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The continuing problem of incorrect heart rate estimation in psychophysiological studies: an off-line solution for cardiotachometer users

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Abstract

A wide variety of procedures are commonly used to record and estimate heart rate in psychophysiological studies. We analyze biases inherent in some estimates of mean heart rate based on cardiotachometers. Two types of errors are described, the time lag error and the incorrect weighted averaging error. These lead to an overestimation of the true heart rate, even when the analysis is based on digitized samples. Digitized samples provide a series of heart rate values per beat which correspond to the prior interbeat interval but during a time which does not correspond to the prior interval, but to the current one. A simple and practical solution, which eliminates both types of errors, is presented: an algorithm that corrects off-line the cardiotachometer data, reproducing the heart rate value with a length of time equal to the length of its own R–R interval. Several comparisons between the corrected and uncorrected data are made to illustrate the magnitude of the error. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Heart rate and its reciprocal, heart period, are among the most frequently used recorded variables in psychophysiological studies. From 1987 to 1996, 203 *Psychophysiology* papers used either heart rate or heart period as one of their dependent variables. Although these papers used a wide variety of procedures to record and estimate heart rate and heart period (see Table 1), computerized R–R interval analysis (39.4%), blood pressure instruments (17.7%) and cardiotachometers (17.2%) were the most common methods. With few exceptions, these papers did not fully describe all the components of the recording system used. More importantly, most papers did not explain how average heart rate or heart period values were calculated. When such information was available, it is clear that some investigators had used incorrect methods. That is, many researchers did not follow the suggestions given by *Psychophysiology* in the article '*Publications guidelines for heart rate studies in man*' (Jennings et al., 1981).

Since 1972 various articles in *Psychophysiology* have identified sources of bias in the estimation of heart rate from different recording systems (especially from cardiotachometers) and have given specific recommendations concerning the use of heart rate versus heart period measures (Khachaturian et al., 1972; Jennings et al., 1974; Thorne et al., 1976; Graham, 1978a,b; Richards, 1980; Jennings et al., 1981). In general, heart rate measures are recommended when the cardiac activity is expressed in real time units—i.e. second-by-second—and heart period measures when the cardiac activity is expressed in organismic units—i.e. beat-by-beat—(see also Graham, 1980; Papillo and Shapiro, 1990; Siddle and Turpin, 1980; Turpin, 1985). Recently, the recommendation concerning heart period measures has been extended to experimental conditions producing large deviations in the basal chronotropic activity—i.e. pharmacological blockade or stimulation of autonomic reflexes—given the better linearity between autonomic outflows and heart period (Berntson et al., 1995; Quigley and Berntson, 1996). Nevertheless, the majority of researchers, except those who analyze cardiac activity in the frequency domain, continue to prefer heart rate over heart period probably because it is easier to obtain and interpret through cardiotachometers and other recording systems.

Table 1
Summary of the recording systems used to estimate heart rate and/or heart period in the papers published in '*Psychophysiology*' from 1987 to 1996

Recording system	Number of papers	Percentage
Computerized R–R analysis	80	39.4
Blood pressure instruments	36	17.7
Cardiotachometers	35	17.2
Counting procedure based on the ECG or blood pulse	25	12.3
Ensable average of impedance cardiography	12	5.9
Biofeedback/ambulatory devices	5	2.5
ECG with no further information	10	4.9

Cardiotachometers measure beat-by-beat heart rate by electronically measuring the reciprocal of the time interval between successive beats (normally successive R waves of the electrocardiogram). This is done by generating a voltage which decreases hyperbolically during the R–R interval and by holding and displaying that voltage (the heart rate) during the subsequent R–R interval; thus, a faster heart rate results in a larger voltage.

It has been known for some time that the use of beat-by-beat cardiotachometer values to estimate the mean heart rate for a recording period, or epoch, may lead to heart rate overestimation's (Thorne et al., 1976). The origin of this error is that the individual beats are treated as having equal weight for the epoch without correcting for variability in the length of time taken by different heart beat intervals. Thorne et al. (1976) demonstrated that this overestimation increased as the heart period decreased, as the heart period variability increased and as the asymmetry and kurtosis of the heart period distribution increased. To guard against such biases, they recommended simply counting beats during the period of interest rather than averaging beat-by-beat cardiotachometer values, a procedure still used in a significant number of papers published in *Psychophysiology* (see Table 1).

The counting procedure—when applied to prolonged time epochs—, although suppressing the error, has the serious disadvantage of precluding the study of phasic responses, as well as response patterns. The procedure prevents the assessment of variability measures, important indices of self-regulatory hemodynamic processes. Moreover, the counting procedure, if incorrectly applied—as it is the case in some papers—, introduces a new bias whose magnitude increases as the time epoch decreases. The counting procedure must be considered a particular instance of the heart period averaging procedure: sum of all full and partial heart periods along a time epoch (which is equal to the time epoch) divided by the number of counted beats during that epoch. This arithmetic (unweighted) average of heart period, transformed into heart rate, is the counting procedure. The error commonly introduced in this procedure occurs at the beginning and the end of the counting epoch if partial beats are not properly counted. The first beat within the epoch cannot be counted as a complete beat unless the previous beat coincides with the beginning of the epoch. Similarly, the last beat within the epoch cannot be counted as the last beat unless it coincides with the end of the epoch. A correct application of the counting procedure, taking into account partial beats, should provide exactly the same information as the heart period averaging procedure. A better recommendation than the counting procedure suggested by Thorne et al. (1976), would have been an application of the procedure suggested for cardiotachometer data: to transform each heart rate into heart period, then to obtain the arithmetic mean and finally to transform the resulting value to heart rate.

It should be noted that the unweighted averaging error is not unique to cardiotachometers. The same error is produced in any recording system—even in the digital R–R interval analysis procedure through computers—if each R–R interval is transformed first into heart rate and no weighted averaging is applied later. Unfortunately, it was difficult to asses how widespread this problem is for data reduced by the computerized R–R interval method. Of the 80 papers using this method, 51% did not indicate the statistical method they used. Of the remaining 49%, only 87% analyzed the data properly. Conversively, cardiotachometers can provide weighted averages of heart rate which eliminate the bias pointed by Thorne et al. (1976). This is the case when using computerized recording systems with A/D converters and when arithmetic averages are obtained from the cardiotachometer's digitized samples. The digitized data of the cardiotachometer do not provide one value per beat, but a series of values whose exact number depends on the selected sampling rate and the length of the interbeat interval. Each interbeat interval is then given a different weight proportional to its contribution to the total analysis period —an indirect weighting. Unfortunately, this procedure per se does not completely eliminate the error inherent to unweighted estimates of individual heart rate values. This problem is related to another error present in cardiotachometer outputs: the time lag error.

2. Two types of errors

Table 2 illustrates the first type of error—unweighted averaging—introduced when mean heart rate and mean heart period are obtained from individual beats as compared with the digitized samples from the analog output of the cardiotachometer. In these examples the time lag error is obviated. It should be noted that while the averaged heart rate estimated from the individual beats is incorrect, due to unweighted averaging, the averaged heart rate estimated from the digitized samples is correct, due to the indirect weighting. The opposite occurs for heart period, given its reciprocal relationship with heart rate: the averaged heart period estimated from individual beats is correct, no weighting is needed, while the averaged heart period estimated from the digitized samples is incorrect, due to the indirect weighting. In both cases, the error leads to an overestimation of the true heart rate or true heart period. Consequently, there should be a clear choice for averaging heart rate, instead of heart period, from the cardiotachometer' digitized samples, as has been recommended in the literature (Graham, 1978a,b, 1980). But this recommendation is correct only if the second error—the time lag—is not confounded with the averaging error.

The time lag error is due to the fact that the output of the cardiotachometer at a given moment corresponds to the interbeat interval immediately prior to the current one. As the interval cannot be measured until it has finished, the cardiotachometer always has a certain lag. But the length of time in which the cardiotachometer shows the heart rate value corresponding to the prior interbeat interval depends on the length of the current interval, not of the prior one. Fig. 1 shows a simulated ECG recording and its corresponding cardiotachometer output. In this example, the heart rate value of the second R–R interval of the Electrocardiogram (2 in bottom panel) appears in the cardiotachometer output (2 in top panel) with the corresponding length of the third R–R interval of the Electrocardiogram (3 in bottom panel). The consequence of this is an incorrect weighting of the interbeat interval when the arithmetic average is obtained from the digitized samples, since

Table 2
Illustration of the error due to weighted versus unweighted averages of heart rate and heart period from both individual beats and digitized samples

Example: two consecutive R-R intervals, the first interval of 600 ms (heart rate of 100 bpm), and the second interval of 400 ms (heart rate of 150 bpm)

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HR:      100          150
     R--------------R-------R
HP:      600          400
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True Average Heart Rate based on the counting procedure (2 beats in 1 second) = **120 bpm**

True Average Heart Period based on the counting procedure (2 beats in 1000 ms) = **500 ms**

(1) Unweighted versus weighted average of the HR and HP obtained from **individual beats**:

. Unweighted HR = (100 + 150)/2 = 125 bpm (incorrect)
. Weighted HR = (100 x 600/1000) + (150 x 400/1000) = **120 bpm (correct)**

. Unweighted HP = (600 + 400)/2 = **500 ms (correct)**
. Weighted HP = (600 x 600/1000) + (400 x 400/1000) = 520 ms (incorrect)

(2) Average of the HR and HP obtained from the **cardiotachometer' digitized samples** assuming no time lag (sampling rate of 100 Hz):

. HR = ((100 x 60) + (150 x 40))/100 = (6000 + 6000)/100 = **120 bpm (correct)**

. HP = ((600 x 60) + (400 x 40))/100 = (36000 + 16000)/100 = 520 ms (incorrect)

the relative weight given to each R–R interval does not correspond to its own interval, but to the following one. As illustrated in Fig. 1, the third R–R interval is given the weight of the fourth R–R interval, artificially decreasing its contribution to the overall mean. Similarly, the fifth R–R interval is given the weight of the sixth R–R interval, artificially increasing its contribution to the overall mean. In both cases, the consequence is a positive bias in the estimation of heart rate, meaning that the error always goes in the direction of overestimating its true value.

Various conditions occur in which the error can be especially important, as already pointed by Thorne et al. (1976). Certainly, medical conditions that involves ectopic beats, bigeminal rhythm and other types of arrhythmia's, are particularly vulnerable to such an error. But this could also be the case in most psychophysiological investigations in which the experimental manipulation produces variations in the conditions which affect the error: changes in heart rate mean and variability. In these cases, the error will differ between conditions contributing to an artificial increase or decrease of the experimental effect. Furthermore, when second-by-second heart rate is analyzed during phasic responses for a certain epoch, the error could vary with different phases of the response, depending on the variability and sequencing of fast and slow beats. The bias introduced could result in incorrect estimation of true heart rate in any of its parameters (both central tendency and variability measures).

3. The off-line solution

A variety of procedures are available that avoid the incorrect heart rate weighting due to the time lag error inherent to the cardiotachometer. The most common procedure omits the cardiotachometer and uses a logic signal from the R wave to trigger a counter which measures directly the interbeat interval in milliseconds between consecutive R waves. Subsequently, a weighted mean of the heart rate based on the length of its own interval is obtained taking into account the proportion occupied by each interbeat interval within the averaging epoch (see Cook, 1992). This procedure is usually done off-line with no visual information in analog form provided during the on-line recording. Such a procedure represents a clear disadvantage in relation to cardiotachometers which facilitate on-line visual inspection and analysis of the relationships among simultaneously recorded variables, something desirable in traditional psychophysiological training.

A simple and practical solution based on the cardiotachometer record is to correct off-line the time lag error. We propose an algorithm that corrects off-line the cardiotachometer data, reconstructing the heart rate value corresponding to each R–R interval with a length equal to that interval, rather than to the length of the next R–R interval. The algorithm assumes a fixed sampling rate during the A/D recording. Firstly, the algorithm detects the change in heart rate—i.e. the shift from

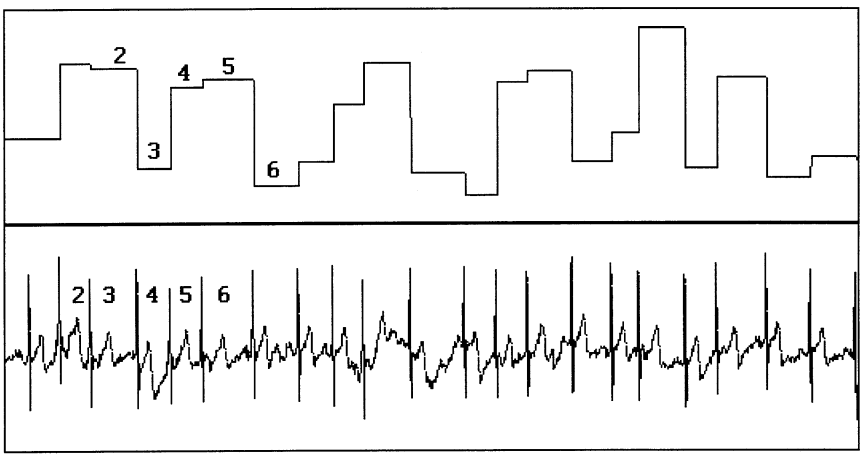

Fig. 1. Simulated ECG recording (bottom panel) and its corresponding cardiotachometer output (top panel).

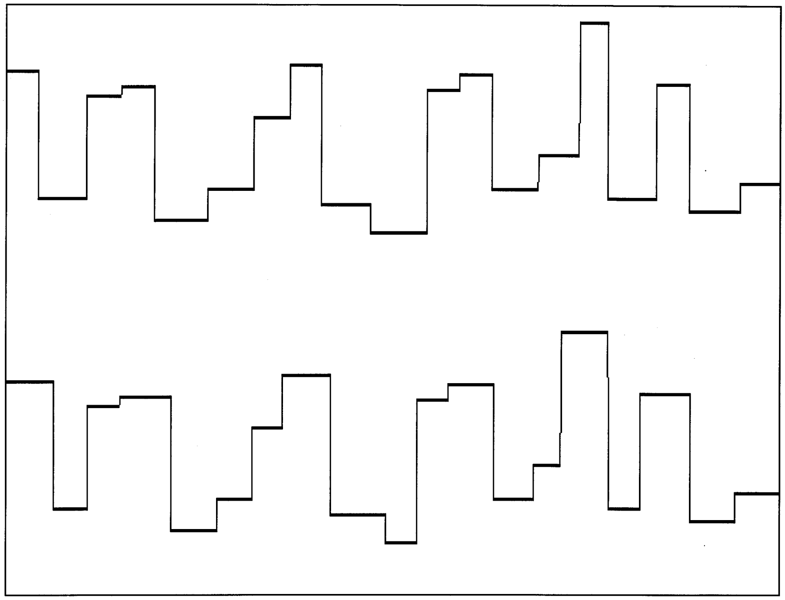

Fig. 2. Uncorrected (bottom panel) and corrected (top panel) cardiotachometer records eliminating the time lag error. Data start at interbeat interval labeled 2 in Fig. 1.

one R–R interval to the next—and counts the number of samples which are included in each R–R interval. The program then detects those cases with two or more consecutive R–R intervals with identical value. This is done by transforming the heart rate of each detected R–R interval into heart period and then into the expected number of samples. A mismatch between the expected number of samples and the observed number of consecutive samples within the detected R–R interval indicates that the interval includes two or more R–R intervals with an identical heart rate. If this is the case, the program corrects the previous R–R values by dividing the interval into two or more intervals, as appropriate. Secondly, the program reconstructs the digital file of the cardiotachometer assigning to all the samples within each R–R interval the heart rate value of the next R–R interval in the original file. This corrects the time lag error (the heart rate value advances one beat) and, consequently, the weighting error since the number of samples in each R–R interval is now proportional to its true duration.

Once the time lag error is eliminated, the arithmetic average of the cardiotachometer's digitized samples provides a correctly weighted average for any kind of selected epoch: each half s, each s, or the overall period. Fig. 2 shows the application of the algorithm to the cardiotachometer data of Fig. 1. Various comparisons between uncorrected and corrected data have been made to illustrate the magnitude of the error. As mentioned above, Figs. 1 and 2 correspond to a simulated record in which variability has been deliberately maximized alternating long and short interbeat intervals. The mean heart rate derived from the original uncorrected cardiotachometer data (Fig. 2, bottom panel) is 98.3 beats per min and that of the corrected one (Fig. 2, top panel) is 92.2, an error of 5.5%. When the same data are analyzed obtaining second-by-second averages, the differences are even more pronounced. Table 3 shows the averaged second-by-second heart rate from the uncorrected and corrected cardiotachometer data. As can be seen, discrepancies between both types of data can reach up to 16 beats per min, an error of approximately 13.2%.

Other comparisons carried out with cardiotachometer records from actual subjects under typical research conditions (resting, competitive reaction time, intense auditory stimulation, etc.) showed attenuated differences. In general, as regards the overall mean, the differences did not exceed in any case 1.25 beats per min. Notwithstanding, the differences in the second-by-second averages remain very pronounced, exceeding in some cases 12 beats per min, but more typically being around 5 beats per min. These discrepancies may not be important if the research is focused on general patterns of change, but they are crucial if one is interested in specific temporal points to obtain maximum response amplitude or latency. As the error always affects the temporal sequence of the second-by-second averages, any analysis of the uncorrected cardiotachometer data in the time domain will be affected by the error.

4. Concluding remarks

In spite of its apparent simplicity, heart rate measures continue being incorrectly recorded and estimated in many psychophysiological studies. Researchers should, firstly, be alert against using unreliable recording systems which do not provide specific information on how heart rate or heart period is measured. Such descriptive information is necessary to assess the correctness of the recording method. Sec-

Table 3
Second-by-second heart rate (bpm) from the uncorrected and the corrected cardiotachometer outputs represented in Fig. 1

Seconds	Uncorrected	Corrected	Difference
1	109.7	98.6	11.1
2	101.3	102.5	−1.2
3	100.6	86.6	14
4	77.1	80.4	−3.3
5	112.9	112.3	0.6
6	88.7	75.9	12.8
7	82.9	80.4	2.5
8	114.7	107.8	6.9
9	85.6	86.6	−1
10	122.1	106.0	16.1
11	103.3	97.4	5.9
12	80.8	76.5	4.3

ondly, researchers should pay special attention to the biases introduced by the treatment given to the data to estimate average heart rate or heart period over a time epoch: heart rate values should always be weighted by the proportion of the epoch occupied by each interbeat interval while heart period values should never be weighted. Additional averages over a longer time epoch, based on the previous averages, require the inverse treatment: heart rate weighted average values should not be weighted again, while heart period unweighted average values should now be weighted by the number of beats within each sub-epoch. For example, in the illustration of Table 2 if we add a new R–R interval of 1000 ms (60 bpm) to the two previous R–R intervals of 600 and 400 ms, respectively and we want to obtain the average heart rate and heart period over the 2 s epoch, based on the average values already obtained for the first s (120 bpm and 500 ms), the correct procedure should be the following one: (1) Heart rate (unweighted) average: $(120+60)/2=90$ bpm; (2) Heart Period (weighted) average: $((500\times 2)+(1000\times 1))/3=666$ ms.

Therefore, information on the averaging system is also absolutely necessary to assess the correctness of the estimation method. The counting procedure, still used in many psychophysiological studies, should be considered a particular instance of the heart period averaging procedure and, consequently, applied taking into account full and partial beats. Cardiotachometers are also a recording system still used in a significant proportion of psychophysiological studies. Cardiotachometers are reliable recording systems if the two errors inherent to all systems—the time lag and the incorrect weighting—are appropriately treated. Both errors can be corrected through computerized off-line solutions. Finally, researchers who use the digital R–R interval analysis method—the most frequently used technique in recent years—should be aware that the method is not free of measuring problems. Necessary precautions should be taken concerning both time lag and correct averaging.

There are important implications derived from the time lag error which are worthy of attention. Given that the cardiotachometer and other recording systems always show the heart rate value of the prior interbeat interval, the first value recorded by the cardiotachometer corresponds to the interbeat interval which occurred before the actual record began. On the other hand, the heart rate of the last beat of the recording period is never recorded by the cardiotachometer. Consequently, a correct definition of the beginning and end of an event-related heart rate response, or of an experimental period, should take into account this time lag error (Jennings et al. 1981).

The concerns raised also apply to the use of cardiotachometers to analyze respiratory sinus arrhythmia and baroreflex sensitivity in the time domain. Analysis of respiratory sinus arrhythmia using the peak-valley method (Grossman and Svebak, 1987; Reyes, 1992) requires correct definition of the respiratory periods in which the maximum and minimum heart period are going to be searched. The respiratory periods must be defined with the cardiotachometer time lag in mind. On the other hand, analysis of the baroreflex sensitivity in the time domain (Steptoe and Sawada, 1989; Reyes, 1994) requires correct detection of sequences of systolic blood pressure and heart period. It is important to bear in mind that each systolic blood pressure value is not associated with the heart rate value shown by the cardiotachometer immediately after, but with the following one.

Finally, researchers who use heart rate as dependent variable should be aware of the error committed when obtaining mean heart rate, both overall and second-by-second, directly from the arithmetic averages of computerized cardiotachometer records. Those researchers interested in stimulus elicited phasic responses should be especially alert, since the error is maximized when second-by-second heart rate values are estimated from second-by-second averages of uncorrected cardiotachometer samples. To avoid such an error, a simple algorithm can be used which corrects off-line the cardiotachometer time lag providing a true heart rate estimation based on the arithmetic average of the cardiotachometer's digitized samples. The correction of the time lag also allows a better definition of the beginning and end of the cardiac phasic responses.

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