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A Heart Rate Evaluation Approach to Determine Cost-Effectiveness an Ergonomics Intervention

Gregory Z. Bedny

Essex County College, Newark, NJ, USA

Waldemar Karwowski

Center for Industrial Ergonomics,
University of Louisville, KY, USA

Mark H. Seglin

The Montrose Group, South Orange, NJ, USA

This paper describes a hear-rate methodology to determine the cost-effectiveness of an ergonomics intervention to reduce workload and improve working conditions. This is a practical approach as opposed to the energy expenditure technique that is difficult to implement in natural settings. This was a laboratory study using a large excavator cabin with devices to simulate excavation operations. Mean heart rate was used to calculate the required rest time during a shift with or without air-conditioning. The criterion for evaluation was differences in required rest time during a shift under these 2 conditions. The simplicity and objectivity of this approach invites use to solve the problem of the economic evaluation of ergonomics interventions.

fatigue   break time allowances   heart rate evaluations   energy expenditure

1. INTRODUCTION

Psychophysiological methods are widely used in ergonomics. Neither the description of these methods, nor their theoretical analysis is the basis of this article. The purpose of this work is to exhibit the use of a psycho-

Correspondence and requests for reprints should be sent to Gregory Z. Bedny, 328 Academy St., South Orange, NJ 07079, USA. E-mail: <innchik@aol.com>.

physiological criterion—heart rate—for the evaluation of the economic efficiency of interventions directed at reducing workload and the improvement of working conditions. Often, commercial companies are not motivated to invest financially in reducing physical workload and improving working conditions. This may be attributed to their inability to evaluate the financial benefits of such interventions. We shall address this issue with a practical example that involves the introduction of air-conditioning in a large earth excavator.

Introduction of the air-conditioning increases the cost of such excavators. Purchasers of such equipment need to have objective data to justify these expenditures based on some estimates of the benefits that will accrue. The same problem often emerges when people performed heavy physical labor or perform jobs in inhospitable environments. Usually, cost-benefit calculations are performed without the involvement of physiologists or ergonomists. Other approaches are based on an analysis of productivity without taking into consideration physical efforts required of the workers. Practitioners currently appraise the effectiveness of work environments and performance enhancement interventions on the basis of productivity and gains through empirical data.

This study introduces a method developed to establish the benefit of ergonomics interventions. For this purpose we utilize heart rate evaluation during the performance of a physical job. Heart rate elevation is widely used as the criterion for the evaluation of physical demands of work and for determining rest allowances (Kiser & Rodgers, 1986; Rohmert, 1973). This method, developed in the former USSR by Rosenblat and his colleagues (Rosenblat, 1975), has substantial theoretical ground and is time-tested in practical application (Soviet Union Hygiene Standards, 1963). According to these standards, dynamic physical work that raises heart rate above 100 beats/min requires additional break time. These recommendations correlate with some studies in Western Europe. For example, Lehmann (1962) cited the German Work Research Association recommendation that the amount of energy expended should not be more than 4.17 kcal/min, which corresponds to a heart rate of 100 beats/min for dynamic work. Because the evaluation of energy expenditure in a work situation is very difficult, Rosenblat suggests a simple method of determining rest allowances by using the average heart rate during a shift. When studying dynamic physical work, heart rate is the most informative measure for evaluating physical workload and environmental stress. Heart rate is not an informative measure when studying static physical workload because the relationship between static work and heart rate is not linear. The study of physical workload calls for the study of systems that supply energy for most behavior activities. The latter allows for the selective involvement and integration of various physiological mechanisms in order to perform a particular activity.

When evaluating physical fatigue such indices as heart rate, blood pressure, respiration rate, hand strength, endurance, arm tremors (static and dynamic) are used. As the overload of one functional system cannot be compensated for by the diminution of another (Bedny & Seglin, 1997), it is important to identify the more critical criteria. Often, the cardiovascular functional system is subject to overloading in a stressful physical work situation or in an overheated environment. Reduced oxygen requirements do not compensate for excessive load on the cardiovascular system. Therefore, when comparing different functional criteria it is critical to identify those relevant to overload for a specific system. Further, this illustrates the importance of using pulse rate as a specific index of cardiovascular stress and basis of evaluation for required break time. Measurement of the average heart rate during a shift according to this method involves no fewer than 10 participants in a particular kind of work. Bedny and Seglin (1997) and Bedny and Meister (1997) described this method previously. In this work we use heart rate as a tool for the evaluation of economic efficiency derived from ergonomics interventions. If the cost of work of the excavator per time units and the time are known, and the savings by reducing rest periods from the use of air-conditioning, the economic profit we have from its installation may be calculated. In the same way we perform calculations in other situations when we try to perform economic calculations connected with reducing physical workload and improving working conditions.

For example, according to a physiological calculation for the prevention of fatigue, a worker performing a heavy physical job must rest about 60 min per shift. However, after introducing some mechanization of tasks, the physical workloads are reduced. In this situation, physiological calculation demonstrates that break time can be reduced to 30 min. If we know the hourly labor and overhead costs, then we can calculate the economic returns from reducing rest time to 30 min per shift.

For practical applications of this method we offer heart rate as a simple procedure for the calculation of required break time during the performance of heavy physical jobs, or the performance of physical job under stressful physical conditions. The method must be simple and usable in a production situation and available even for nonmedical practitioners.

2. BREAK TIME AS CRITERION OF EVALUATION OF ERGONOMICS INTERVENTIONS

Preintervention and postintervention outputs fail to appreciate the long-term effects of the intervention on the work force. Short-term productivity increases may be achieved at serious long-term costs of overloading the work force. On the other hand, low productivity can be the result of suboptimal exploitation of worker potential. Therefore, a scientific approach to evaluation of the economic efficiency of different interventions should be based on a ratio of productivity and expenditure of worker effort. For this purpose we propose the notion of the functional state of the organism utilized in the theory of activity (Bedny & Meister, 1997).

The functional state of the organism refers to organization and integration of physiological and psychological processes over a time with qualitative characteristics that subserves specific behavioral outcomes. During work the functional state of the organism continuously changes. For example, extended periods of excitement engender high levels of activity that in turn tend to lead to fatigue that elicits a tendency to rest.

Break time is one method for preventing overload. Determination of the duration of break time during work performance should be based on an analysis of the functional state of the organism. During the performance of physical work the functional state of the worker is best evaluated on the basis of energy expenditure. Energy expenditure of individuals may be measured in kilocalories (kcal). Energy created during muscle contraction is connected with the consumption of oxygen. Therefore, energy expenditure may be determined by calculation of the amount of oxygen consumed and carbon dioxide expired. German Work Research Association (as cited in Lehmann, 1962) recommends that the amount of energy expenditure may not exceed 4.17 kcal/min. Lehmann gives a similar recommendation. According to his recommendation, energy expenditure should not exceed 4.00 kcal/min. If the amount of energy expended in terms of kilocalories exceeds this limit, then a break period is required. Both Lehmann (1962) and Murrel (1965) provide formulas for the calculation of break time based on the evaluation of the expenditure of energy in kilocalories during the performance of physical work.

However, the evaluation of energy expenditure in a work situation is a very difficult problem. Thus, often in practice during the evaluation of dynamic work, instead of using a method of evaluating energy expenditure, the practitioner uses the heart rate technique. In this kind of job heart rate correlates with energy expenditure (Kiser & Rodgers, 1986; Scherer, 1967). In addition, heart rate of more than 100 beats/min reflects overload of the cardiovascular system. Therefore, this type of workload also requires break time (Rosenblat, 1975). Accordingly we use the very simple method of calculating break time based on the heart rate technique developed by Rosenblat and described in our preliminary publications (Bedny & Meister, 1997; Bedny & Seglin, 1997). Rosenblat suggests that during the performance of dynamic work, instead of energy expenditure, one may use a heart rate estimation procedure. Energy expenditure of 4.17 kcal/min corresponding to a heart rate of 100 beats/min is a boundary between easy and heavy work criterion according to the former Soviet Union hygiene standards. If the average heart rate (PA_{sh}) during a shift is more than 100 beat/min, additional break time is needed. Measuring heart rate under production conditions is easier than measuring energy expenditure. The first step of this method calls for calculating the average heart rate during work (PR_w):

$$PR_w = (P_1T_1 + P_2T_2 + \ \ldots \ + P_nT_n)/T_s, \tag{1}$$

where,

P_1, P_2, ... P_n are the heart rates of the first, second, and so forth, operation;
T_1, T_2, ... T_n are the performance times of the first, second, and so forth, operation;
T_s is the overall duration of the actual work performance during the shift.

$$T_s = T_1 + T_2 + \ \ldots \ + T_n. \tag{2}$$

The average heart rate during break time PA_{br} is calculated as PR_w. The next step involves the calculation of heart rate during the shift PA_{sh} according to the following formula:

$$PA_{sh} = (PR_wT_s + PA_{br}T_{br})/(T_s + T_{br}). \tag{3}$$

PA_{sh} is the major criterion for evaluating the intensity of work and for the estimation of break time. If the value for PA_{sh} is less than 100 beats/min, one needs no additional time to rest. If PA_{sh} is more than 100 beats/min, additional break time should be allotted (Rosenblat, 1975). The first step in calculating break time involves calculation of the theoretical break time that is designated as BT_{cal}, which is evaluated as a percentage of the shift time. Using the theoretical break time and the real break time (BT_{rl}), required break time (BT_{rq}) is calculated as a percentage of shift time (Rosenblat, 1975). BT_{cal} for an 8-hr shift is calculated with the following formula:

$$BT_{cal} = 100\ (PR_w - 100)/(PR_w - PR_{br})\%. \tag{4}$$

The next stage requires calculating BT_{rq} as a percentage of the shift time.

$$BT_{rq} = (BT_{rl} + BT_{cal})/2\% \qquad (5)$$

BT_{rl} may be obtained from time studies. More details about this method can be found in Bedny and Meister (1997) and Bedny and Seglin (1997). Bedny (1987) suggests extending this method in order to evaluate the cost-effectiveness of mechanization improvement of shops' environment, and so forth, as presented further.

At a given level of productivity we determine the amount of break time for existing conditions by using the described heart rate technique. Following that one can calculate break time under the projected improvements with appropriate mechanization, automation, improvement of microclimate, and so forth. Savings created by the new work environment are indexed by the differences before and after implementing the break time changes. There are well established data that describe cost of equipment and human work measured in labor hours. Based on this data one can infer effective gains in terms of work time thereby indexing the effective gains from the intervention. This approach may be used in situations when average heart rate is higher than 100 beats/min during the shift.

The heart rate criterion may also be used in time studies. In such cases this method is tightly connected with the evaluation of the pace of physical work performance. The heart rate criterion can be used for increasing the pace of work when heart rates are much less than 100 beats/min. When heart rate exceeds 100 beats/min the same method may be used to recommend decreasing the pace of work performance. Therefore, this method may be used for regulating the pace of dynamic work. Thus, as may be seen, we suggest the aforementioned technique of heart rate evaluation for a totally different purpose—for calculating economic efficiency of some ergonomics interventions and time studies.

3. EXAMPLE OF ESTIMATING THE COST-EFFECTIVENESS OF ENVIRONMENTAL IMPROVEMENT

Further we describe how this technique may be used to estimate cost-effectiveness of air-conditioning in the cabin of a large excavator. The task was to determine the cost-effectiveness of air-conditioning the cabin of a large earth removal excavator by creating the following simulation of the physical and psychological activity.

An excavator's cabin was placed in a laboratory (Figure 1). Participants moved control levers of a simulator so that vertical rods would not touch the walls of the slots in which they were mounted. If contact occurred between the rods and the slot, a lamp flashed. If contact was made against the right slot by the right hand, a red lamp flashed; if contact was made with the left slot by the left hand, a green light flashed. The errors were counted by a special device that allows for continuous self-monitoring. The ambient temperature was set to approximate normal working conditions. The independent variable was the presence or absence of air-conditioning in the cabin. Ten participants, all trained in the use of the excavator simulator, took part in the study. The experimental procedure took 2 hrs each. Before the tasks began, each participant spent 25 min in the cabin adapting to the existing climate.

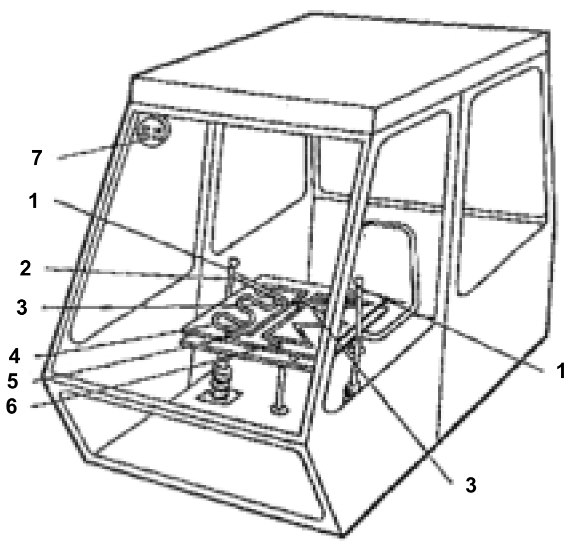

Figure 1. Excavator's cabin with simulator. *Notes.* 1—control levers, 2—handles, 3—vertical rod, 4—board, 5—red lamp, 6—green lamp, 7—error counter.

During the experimental simulation we counted heart rate and breathing rate. Heart rate was determined with a photopleismograph. A heart rate detector was fixed to the ear lobes of the participant. Breathing rate was determined with a gauge fixed to the operator's nostrils. We also registered blood pressure using standard medical methods.

The preintervention portion of work break time (existing break time rest BT_{rl}) equals the production pauses during work shift t_{pp} that can be determined from a handbook for the utilization of construction machinery

(Kantorer, 1977). According to handbook data t_{pp} is 17.88% or BT_{rl} for the shift. It equals 88 min for a shift of 492 min. Accordingly, for 1 hr of work the rest period equals 11 min and work time equals 49 min. Therefore, the participants in our experiment had the opportunity to rest twice, first for 5 min, then for 6 min. Thus we attempted to simulate an operator's load close to real conditions.

Preliminary experiments were conducted to establish base line functional state of the participants (cf. Table 1), later to be called the relaxed state. Following initial measurements the participants began to work in the excavator's cabin; each participant was exposed to both control and experimental conditions. Under control conditions participants worked without air-conditioning. The conditions inside the cabin with no air-conditioning were made to approximate summer temperatures (air temperature 40–41 °C, wind speed 1 m/s; relative humidity 55%). These values for the microclimate were selected because they simulate conditions in some of the warm climates of the former Asian Soviet Republics.

TABLE 1. Pretest Functional Measures: Heart Rate, Breathing Rate, Arterial Blood Pressure

			Arterial Blood Pressure	
Participants	Heart Rate (beats/min)	Breathing Rate (beats/min)	Systolic (mm Hg)	Diastolic (mm Hg)
1	80	12	125	85
2	78	13	120	80
3	70	16	115	75
4	67	10	110	74
5	70	12	120	75
6	65	11	117	68
7	68	10	120	67
8	66	14	110	69
9	65	13	119	70
10	68	10	117	70
Mean	69.7	12.1	117.3	73.3

The results of the trials without air-conditioning are presented in Table 2. Average heart rate was 105 beats/min. According to a Russian classification the results of heart rate under control conditions (without air-conditioning) place the strenuousness of this job into Category Three (Bedny & Seglin, 1997; Rosenblat, 1975). The mean heart rate is substantially increased over

TABLE 2. Functional State of Participants During Work Process

	Functional State of Participants Without Air-Conditioning						Functional State of Participants With Air-Conditioning					
	Heart Rate (beats/min)		Breathing Rate (beats/min)		Blood Pressure (mm Hg)		Heart Rate (beats/min)		Breathing Rate (beats/min)		Blood Pressure (mm Hg)	
Participants	Work	Rest	Work	Rest	Systolic	Diastolic	Work	Rest	Work	Rest	Systolic	Diastolic
1	108	97	24	19	138	97	88	82	19	14	130	92
2	110	98	23	18	135	90	92	80	18	15	125	85
3	107	96	25	17	130	88	85	82	16	15	120	80
4	108	98	21	14	120	82	80	65	19	14	110	75
5	105	95	22	16	115	80	82	77	17	13	117	77
6	102	93	18	16	125	80	84	70	15	15	110	70
7	104	91	20	14	110	70	80	74	18	13	115	77
8	106	96	21	15	118	64	77	70	16	12	118	75
9	98	89	19	14	116	69	79	69	17	14	120	80
10	103	93	22	17	110	75	82	72	18	13	110	67
Average	105.1	94.6	21.5	16.0	121.4	79.5	82.9	74.1	17.3	13.8	117.5	76.9

that of the relaxed state. The substantial heart rate increase combined with the absence of increased blood pressure suggest that work under hot climate conditions produces substantial stress (Klenovich, 1968). The high load to circulatory and respiratory systems correlates with dilating blood vessels in the skin. This, in turn, causes a reduction of blood pressure. Thus concurrent substantial shifts in heart and breathing rates with small shifts of artery blood pressure are a negative indicator.

An analysis of individuals Number 5, 7, 9, and 10 in Table 2 reveals that their arterial systolic pressures in the relaxed state (Table 1) were even higher than at work time. PR_w and breathing rate (BR) substantially increased, so we infer that the activity of the heart and cardiovascular system of these individuals was most affected. At break time their breathing and heart rates maintained high levels. This means that the operator's work in the excavator's cabin presents significant stress on the body from microclimatic conditions.

The next series of experiments (experimental conditions) were conducted with air-conditioning (air temperature 24 °C; wind speed 1 m/s; relative humidity 45%). The results of the trials under the air-conditioning are presented in Table 2. Average heart rate was 83 beats/min. Breathing rate increased insignificantly and systolic blood pressure increased negligibly in comparison with the relaxed state (compare Table 1 and Table 2 with air-conditioning). Further, during work breaks the indices approached their initial values. In terms of the Russian classification, this work with air-conditioning would be assigned to the second level of strenuousness, in which the heart rate is over 80 beats/min. Individuals performing excavation work with air-conditioning are assigned to this intermediate level of stress. Student's *t* for interdependent data was calculated to determine the significance of the differences between average values in air-conditioning versus values in its absence as presented in Table 2. In this experiment Student's *t* was used to compare heart rate in a work period without air-conditioning versus heart rate in a work period with air-conditioning, heart rate during a rest period without air-conditioning compared with heart rate during a rest period with air-conditioning. In the same way other physiological data were statistically evaluated.

The differences of heart rate between an air-conditioned and unair-conditioned situation were statistically significant according to Student's *t* index ($p < .01$). Differences in breathing rate were also statistically significant at ($p < .05$). Differences in blood pressure were not statistically significant. This experiment shows that air-conditioning changes the excavator's job from the third to the second category of strenuousness without any loss of productivity.

Next, let us utilize heart rate to calculate the necessary break times when working without air-conditioning. Average heart rate (PR_w) during work time is 105.1 beats/min; during break time PA_{br} drops to 94.6.

According to Equation 4

$$BT_{cal} = 100\,(105.1 - 100)/(105.1 - 94.6) = 48.57\%.$$

Taking into consideration that the preintervention proportion of work break time $BT_{rl} = t_{pp}$, which has been determined from the handbook of Kantorer (1977) to be 17.88%, the required proportion of rest time can be determined from the formula for the calculation of required break time according to Equation 5:

$$BT_{rq} = (17.88 + 48.57)/2 = 33.22\%.$$

In other words, to obtain an average shift of heart rate (PR_{sh}) of less than 100 beats/minute, 33.22% break time must be provided instead of the prescribed 17.88% of work time. This means that we need to increase break time by 15.34% of the overall work time on the excavator ($T_{ex\ w}$). The time worked on the excavators during a shift includes breaks for maintenance and other technical reason t_{tr}. According to standard requirements, t_{tr} = 39 min* (Kantorer, 1977). In the case at hand the time of work ($T_{ex\ w}$) when the excavator operated during a shift becomes

$$T_{ex\ w} = T_{sh} - (t_{pp} + t_{tr}). \tag{6}$$

Thus, $T_{ex\ w}$ = 492 – (88 + 39) = 365 min. The required increase for work breaks (BT_{rq}) should be 15.34% from 365 min. So, in the absence of air-conditioning we need an additional 56 min (15.34%) of break time per shift.

Working in an air-conditioned environment generates heart rates much lower than 100 beats/min. This reduces the need for additional work breaks. In the present case air-conditioning resulted in savings of 56 min of work time per shift. Knowing the hourly expense of running the excavator it is easy to calculate the economic gain from introducing air-conditioning into the

* Time for production pauses and breaks for maintenance or other technical reasons may vary from country to country.

cabin of the excavator. When we take into account that average heart rate equals 83 beats/min under air-conditioning, the value added of air-conditioning can be formulated as consisting of a given level of productivity being reached at a lower level of the functional state of the organism.

4. CONCLUSIONS

The results of these experiments allow us to draw the following conclusions.

1. This study shows that without air-conditioning, operators must have an additional 56 min of break time per shift in order to avoid overloading the cardiovascular system. With air-conditioning additional rest time is not required. This means that air-conditioning yields 56 min of additional excavator use per shift.
2. In the evaluation of physical work, especially in adverse microclimate, overload is typically more a function of the cardiovascular system than a function of energy expenditure. Under these conditions, analysis of energy expenditure is not sufficient. An evaluation of loads imposed on the cardiovascular functional system is more adequate.
3. Evaluation of the cost-effectiveness of interventions reducing the physical workload and stress through environmental improvements and other technical innovations can be made on the basis of heart rate recorded during work periods. This method contrasts required work break time with and without implementations of work improvements.
4. The proposed method of cost-effectiveness calculations of different interventions can be applied both when work heart rate exceeds 100 beats/min, and when it is much lower. When heart rate exceeds 100 beats/min, some intervention to reduce the workload by using break time evaluation is indicated. When heart rate is lower than 100 beats/min it implies that the pace and workload can be safely increased.
5. Evaluation of the cost-effectiveness of reducing workload and stress by different innovations can be achieved for the evaluation of required break time before and after the introduction of stress reducing innovations.

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