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THE ENTRAINMENT OF BREATHING FREQUENCY BY EXERCISE RHYTHM

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SUMMARY

1. The incidence of entrainment of breathing frequency by the rhythm of exercise was detected by a cross-correlation of the two frequencies.

2. During moderate, steady-state exercise on a bicycle ergometer at 50 rev/min, eight of fifteen volunteers (53 %) showed entrainment when pedalling speed was kept constant with a metronome, and three of fifteen volunteers (20 %) showed entrainment when pedalling speed was kept constant with a speedometer.

3. At 70 rev/min, in a second group of fifteen volunteers, the results were nine of fifteen (60 %) and five of fifteen (33 %) respectively.

4. During moderate, steady state exercise on a treadmill, in a third group of fifteen volunteers, eight of 15 volunteers (53 %) showed entrainment while walking, and twelve of fifteen volunteers (80 %) showed entrainment while running.

5. It is concluded that the rhythm of exercise is likely to affect the rhythm of breathing and that this controlling factor must be considered during studies of breathing pattern in exercise.

INTRODUCTION

During exercise, the study of breathing patterns in terms of tidal volume and breathing frequency may be complicated by the effect of the steady rhythm of exercise. The alteration of breathing frequency to become 'in step' with the exercise rhythm will be termed the entrainment of breathing frequency by exercise rhythm in this report.

The possibility of entrainment has been recognized for some time (Asmussen, 1965; Astrand & Rodahl, 1970), but its detection is difficult to quantify. One method is to measure breathing frequency and determine whether it is related to some submultiple of the exercise frequency, on the theory that if breathing frequency has been entrained then the two frequencies will likely be in some integer ratio to one another. Hey, Lloyd, Cunningham, Jukes & Bolton (1966) observed that breathing frequency was often a submultiple of the number of steps per minute as did Bannister, Cunningham & Douglas (1954) in treadmill running. However, Kelman & Watson (1973) observed no such relation in bicycle ergometer exercise and Kay, Petersen & Vejby-Christensen (1975) did not observe this relation in either bicycle ergometer exercise (five subjects) or treadmill exercise (two subjects). They speculated that previous observations may have been influenced by the use of a metronome to set the exercise rhythm.

This investigation tested for entrainment by the on-line cross-correlation of pulse trains derived from exercise rhythm and breathing rhythm on a breath-to-breath basis. The exercise circumstances included a bicycle ergometer at two pedalling frequencies both with and without a metronome, and walking and running on a treadmill. We also tested to see whether or not the hypothesis that the ratio of mean breathing period to mean exercise period is an integer in entrained breathing could be used as a reliable predictor of entrainment.

METHODS

During the exercise, the volunteers breathed through a low resistance Lloyd valve (W. E. Collins, P-312) and wore earphones playing 'classical' music, except for the bicycle exercises where a metronome was used to set pedalling speed. The expiratory side of the valve was left open to room air while wide bore (1·5 in.) tubing connected the inspiratory side of the valve to a spirometer (Med. Sci., 270 Wedge) set to measure inspired volume on a breath-by-breath basis (Goode, Duffin, Miller, Romet, Chant & Ackles, 1975). An electrical pulse signalling the end of each inspiration was derived from this apparatus. Pedalling period was measured during bicycle exercise by using a photoelectric beam relay (Heath GD 1021) to detect the right foot at the bottom of its pedal stroke and emit an electrical pulse. Stepping period was measured during treadmill exercise by using a microswitch fastened to the right shoe to detect the right foot as it touched down each pace and emit an electrical pulse. The exercise period pulse and breath-by-breath inspired volume were recorded on a multi-channel HP-Sanborn recorder. In addition, heart rate was palpated just before the end of each exercise.

The pulses corresponding to breathing period and exercise rhythm period were connected to the inputs of a specially designed, on-line cross-correlation computer (Anderson & Duffin, 1976). The cross-correlogram (256 bins of 50 msec per bin) was computed on-line and continuously displayed on an oscilloscope (Tektronics 5000) during the last 3 min of all the 8 min exercise periods, and additionally, during the first 3 min of the 50 rev/min bicycle exercises. Subsequently, approximately 100 bins of the cross-correlogram was written off-line on a chart recorder (HP-Moseley 7100 B) for a permanent record.

The technique of cross-correlation to detect relationships between trains of impulses is directly related to the post-stimulus histogram. In this case the stimuli are the pulses corresponding to exercise rhythm and the responses are the pulses corresponding to breathing rhythm. The cross-correlation computer operated as follows. Each exercise rhythm pulse started a sequence in the computer whereby an 'enabling function' was incremented from bin 1 to bin 256, stepping from 1 bin to the next every 50 msec. This 'enabling function' allowed the bin at which it was located to add one count to its contents. The count was only added, however, when a breathing rhythm pulse occurred. In this way, the exercise rhythm gave rise to a sequence in which a series of 'enabling functions' stepped along the bins from 1 to 256 at the rate of one step every 50 msec. If the breathing rhythm was entrained, then the timing was such that the same bins received counts each time thereby building a series of peaks in the cross-correlogram. If the breathing rhythm was unentrained, then the counts were scattered randomly among the bins and they filled up evenly.

Three sets of fifteen volunteers were tested. All were healthy individuals who were fully informed as to the testing procedure but unaware of the purpose of the experiment. They were recruited by personal contact mostly from among the students of the University. Ten of the forty-five volunteers were enrolled in medicine or physiology but none specialized in respiratory physiology. The first group consisting of twelve males and three females and ranging in age from 21 to 46 were studied while exercising on a bicycle ergometer (Monark–Crescent AB) at a moderate load (approximately 60 % maximum) for two 8 min sessions separated by a 20 min rest period. For one session the volunteer was asked to pedal in time with a metronome set at 100 beats per minute and for the other session at a constant speedometer reading. The sequential order of the sessions was chosen at random.

The second group of volunteers consisting of ten males and five females and ranging in age from 20 to 52 were studied similarly to the first group except that the pedalling speed was 70 rev/min.

The third group of volunteers consisting of thirteen males and two females and ranging in age from 20 to 25 were studied while exercising on a treadmill (Quinton Instruments Model 18-49B) at a moderate load (approximately 60 % maximum) for two 8 min sessions separated by a 20 min rest period. For one session the speed of the treadmill was set at a comfortable walking pace and for the other at a comfortable running pace. The gradient was altered to provide similar exercise loads and the sequential order of the sessions was chosen at random.

From the records of the last 3 min of exercise, calculations were made of the average breathing period, the average exercise rhythm period, their ratio, the average ventilation and, for the bicycle exercise, predicted maximum oxygen uptake by the Astrand (1954) method.

RESULTS

The cross-correlograms for each test were examined and classified into three categories. A strong cross-correlation, type A, shown in Fig. 1, indicated that breathing frequency was entrained by exercise rhythm throughout the measurement period. A weak cross-correlation, type B, shown in Fig. 2, indicated that either entrainment had occurred for a significant part of the measurement period or that the phase of the entrained breathing frequency had shifted with respect to the exercise rhythm during the measurement period. No cross-correlation, type C, shown in Fig. 3, indicated that respiratory frequency was independent of exercise rhythm. Table 1 shows the number of types which occurred for each exercise. The percent entrained is a combination of types A and B.

The ratio of average breathing period to average exercise rhythm period (the reciprocal of average limb movement frequency) was calculated for the last 3 min of each 8 min exercise. According to the hypothesis that breathing period is an integer multiple of half the exercise period during

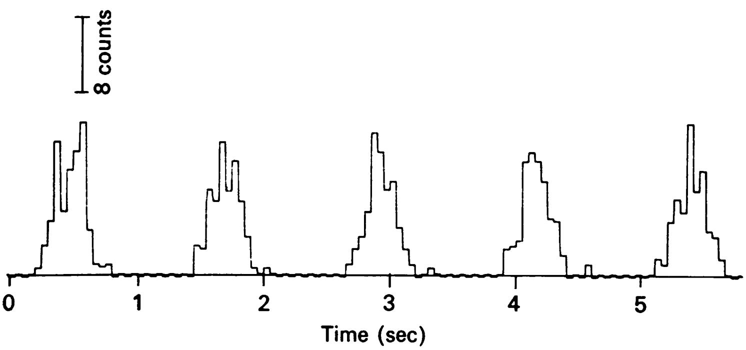

Fig. 1. A cross-correlogram of breathing period with exercise rhythm period recorded during the fifth to eighth minute of exercise on a bicycle ergometer with pedalling speed set at 50 rev/min with a metronome. The well defined peaks, spaced at 1·2 sec (the pedalling period) show that the breathing frequency was fully entrained by the exercise rhythm. Type A.

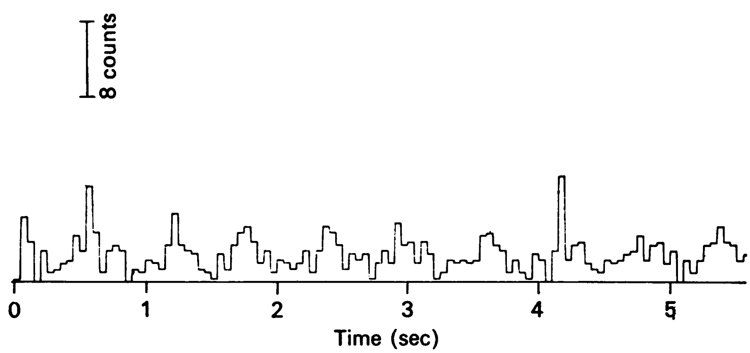

Fig. 2. A cross-correlogram of breathing period with exercise rhythm period recorded during the fifth to eighth minute of exercise on a bicycle ergometer with pedalling speed set at 50 rev/min with a speedometer. The regular peaks spaced at 0·6 sec (half the pedalling period) show that breathing frequency is partly entrained by the exercise rhythm. Type B.

entrained breathing, the ratios should be values of 0·5, 1·0, 1·5, 2·0, etc. The measured ratios within 0·1 of those hypothesized were assumed to predict entrainment and the ratios not within 0·1 of those hypothesized were assumed to predict the absence of entrainment. The predictions were compared with the measured results considering types A and B as entrained and type C as not entrained. Table 2 shows the number of correct predictions in each exercise for entrainment and no entrainment.

Each of the three groups did two exercises each and the order in which the exercises were done was varied from person to person on a random basis. To test whether order was a factor in the entrainment during each exercise, the number of entrained among those who did the exercise first was compared to the number entrained among those who did the exercise second. The results are included in Table 2.

The predicted maximum oxygen uptakes for all subjects ranged from

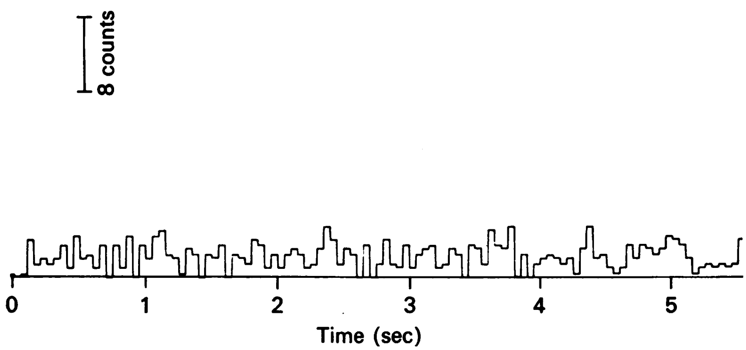

Fig. 3. A cross-correlogram of breathing period with exercise rhythm period recorded during the fifth to eighth minute of exercise on a bicycle ergometer with pedalling speed set at 50 rev/min with a speedometer. The absence of regular peaks show that breathing frequency is not entrained by the exercise rhythm. Type C.

TABLE 1. Classification of cross-correlograms of breathing period and exercise rhythm period as type A, fully entrained; type B, partly entrained; and type C, not entrained

Exercise	Number fully entrained (A)	Number partially entrained (B)	Number not entrained (C)	% entrained (A+B)
Group 1				
Bicycle 50 rev/min – speedometer				
First 3 min	0	3	12	20
Last 3 min	0	3	12	20
Bicycle 50 rev/min – metronome				
First 3 min	6	5	4	73
Last 3 min	5	3	7	53
Group 2				
Bicycle 70 rev/min				
Speedometer	0	5	10	33
Metronome	1	8	6	60
Group 3				
Treadmill				
Walking	1	7	7	53
Running	4	8	3	80

21 to 61 ml./kg.min with an average value of 42 ml./kg.min. Of the eight volunteers from groups 1 and 2, that showed entrainment while exercising on a bicycle using a speedometer to maintain a constant pedalling rate, six were below and 2 above the average predicted maximum oxygen uptake. Of the seventeen volunteers from groups 1 and 2 that showed entrainment while exercising on a bicycle using a metronome to maintain a constant pedalling rate, ten were below and seven above the average predicted maximum oxygen uptake.

TABLE 2. Results of the ratio test (see text) for entrainment. Column (1), the number of correct predictions of entrainment, and column (2), the number of correct predictions of no entrainment. Columns (3) and (4) show the number of volunteers entrained (A + B) for each exercise out of the number of volunteers that took the exercise first or second respectively

Exercise	Correct prediction of entrainment (A+B) (1)	Correct prediction of no entrainment (C) (2)	Number entrained: First exercise (3)	Number entrained: Second exercise (4)
Group 1				
Bicycle 50 rev/min				
Speedometer	1 of 3 (33%)	5 of 12 (42%)	0 of 8 (0%)	3 of 7 (43%)
Metronome	6 of 8 (75%)	2 of 7 (29%)	5 of 7 (71%)	3 of 8 (38%)
Group 2				
Bicycle 70 rev/min				
Speedometer	1 of 5 (20%)	4 of 10 (40%)	3 of 8 (38%)	2 of 7 (29%)
Metronome	6 of 9 (67%)	3 of 6 (50%)	5 of 7 (71%)	4 of 8 (50%)
Group 3				
Treadmill				
Walking	4 of 8 (50%)	4 of 7 (57%)	5 of 7 (71%)	3 of 8 (38%)
Running	6 of 12 (50%)	2 of 3 (67%)	6 of 8 (75%)	6 of 7 (86%)

Three volunteers underwent the bicycle exercise at 50 rev/min for a second time a few days later. Their results were unchanged for exercise with the metronome but two of the three changed their incidence of entrainment during exercise using the speedometer, one from entrained to unentrained and the other the reverse.

DISCUSSION

The method used to detect entrainment of breathing frequency by exercise rhythm in these experiments was the cross-correlation of breathing period with exercise period. This method is both rigorous and highly sensitive. The occurrence of either a constant breathing frequency or an irregular breathing frequency, neither connected with exercise rhythm, produces a flat (type C) cross-correlogram. Only when breathing frequency and exercise rhythm are linked to each other do peaks appear in the cross-correlogram, and this occurs whether or not the frequencies are constant.

The factors which may affect entrainment include rhythmic sensory input from the working limbs, rhythmic interference with the mechanics of breathing and rhythmic external sensory inputs. In addition, several factors may increase the susceptibility to entrainment such as the severity of the exercise, the frequency of movement, the degree of fitness of the volunteer, whether or not steady state has been reached and the degree of familiarity with the exercise testing procedure. Although the number of volunteers assessed is small for statistical analysis, nevertheless, the trends in the results do provide tentative conclusions about the factors affecting entrainment.

There is definite indication that the external stimulus of a metronome is an aid to entrainment since at both pedalling speeds the percent entrained rose by about 30% when a metronome rather than a speedometer was used to keep pedalling rate constant. Similarly, the increased involvement of the upper body in the exercise with the resulting alteration in the mechanics of breathing is clearly shown by the trend towards increased entrainment from bicycle exercise (20–33%) to treadmill walking (53%) to treadmill running (80%).

The influences of the secondary factors which may affect entrainment are not so clearly discernible. There was an increase in the percent entrainment by about 10% as pedalling rate increased from 50 to 70 rev/min which may support the idea that an increased frequency of limb movement increases the chance of entrainment. An increased fitness, as measured by the predicted maximum oxygen uptake, appears to decrease the chance of entrainment but it would be speculative to attempt an explanation of this finding based upon the data of this study.

In one group, pedalling the bicycle at 50 rev/min, the cross-correlogram was calculated during the first 3 min of exercise as well as the last 3 min. The results were similar when the speedometer was used, but when the metronome was used the percentage entrained during the first 3 min of exercise was 20% higher than during the last 3 min. Although this result was only documented for one group it was a common observation throughout these experiments. It would appear that the effectiveness of the metronome for entrainment decreases with time, due to familiarization and the increase in other factors affecting respiration. The effect of familiarity with the experimental procedure was also considered with respect to the order in which the two exercise runs were carried out by each volunteer. The order was chosen randomly for each volunteer so as to avoid such a bias, and the results (Table 2) do not show any large systematic differences between those who performed a particular exercise first or second.

Finally, two additional factors which may tend to obscure entrainment should be mentioned. These are abrupt changes in phase between breathing and movement such as might be caused by swallowing or a sigh, and changes in the ratio of breathing period to exercise period. The first factor was not rigorously determined since its effectiveness depends not only upon the number of times such a phase shift occurred during a cross-correlogram measurement, but also upon the stability of the change. The second factor was observed in only one experiment, where the ratio of breathing period to pedalling period changed from 3 to 2.

The attempted prediction of entrainment or non-entrainment from ratios of breathing period to pedalling period often failed. While this result must rule out the ratio as a test for entrainment it does not disprove the hypothesis which led to the test. In fact only 2 of the 11 cases of type A entrainment were incorrectly predicted by the ratio test. The test's failure is likely due to the fact that unless entrainment is fixed for the whole 3 min exercise period as in type A, the average value of breathing period will be adversely affected by the period of the breaths that are either unentrained, or entrained at another fixed ratio. The test cannot therefore accurately detect type B entrainment which makes up the majority of the entrainment observed in these tests. Similarly, tests such as those used by Kay *et al.* (1975) to detect entrainment will likely detect only type A entrainment and not type B, and this factor may explain why they did not find evidence for entrainment.

One of the main reasons for undertaking this study was to assess the likelihood that entrainment would obtrude into studies of tidal volume-breathing frequency relationships. The overall impression has been gained that although the possibility of entrainment seems to be minimized while exercising on a bicycle ergometer at 50 rev/min, the possibility is not absent, and it varies from individual to individual and from time to time within the same individual. In addition, the reliable detection of entrainment cannot be made by calculating the average ratio of breathing period to exercise period.

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