 + a_3 P(t)} \qquad (6)$$

where the scaling constants may be determined empirically (for this study, $a_1 = 1$, $a_2 = 10$, and $a_3 = 100$), and c is a correction term for very low heart rate measurements:

$$c = \begin{cases} 25\,\text{bpm} - \overline{H}_N(t) & \text{if } \overline{H}_N(t) < 25\,\text{bpm} \\ 0 & \text{otherwise} \end{cases} \qquad (7)$$

In unusual cases, $P(t)$ may be large throughout a recording. This can occur in the context of sustained atrial fibrillation, or if the recording quality is uniformly poor, resulting in many detector errors. In such cases, random fluctuations in $P(t)$ might have a dominant influence on $A(t)$. In HRV studies, such recordings are typically excluded, so that this behavior is not usually a problem. It may be avoided if necessary by placing an upper bound on $P(t)$ before determining $A(t)$.

Evaluation

The algorithm described above was implemented in a short C-language program (see the appendix below). The program was tested using a set of 35 ECG recordings (originally compiled for another study) for which a simultaneously recorded gait (walking cadence) signal was available as an independent activity indicator[1]. These recordings were made using conventional two-channel ambulatory ECG recorders, but up to four foot switch signals were multiplexed and recorded in lieu of one of the ECG signals. Each recording was between 18 and 79 minutes long; most were approximately 35 minutes. Three activities were recorded: in the first phase (R), subjects rested in a supine position for five to twenty minutes; in the second phase (S), subjects were asked to stand for six minutes; and in the third phase (W), subjects walked at a comfortable pace for at least eight minutes. The population included twelve young (aged 27 ± 5) and eleven elderly (aged 76 ± 5) subjects; the ages of the remaining subjects were not noted.

The ARISTOTLE arrhythmia detector[2] analyzed the ECG signal from each recording, generating an annotation file containing encoded beat labels. The `tach` postprocessor[3] extracted the interbeat intervals from ARISTOTLE's annotation file and generated a uniformly

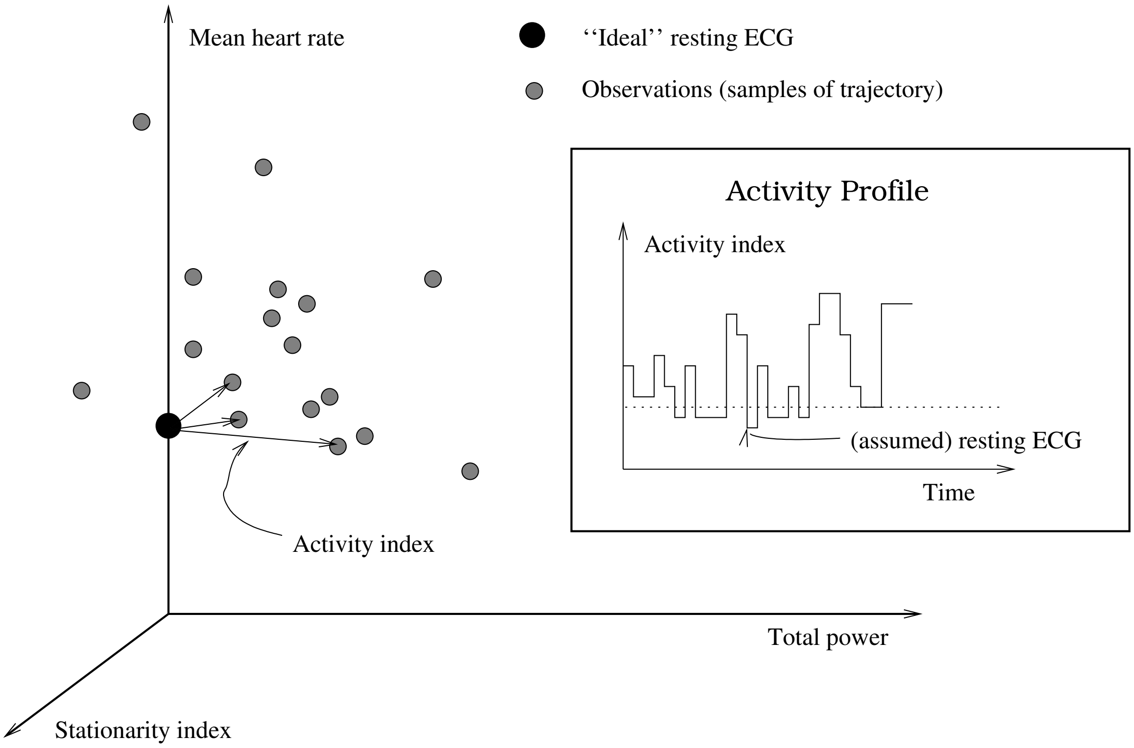

Figure 1. Derivation of the activity index.

sampled (2 Hz) instantaneous heart rate signal for each recording using the method of equation (1). This signal was used as the input to the activity estimator.

Software developed for the purpose analyzed the foot switch signals, producing step annotation files similar to ARISTOTLE's beat annotation files for each record. In order to obtain an accurate independent index of activity, the step annotations were corrected manually as necessary (note that no corrections were applied to the beat annotations, however). The corrected step annotations were then processed using `tach` as for the beat annotations, to obtain a uniformly sampled instantaneous gait signal. This signal was taken as the "gold standard" measurement of physical activity. The three phases of the experimental protocol (R, S, and W) are easily identified from the gait signal.

The ECG-based activity index was derived from the instantaneous heart rate signal at 2.5-minute intervals throughout each recording. A typical example is presented in Figure 2.

For each recording, the five-minute period for which the activity index was minimum was identified. In all 35 cases, this period fell entirely within the resting phase, as had been determined independently from observation of the gait signal. For comparison, alternative indices containing only one component of $A(t)$ were tested. The resting phase was identified successfully in 30 of 35 cases using $\overline{H}_N(t)$, in 21 of 35 cases using $S(t)$, and in 27 of 35 cases using $P(t)$.

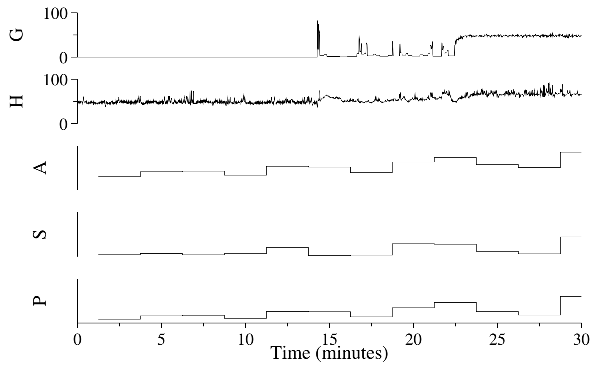

Figure 2. An example of the recordings used to evaluate the activity index. G: instantaneous gait (steps per minute); H: instantaneous heart rate, $H(t)$ (beats per minute); A: activity index, $A(t)$; S: stationarity index, $S(t)$; P: power, $P(t)$. $A(t)$, $S(t)$, and $P(t)$ are updated at intervals of 2.5 minutes. The recording begins during the resting phase. The standing phase begins during minute 14 and ends during minute 23, when the walking phase begins. The minimum activity index occurs in the first five minutes in this case.

Conclusions

Periods of minimum physical activity can be identified reliably using the methods described above, given uncorrected ECG annotations of the quality obtained by ARISTOTLE on the test recordings. This technique should be particularly useful in multi-patient studies of heart rate variability as a means of reducing intra-patient variability, when independent records of physical activity are not available.

Acknowledgements

The author wishes to thank Jeffrey Hausdorff for making available the recordings that were used to evaluate the methods described above; and Ary Goldberger, Jeffrey Hausdorff, Roger Mark, Joseph Mietus, and David Rigney for discussions of these and related issues.

References

[1] J.M. Hausdorff, D.E. Forman, D.M. Pilgrim, D.R. Rigney, J.Y. Wei. A new technique for simultaneous monitoring of electrocardiogram and walking cadence. *Am. J. Cardiol.* **70**:1064–1071, Oct. 1992.

[2] G.B. Moody, R.G. Mark. Development and evaluation of a 2-lead ECG analysis program. *Computers in Cardiology* **9**:39–44 (1982).

[3] G.B. Moody. `tach` [C-language software, available from PhysioNet, `http://www.physionet.org/`].

Appendix

The C program below determines the period of minimum activity using the techniques described above. Its input should be a list of instantaneous heart rates (in bpm) at uniform intervals of 0.5 seconds; `tach`[3] can produce these data given a list of beat arrival times. The program makes a measurement of the activity index once every 2.5 minutes; each measurement reflects activity over the previous five minutes.

```
#include <stdio.h>
#include <math.h>
#define DT (0.5)
#define N 300

main()
{
  double a, amin = -1.0, h[2*N], hs0, hs1, mh,
         p, s;
  int i = 0, i0 = N;
  long t, tmin;

  for (t = 1L; scanf("%lf", &h[i]) == 1; t++) {
    if (++i >= i0+N) {
      if (amin < 0.)
        for (i = 0, hs0 = 0.; i < N; i++)
          hs0 += h[i];
      else hs0 = hs1;
      for (i = i0, hs1 = 0.; i < i0+N; i++)
        hs1 += h[i];
      mh = (hs0 + hs1)/(2*N);
      s = fabs(hs0 - hs1)/N;
      for (i = 0, p = 0.; i < 2*N; i++)
        p += (h[i] - mh)*(h[i] - mh);
      p /= 2*N;
      if (p > 100.) p = 100.;
      a = sqrt((mh-40)*(mh-40) + 10*s*s + 100*p);
      if (mh < 25.) a += 25. - mh;
      if (a < amin || amin < 0.) {
        amin = a;
        tmin = t;
      }
      i = i0 = N - i0;
    }
  }
  if (amin >= 0.)
    printf("Minimum activity from %g to %g\n",
           (tmin - 2*N)*DT, tmin*DT);
}
```

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