Identification of Steady States and Quantification of Transition Periods from Beat-by-Beat Cardiovascular Time Series: Application to Incremental Exercise Test

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Abstract

A recently proposed procedure for checking the cardiovascular steady state from beat-by-beat values of blood pressure and heart rate was used for investigating incremental exercise tests. We measured continuous blood pressure in 5 volunteers during rest, incremental exercise until volitional exhaustion, and recovery, and derived a "steadiness profile" over the whole recording. During exercise, the level of steadiness was higher in the best trained subjects. Steady state was lost at the maximum workload, WL_{max}, in all the subjects. Recovery time, measured as the period to reach a new steady state after exercise, seems to be inversely related to WL_{max}, ranging from 254s for the best trained subject (WL_{max} = 275W) to 350s for the less trained one (WL_{max} = 175W). The analysis showed that the procedure can check the hypothesis of steady state during exercise tests, and provide useful information to better describe the level of physical fitness.

1. Introduction

The steady state of the cardiovascular system is often required in studies aimed at evaluating the functional characteristics of circulation from spontaneous fluctuations of blood pressure and heart rate. Indeed, any activation of the cardiovascular system, like during physical exercise, mental stress or pharmacological stimulation, is frequently evaluated by comparing blood pressure and heart rate data collected in this condition with data recorded in baseline conditions where the steady state of the subject is assumed.

In this context, we recently proposed an algorithm to automatically check the steady-state hypothesis from blood pressure and heart rate variabilities [1]. The algorithm is based on the "run-test" (a test to detect trends), applied on systolic and diastolic blood pressures and on R-R intervals to get a global index. The steady-state hypothesis is rejected if this global index is lower than a certain threshold. The algorithm allows us to evaluate the steadiness of the cardiovascular system during experimental session, or during long-term recordings in free-behaving subjects.

Another application of the algorithm, however, became apparent when we studied exercise tests. We realized that our algorithm can be used not only to identify periods of steady state, but also to describe how the cardiovascular system reacts to a physical effort by quantifying the duration of transients between steady states.

It is recalled that exercise tests are commonly used to quantify the level of physical fitness in patients during cardiovascular rehabilitation and athletes. The test consists of signals recording during a reference period at rest, and during a subsequent exercise session. Exercise is performed at a fixed workload or, in case of incremental exercise test, with a workload which increases linearly until volitional exhaustion or until a certain fraction of the subject's maximal heart rate is reached. The recording continues after the end of exercise during the recovery period. A widely used index of fitness is the recovery time, defined as the time needed by the cardiovascular variables to reach the values they had before exercise. This definition, however, is critical. First, because it assumes that the cardiovascular variables are measured in a steady state during the reference condition before exercise; second, because after exercise the cardiovascular system may stabilize to a new working point, different from that observed before exercise; and third, because the spontaneous cardiovascular variability makes it difficult to univocally evaluate when the cardiovascular variables reach a certain reference level. In practice, recovery time is usually estimated by visual inspection of the time series, or through semi-empirical rules (like the period needed by the heart rate to fall below a threshold arbitrarily defined on the base of pre-exercise data). Our procedure could provide an objective measure of the recovery time, independent from the conditions before exercise, by quantifying it as the time period needed to reach a new steady state after the end of exercise.

In this study we investigated whether our procedure for the identification of cardiovascular steady states may be used to better analyze incremental exercise tests. In particular, we applied our algorithm 1) to verify the hypothesis of steady state during rest; 2) to identify the load at which the steady state is lost; and 3) to verify whether the end of exercise is associated with a condition of unsteady state and, in this case, if the transition time to a new steady state can be considered as a measure of physical fitness.

2. Methods

Blood pressure (Finapres) and ECG were recorded in 5 healthy subjects sitting on a cycloergometer: 1) at rest (15 min); 2) cycling at progressive loads (25W/min) from 0 W up to the maximum volitional load; and 3) during the recovery period.

Beat-to-beat values of systolic and diastolic blood pressure (SBP and DBP) and of R-R intervals (RRI) were derived from each recording (fig.1).

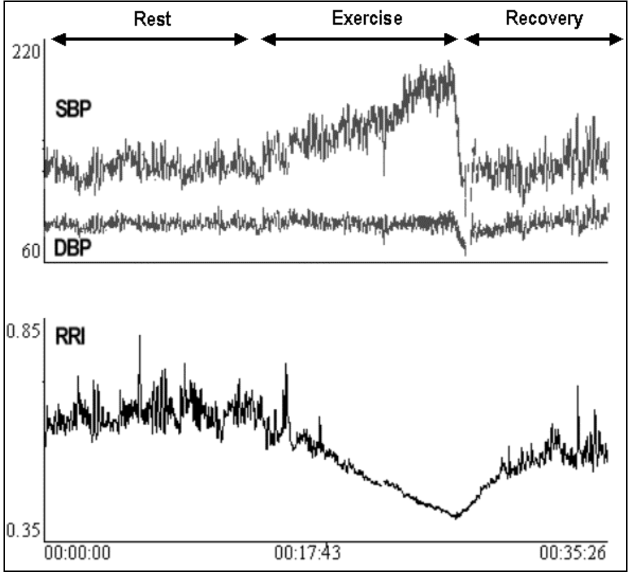

Figure 1. Example of beat-to-beat data during incremental exercise test. Systolic (SBP) and diastolic (DBP) blood pressures, in mmHg; R-R intervals (RRI), in s.

A "steadiness" profile was derived by applying our procedure described in [1]. Core of the procedure is the "run test", a statistical test for detecting trends in time series [2]. Briefly, we split each beat-by-beat series into consecutive, non-overlapping windows of length T=20 s, and computed the mean value in each window. The calculation of means over 20 seconds removes the fast fluctuations due to respiration and to the "ten-seconds" rhythm, which may mask trends in the time series.

Then we considered a running segment of N=14 means. The *k-th* running segment is composed of means evaluated between $(k-1)T$ and $(k-1+N)T$. In each segment k, we computed the median of the N means; we associated the symbol "+" to each mean when it was greater than the local median, the symbol "-" otherwise; and finally we calculated the number of runs $r(k)$ as the number of sequences of consecutive "+" or "-" symbols in the string of N symbols. Figure 2 illustrates how $r(k)$ is evaluated.

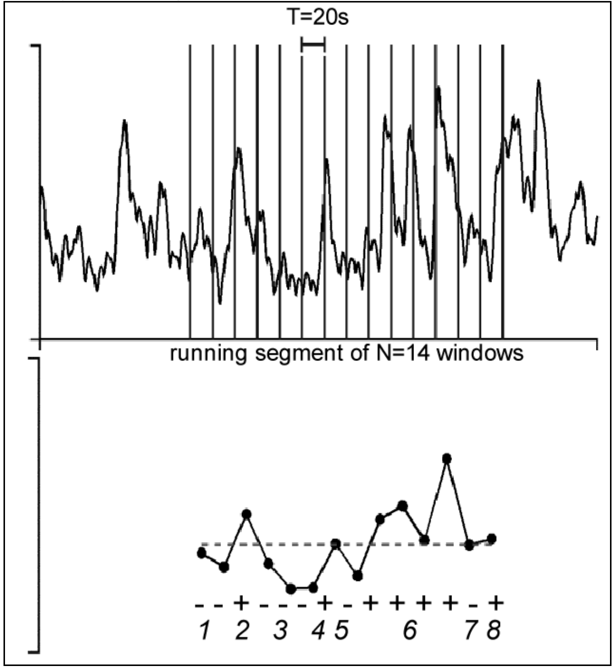

Figure 2. Calculation of the number of runs over a running segment. The series is split into 20-s long windows (upper panel); the means in each window of a running segment of 14 windows are computed (lower panel); a "+" is assigned if the mean is above the median (dashed line), a "-" otherwise; sequences of consecutive symbols are identified; the number of these sequences (8 in the example) is the number of runs.

This procedure was performed on SBP, DBP and RRI series separately, obtaining $r_{SBP}(k)$, $r_{DBP}(k)$ and $r_{RRI}(k)$. Finally, the total number of runs, $r_{TOT}(k)$ was computed as:

$$r_{TOT}(k)= r_{SBP}(k)+ r_{DBP}(k)+ r_{RRI}(k)$$

If a local trend is present in the *k-th* running segment for one or more beat-to-beat series, then the total number of runs tends to be lower than the expected value.

In [1] we derived empirically the critical region of r_{TOT}, r_{CR}, for a segment of N means at the statistical level α=5% obtaining:

$$r_{CR} = 0.69N + 5.68$$

When $r_{TOT}(k)$ is lower than 15.34 (r_{CR} value when N=14), we reject the hypothesis of steady state.

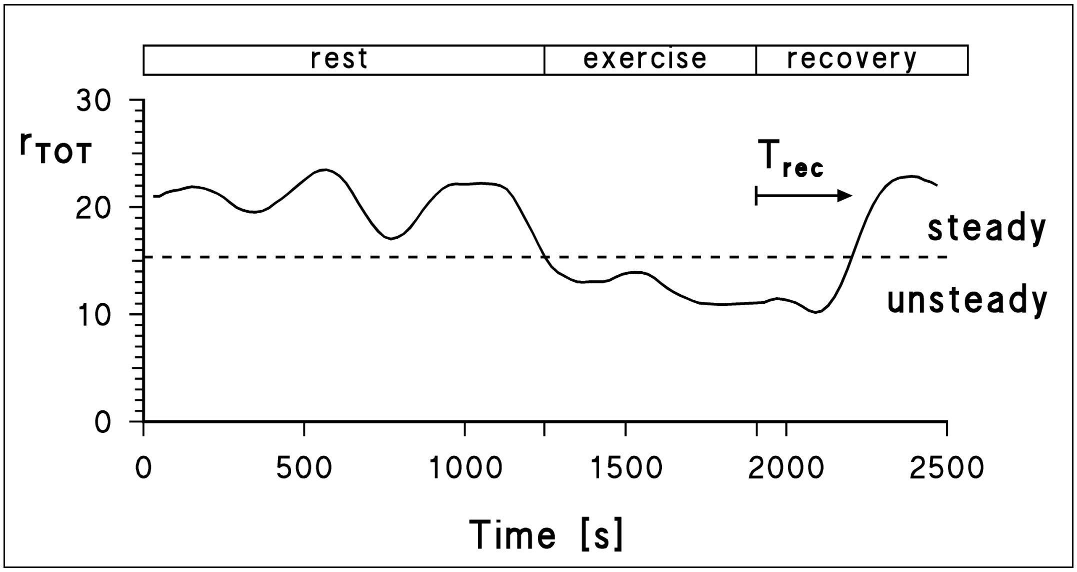

Figure 3. The steadiness profile r_{TOT} in one subject before, during and after the incremental exercise test, with the identified recovery period.

From the "steadiness" profile $r_{TOT}(k)$ we evaluated the following parameters: Rest-Steadiness, RS, defined as the percentage of the rest period in which the system is in steady state; Exercise-Steadiness, ES, defined as the percentage of exercise performed in steady state; excitation time, T_{exc}, defined as the time from the start of exercise needed to lose the steady state; and the recovery time, T_{rec}, defined as the time needed to reach the steady state after the end of exercise.

We also evaluated the maximum workload, WL_{max}, reached by each subject during exercise.

3. Results

Figure 3 shows an example of the steadiness profile $r_{TOT}(k)$ with the identified recovery period (subject n° 4). In this case the whole period of rest is classified as steady, being $r_{TOT}(k)$ always above the threshold. The "steadiness" profile crosses the threshold just 2s after the start of exercise. The cardiovascular system does not reach a steady state for the whole exercise period, and remains in an unsteady condition also during the first part of recovery.

Individual values of the indexes used to describe the exercise test are reported in table 1 ordered by WL_{max}. Although RS is high in all subjects, it reaches 100% in two subjects only, indicating that the steady state may be occasionally lost even during the reference resting period. In most of the cases the cardiovascular system remained in an unsteady state for the whole incremental exercise period (ES=0%). Excitation time values close to 0 in all subjects but one indicate that the steady state was generally lost even at the lightest workload (0 W, namely while pedalling without load). Only one volunteer maintained the steady state for a relatively long period after the start of exercise. It is worth noting that this subject is also the one showing the best performances in terms of the maximum workload and in terms of the recovery time.

From data in table, it appears that recovery time tends to be inversely related to the maximum workload, being the less trained subject in terms of WL_{max} also the one with the highest recovery time, while the opposite is true for the subject with the best WL_{max}

Table 1. Indexes describing incremental exercise

subject n.	RS [%]	ES [%]	Texc [s]	Trec [s]	WLmax [W]
1	100	0	0	350	175
3	94	0	0	257	200
4	100	0	2	296	250
2	89	12	0	270	250
5	86	78	274	254	275

4. Discussion and conclusions

This study demonstrated that the procedure proposed in [1] can be used to evaluate the level of steadiness during exercise test. In fact, as expected, most of the resting period before exercise was identified as steady, and most of incremental exercise, which should be characterized by a continuous shift of the working point of the cardiovascular system, as unsteady. However, it should be noted that rest was completely classified as a steady state (RS=100%) only in two subjects. In other subjects, short unsteady-state periods were present at the beginning of rest, possibly due to the initial adaptation to the experimental set-up and/or a couple of minutes before the start of exercise, possibly because of psychological factors related to the mental preparation to exercise. These findings indicate that the whole resting period cannot be invariably considered as a reference steady-state condition. Interestingly, in the best trained subject we observed steady-state periods also during the incremental exercise, suggesting that this subject performed the exercise with only few adjustments of his cardiovascular system. This would also indicate that also the level of the "steadiness" plot during incremental exercise may provide information on the fitness level.

The proposed method also gives an objective measure of the recovery time, T_{rec}, which is independent from reference values measured during a baseline condition. Thus this measure does not depend on the reproducibility of the baseline recording. It also does not depend on subjective rules, or on the judgement of operators who calculate the recovery time by visual inspection of the data.

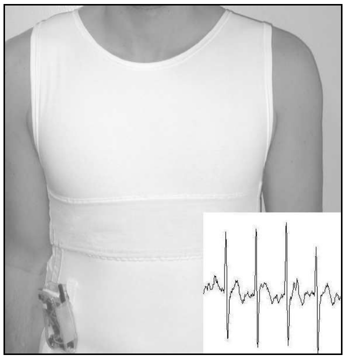

Figure 4. The wearable system for ECG recording; inset: example of measured signal

In the presented approach the cardiovascular steady state was assessed by considering both cardiac (heart rate) and hemodynamics (blood pressure) variables. When a simplified experimental set up is required and/or the maximal liberty should be left to the subject under investigation, only the ECG signal may be recorded. As an ancillary investigation we also explored whether our approach could identify steady states from heart rate only. This was done by recording, in one subject, ECG by a new wearable device (MagIC System, Fondazione Don Gnocchi, Italy) while he was following the same experimental schedule used for the main study. The recording system (see fig.4) consists of a cotton and lycra vest including two woven electrodes, made by conductive fibers, positioned at the thorax level so to obtain a D1 ECG lead. The contact between the textile electrodes and the thorax was guaranteed by the elastic property of the garment, without requiring any additional instrumentation of the subject and thus greatly simplifying the experimental set-up. Through integrated conductive fibres, the ECG fed an electronic board (having the size of a small cell phone) placed on the vest, which transmits the signal through wireless connection to a computer. As illustrated in figure 4, the signal quality was adequate for an accurate estimation of the RRI series.

In this ancillary analysis, use of only RRI signal implied just to set $r_{TOT}(k)= r_{RRI}(k)$ and to evaluate a new r_{CR} in the original algorithm. Results are reported in figure 5.

Although a definitive validation need to consider a larger number of subjects, our data suggest that the proposed algorithm may be used also when only heart rate signal is available. It should be considered, however, that in this case only the steady state of the cardiac contribution to the overall circulatory regulation is checked.

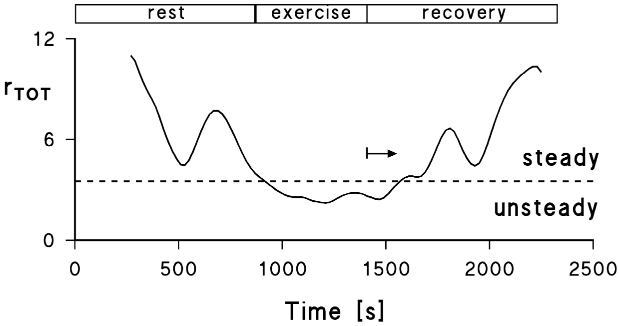

Figure 5. Steadiness profile and recovery time from RRI only.

References

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