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THE ENERGY COST OF COMBAT ENGINEER TASKS

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W. S. Myles

T. T. Romet

Defence and Civil Institute of Environmental Medicine

1133 Sheppard Avenue West, P.O. Box 2000

Downsview, Ontario, Canada M3M 3B9

DEPARTMENT OF NATIONAL DEFENCE - CANADA

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ABSTRACT

Canadian combat engineers performed abatis (blocking a road by felling trees), minelaying and road cratering for 8 hours each day on four consecutive days. Energy expenditure was estimated from heart rate continuously recorded using the VITALOG personal monitoring system (PMS-8). The average heart rates were below 120 bpm for all three combat engineer tasks indicating that, for these subjects, energy expenditure did not exceed 35-40% of their $\dot{V}O_2max$. Since abatis, minelaying and cratering are considered to be the most physically demanding tasks performed by combat engineers, it seems safe to conclude that the average energy expenditure for sustained operations will be at, or below, this level.

This experiment also provided an opportunity to evaluate the PMS-8 as a means of collecting physiological data in a non-intrusive manner during military maneuvers. The system proved to be very robust, reliable and, because data collection is continuous, ideal for intermittent work of varying intensity. In addition, the PMS-8 appears to have considerable potential as a means of monitoring the effect of sleep deprivation and fatigue on the work/recovery cycle in sustained operations.

INTRODUCTION

In 1983, DCIEM was tasked by the Director of Military Engineering Plans (DMEP) to investigate the ability of combat engineers to perform physical work during sustained operations. In particular, DMEP wanted to know whether work output (productivity) could be maintained in the face of accumulating sleep deficit and fatigue. The project was to be conducted in collaboration with personnel from the Operations Research and Analysis Establishment (ORAE), with DCIEM responsible for the physiological component.

The first step was a visit by DCIEM and ORAE personnel to observe combat engineer tasks as performed by 4 Combat Engineer Regiment (4 CER) during an exercise in Hohenfels, Germany. The next stage was to conduct a search of the scientific literature for studies directly and indirectly related to the combat engineer problem. This review (8) concluded that there were no published studies of combat engineers and very little information that was directly relevant to sustained military operations. The review did identify the gaps in existing knowledge and proposed, in very general terms, some experiments to fill them. This report presents data from the first of these proposed studies.

This investigation had several goals. The most important was to use heart rate to estimate the energy expenditure for the three most physically demanding tasks (abatis, minelaying and cratering) performed by combat engineers. Since other tasks are considered by DMEP to be less demanding, this data will establish the upper limit for energy expenditure in sustained combat engineer operations. The second objective was to use continuous recording of heart rate to estimate the intensity and duration of the various intermittent activities (e.g., chainsawing) which are components of the three tasks and to document the work/recovery cycles adopted by combat engineers. Finally, this investigation provided an opportunity to evaluate the VITALOG Personal Monitoring System (PMS-8) as a means of conducting non-intrusive physiological monitoring of military field maneuvers.

METHOD

Subjects

Two Sections of six young men from the 2nd Canadian Combat Engineer Regiment (2 CER) served as subjects. Although no measurements of maximal oxygen uptake ($\dot{V}O_2max$) were made for these particular subjects, a previous study using other soldiers with a similar physical training history (9) indicates that their $\dot{V}O_2max$ determined by a progressive treadmill protocol would be about 50-55 ml/kg/min.

The heart rate recording system

Heart rate was recorded using the PMS-8 manufactured by Vitalog Corporation of Palo Alto, California. The PMS-8 is a general purpose microcomputer designed for continuous collection of data which is stored in a solid state memory for subsequent recovery. The data can be analyzed through its supporting computer (Apple IIc) and associated software. In this study, the PMS-8 was programmed to collect and store heart rates every 10 sec from three chest electrodes in the CM 5 configuration. Each night, data collected during the day was transferred to disc and the PMS-8 units were reprogrammed for the next day. When the experiment was over, the Apple computer was used to reduce the large amount of heart rate data collected and to present it in an appropriate format (raw data, average values etc.).

Experimental protocol

The experiment was carried out in the training area at CFB Petawawa. Heart rates were recorded for 8 hours on four consecutive days, from one Section on days 1 and 2 and from the other on days 3 and 4. Each day the subjects assembled at 0800 hours to have the electrodes attached. These were connected to the PMS-8 which was worn on a belt around the waist. The recording of heart rate began as soon as this connection was established.

Work began at 0815 hours and continued, with a one hour break for lunch, until 1715 hours. Each Section performed the same three tasks each day (abatis for two hours, minelaying for four hours and cratering for two hours) Minelaying was always performed before and after lunch, the other two tasks were alternated between morning and afternoon. The subjects were supervised by a non-commissioned officer and worked at a rate which expert observers confirmed was typical of the normal pace for combat engineers performing these three tasks.

The following is a brief description of the three tasks:

1. Abatis is the blocking of approximately 200 m of road with trees from either side felled at an angle. The Sections used two slightly different techniques. Section I made sure that the trees fell in the correct direction by pulling on a rope, Section II achieved the same end by pushing with a pole. Access was subsequently restored by cutting the trees into sections using chainsaws and moving them to the side.

2. Minelaying is performed by marking out an area with pickets and barbed wire. Inside this area, dummy mines were buried just below the surface in staggered rows about 8 m apart. The soil at Petawawa is sand and gravel and was relatively easy for digging and hammering pickets.

3. Cratering is performed by blocking approximately 100 m of dirt road, using explosives, to form large craters. These were produced by digging 6-8 cylindrical holes with spade and auger. Explosives were placed in these holes and detonated simultaneously. Since the dirt road was hard and stony, augering required brief periods of very intense effort for some individuals.

RESULTS

Figures 1-3 show samples of the raw data collected by the PMS-8. They shows heart rates for three subjects, one operating a chainsaw (in abatis), one rolling wire (in minelaying) and one using the auger (in cratering). The data illustrate the intermittent nature of the work with peaks in heart rate indicating hard work and periods of lower heart rate reflecting light work or rest pauses.

Although high heart rates were observed for brief periods, average heart rates over the duration of the tasks were considerably lower (Table 1). Except in abatis, the average heart rates were below 120 bpm and were similar for the two sections. In abatis, the mean heart rates for sections I and II were 114 and 123 bpm , respectively, with the combined average 118 bpm . This difference may have been due to differences in technique, (e.g., rope pulling versus pole pushing). During the brief period prior to 0815 hours (control) and during lunch, when the subjects were not working, average heart rates were below 100 bpm.

Table 2 shows the three tasks divided into their component activities (chainsawing, digging, augering etc.). The average heart rates for the component activities in minelaying and cratering were all below 120 bpm. Some of the activities in abatis, particularly those involving the chainsaw, had heart rates above 120 bpm. However, the raw data, illustrated in Figure 1, indicate that chainsawing was a highly intermittent activity with frequent rest pauses where the heart rate decreased below 100 bpm.

In Figure 4, the three combat engineer tasks were classified as light, medium or heavy work on the basis of heart rate as proposed by Christensen (5). Figure 4 shows an estimate of the percent time spent with a heart rate in one of three zones (less than 120 bpm, 120-140 bpm, and more than 140 bpm) for the three tasks, with the data for Sections I and II combined. The percentage of time spent with a heart rate above 120 bpm (medium and heavy work) was 45% for abatis, 37% for minelaying and 28% for cratering.

In the samples of raw data provided in Figures 1-3, it is possible to identify periods when the heart rate was above a specified value. This permits characterization of an activity into time working (w) and in recovery (r), which correspond to time spent with a heart rate above and below 120 bpm, respectively. For example, Table 3 shows the average values for w, r and w/r (an arbitrary respresentation of the work/recovery cycle) for six component activities. Also indicated is the average heart rate for the period (w + r) for each activity, taken from Table 2.

DISCUSSION

The Energy Cost of Combat Engineer Tasks

The energy expenditure for the three combat engineer tasks was estimated from continuously recorded heart rate. This method was selected because it was non-intrusive and because the direct measurement of oxygen was considered impractical in the experimental conditions encountered in the training area at CFB Petawawa. Although heart rate provides an accurate estimate of oxygen consumption in steady-state exercise involving large muscle groups (walking, running, cycling etc.), there is the potential for error in other work situations. If the task involves a significant amount of arm work or isometric exercise, heart rate will overestimate oxygen consumption and hence energy expenditure (4,17,18). Other sources of error include heat stress, dehydration and fatigue (12,13). However, in industrial occupations analagous to the combat engineer situation, it has been shown that heart rate provides a reasonable compromise between accuracy and convenience. For example, in a field study of coastal fishermen, Rodahl et al. (11) calculated that the error from all sources should not exceed 15%.

The raw heart rate data, samples of which are presented in Figures 1-3, indicate that for all three tasks there were periods of relatively hard work offset by rest pauses or light work. This pattern reflects a work/recovery cycle that is typical of those recorded from workers in many industrial occupations (11,14,15). Of the component activities, those involving the use of the chainsaw were the most demanding (Table 2). Heart rates in chainsawing reached 150-160 bpm for brief periods (Figure 1) and were above 120 bpm for almost 50% of the time devoted to abatis (Figure 4). By the same criteria, minelaying and cratering were much less demanding tasks. Heart rates below 100 bpm in Figures 1-3 indicate time when the subjects were not working since essentially the same levels were recorded during the control and lunch periods.

The average heart rates for abatis, minelaying and cratering were below 120 bpm (Table 1, combined data). This heart rate corresponds to an energy expenditure of 35-40% of treadmill VO_2max for physically fit young men such as those used as subjects in this study (9,19). Similar levels of energy expenditure have been measured for civilians in various industrial occupations (1,3,10,11,16) and it is generally accepted that men can work at this intensity for at least 8 hours (7,8). Furthermore, abatis, minelaying and cratering are the most physically demanding tasks performed by combat engineers and, in any sustained operation, there will be periods of relative inactivity (such as movement by vehicle from one location to another). It therefore seems safe to conclude that the energy cost of sustained combat engineer operations (48 hours and more) will not exceed 35-40% of $\dot{V}O_2max$.

Although an energy expenditure of 35-40% of $\dot{V}O_2max$ is considered acceptable for the normal 8-hour working day, there appears to be no definitive information regarding the ability to sustain this level for periods of 48 hours or more (8). The next step in this research is to determine the energy expenditure that can be sustained for such extended periods and to investigate the effect of sleep deprivation and fatigue. It is important to identify the level of energy expenditure that is voluntarily adopted when subjects are free to set their own pace. In this situation, sleep deprivation and fatigue may degrade motivation for work and cause work output (productivity) to decline.

<u>The Work/Recovery Cycle in Combat Engineer Tasks</u>

The VITALOG PMS-8 clearly has potential as a non-intrusive method of documenting the work/recovery cycle in sustained military operations. The values in Table 3 give some idea of how the data collected by the PMS-8 might be analyzed. In this analysis, a modified version of the software provided by the VITALOG Corporation was used to calculate the periods when the heart rate was above and below 120 bpm. This heart rate was selected because it represents an energy expenditure of 35-40% of $\dot{V}O_2max$ for subjects of the same age and training state as the combat engineers tested in this study (9,19). The periods above and below 120 bpm were labelled w (work) and r (recovery). The ratio w/r was taken to be an arbitrary representation of the work/recovery cycle.

An examination of the data in Table 3 indicates that there are no consistent relationships between w, r, w/r and the average heart rate for the period (w + r). A likely explanation for this is that the work/recovery cycle is determined by several factors. For example, it was clear from observing the soldiers performing the three combat engineer tasks that the work was intermittent. It was also evident that the duration of the work period was determined, in part, by factors inherent in the job. In abatis, the individual operating the chainsaw had to stop long enough to allow the tree to fall and to move to the next one. Similarly, subjects hammering pickets into the ground or burying mines had to walk from one location to the next. A second factor which can influence the duration of the recovery period is the body's need to recover from a bout of intense activity. It is well documented that self-pacing is an effective means of reducing fatigue and sustaining work for extended periods (2,6). In sustained operations, the added stress of sleep deprivation may have an effect on the work/recovery cycle. In the present study, it was not possible to determine the effect, if any, of these factors on w, r or w/r.

By themselves, the data in Table 3 do not provide any further insight into how individuals self-pace or what factors affect work output. They do, however, illustrate the potential of this type of data analysis as a means of documenting the effect of sleep deprivation and fatigue on the work/recovery cycle in sustained operations. Of the three factors influencing the work/recovery cycle, which were discussed in the preceding paragraph, the characteristics of the job and its total energy cost should not change throughout the period of sustained operations. Any changes documented by the PMS-8 could therefore be attributed to the effects of sleep deprivation and/or fatigue. Subjects may work at a lower exercise intensity, work continuously for shorter periods, and or take longer and more frequent rest pauses when fatigued and/or sleep deprived.

An Evaluation of the VITALOG Personal Monitoring System

Some relatively new technology, the VITALOG PMS-8, has been used in this study. Since the PMS-8 collects and stores heart rate data continuously, it can be used in situations where the work is intermittent and of varying intensity. Traditional ECG telemetry would necessitate sampling heart rate at intervals, a technique which is fraught with error when the work is not steady-state. The computer and software associated with the PMS-8 allow the reduction of the large amounts of data collected to managable form and its presentation in an appropriate format. It is also relatively easy to modify the software provide by the company so that novel data analyses can be attempted. An example of this is the documentation of the work/recovery cycle illustrated in Table 3.

This study provided an opportunity to evaluate the PMS-8 under field conditions. The PMS-8 is non-intrusive and this experiment confirmed that the subjects quickly learn to ignore the device. The investigator need approach them only to change the batteries which last up to 10 days. The system can be used in situations where the subjects are not visible to the investigator. This may occur at night or if the subjects are in separate locations performing different tasks. This study has shown that the PMS-8 unit, attached to the subject's waist, is remarkably durable. It will continue to collect accurate data even when the subject undertakes vigorous activities, such as climbing a tree to attach a rope (as performed by Section I in abatis).

The main disadvantage of the PMS-8 is that the memory capacity is restricted to 31 heart rate levels. This means that, if a wide range of heart rate is required (eg. 60 to 180 bpm), as in the present study, the system cannot discriminate within four heartbeats. For example, heart rates of 150 to 154 bpm will be recorded as 152 bpm, 155 to 159 bpm as 157 bpm etc. Further research, comparing the PMS-8 to direct measurement of oxygen consumption, is therefore required to determine whether this restriction is a significant source of error when the PMS-8 is used to measure energy expenditure. In addition, the validity of the PMS-8 as a means of monitoring work/recovery cycles must be demonstrated for intermittent work where the duration of the work and recovery periods are known.

CONCLUSIONS

1. The average energy cost of combat engineer tasks will not exceed 35-40% of their VO_2max. Although this level of energy expenditure can be maintained for at least 8 hours without undue fatigue, further research is required to determine whether it can be sustained for periods of 48 hours, or more, without sleep.

2. Heart rate measurements indicate that the pace of work for the three combat engineer tasks is intermittent and of varying intensity. Further research is necessary to document how sleep deprivation and fatigue modify the work/recovery cycle in sustained operations.

3. The VITALOG PMS-8 has potential as a non-intrusive method of monitoring work/rest schedules in sustained military exercises. Further research to evaluate this potential is indicated.

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TABLE 1

Average Heart Rates (± SD) for Combat Engineer Tasks

TASK	HEART RATE (bpm)		
	Section 1 (n=6)	Section 2 (n=6)	Combined (n=12)
Control	77 ± 11	81 ± 9	79 ± 10
Abatis	114 ± 22	123 ± 19	118 ± 20
Mine Laying	112 ± 13	112 ± 12	112 ± 13
Lunch	98 ± 11	96 ± 9	97 ± 10
Cratering	110 ± 16	109 ± 16	110 ± 16

TABLE 2

Average Heart Rates (± SD) for the Component Activities of Combat Engineer Tasks

TASK	ACTIVITY	HEART RATE (bpm) Section 1 (n=6)	Section 2 (n=6)	Combined (n=12)
ABATIS	Chainsawing	122 ± 18	128 ± 16	125 ± 17
	Clearing Debris	109 ± 17	129 ± 14	125 ± 15
	Clearing with Chainsaw	145 ± 19	150 ± 11	146 ± 17
	Rope Pulling	112 ± 17	---	112 ± 17
	Pole Pushing	---	127 ± 19	127 ± 19
MINE LAYING	Digging/Laying Mines	114 ± 12	110 ± 10	112 ± 11
	Hammering Fence Posts	114 ± 15	110 ± 14	112 ± 15
	Rolling & Securing Wire	117 ± 13	115 ± 10	116 ± 12
CRATERING	Augering	116 ± 14	115 ± 15	115 ± 15
	Digging	118 ± 12	115 ± 12	116 ± 12
	Preparing Explosives	103 ± 14	104 ± 12	104 ± 13

TABLE 3

Estimation of the Work/Recovery Cycle from Heart Rate

Activity	Work (w) Period (min)	Recovery (r) Period (min)	W/R	Average Heart Rate for period (w + r) (bpm)
Augering	0.4	4.7	0.1	115
Rolling Wire	0.5	2.9	0.17	116
Pushing or Pulling	0.5	1.2	0.42	127
Digging and Laying Mines	0.8	3.5	0.23	112
Hammering Fence Posts	1.3	0.6	2.20	112
Chainsawing	1.4	1.2	1.17	125

Figure 1

A sample of the raw heart rate data for chainsawing (abatis)

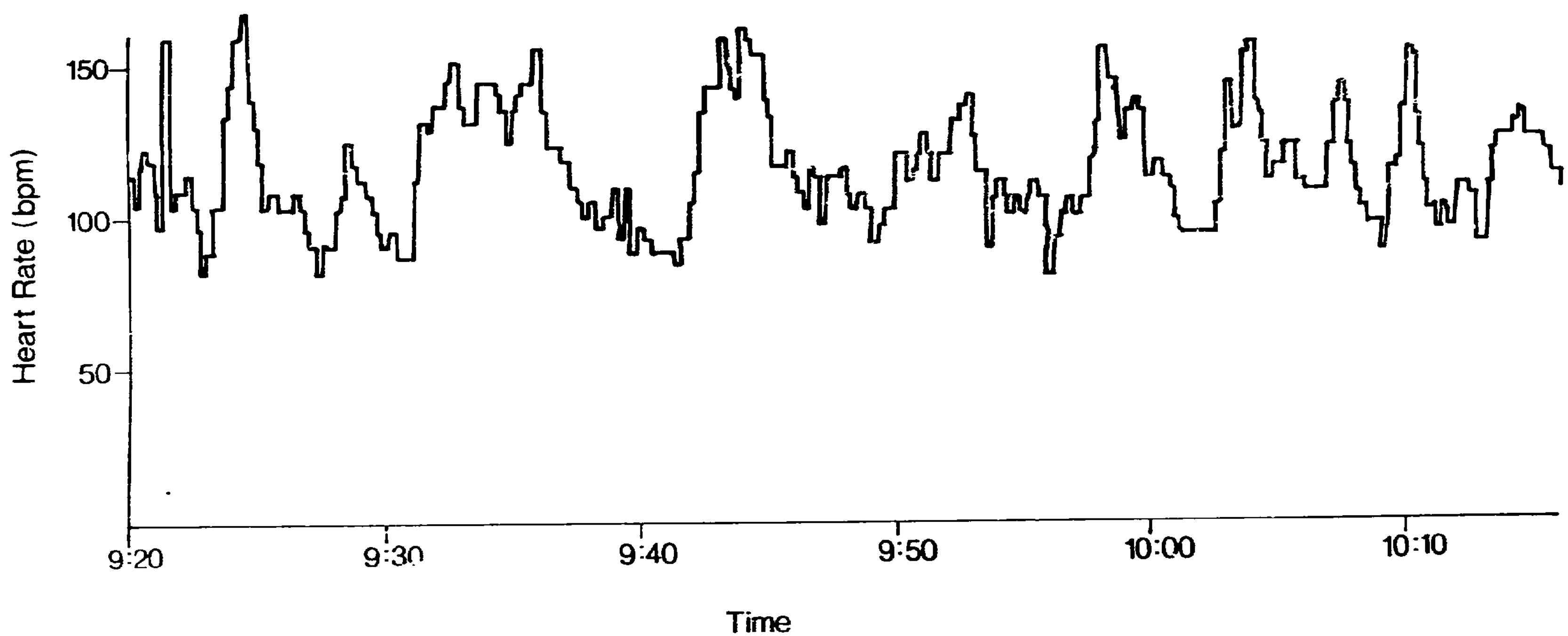

Figure 2

A sample of the raw heart rate data for wire rolling (minelaying)

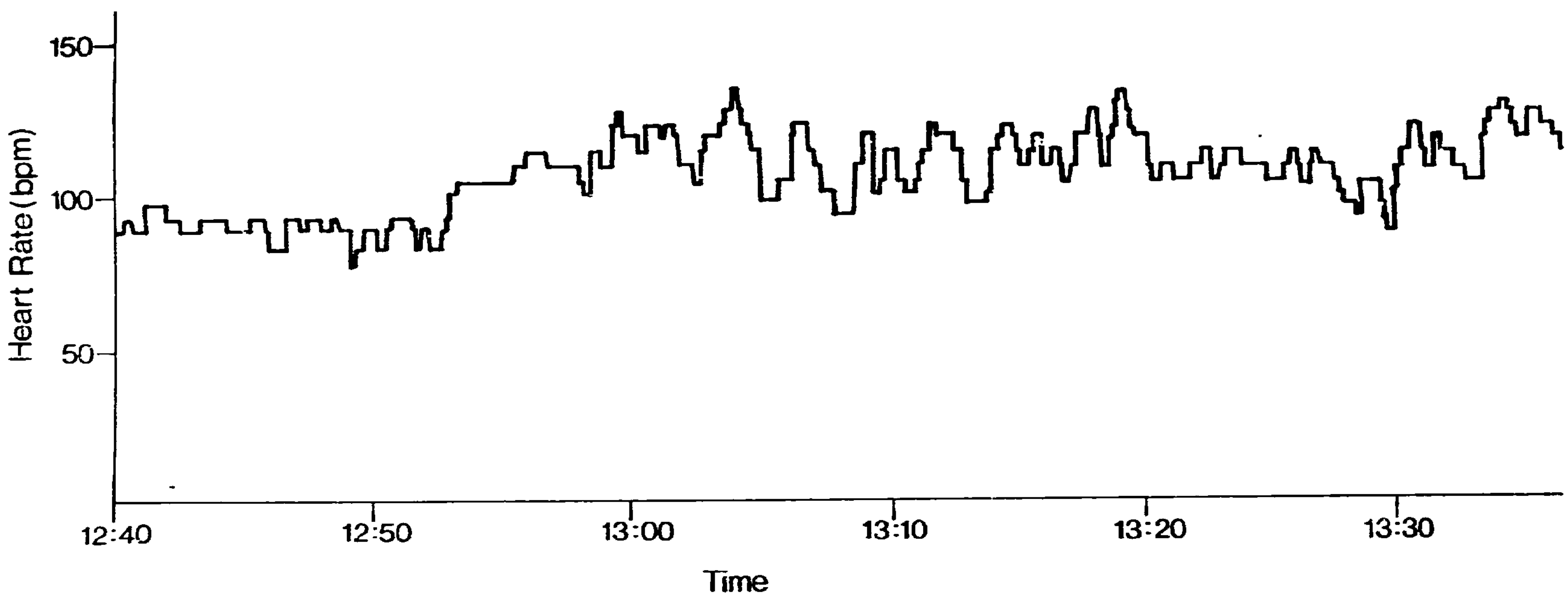

Figure 3

A sample of the raw heart rate data for augering (cratering)

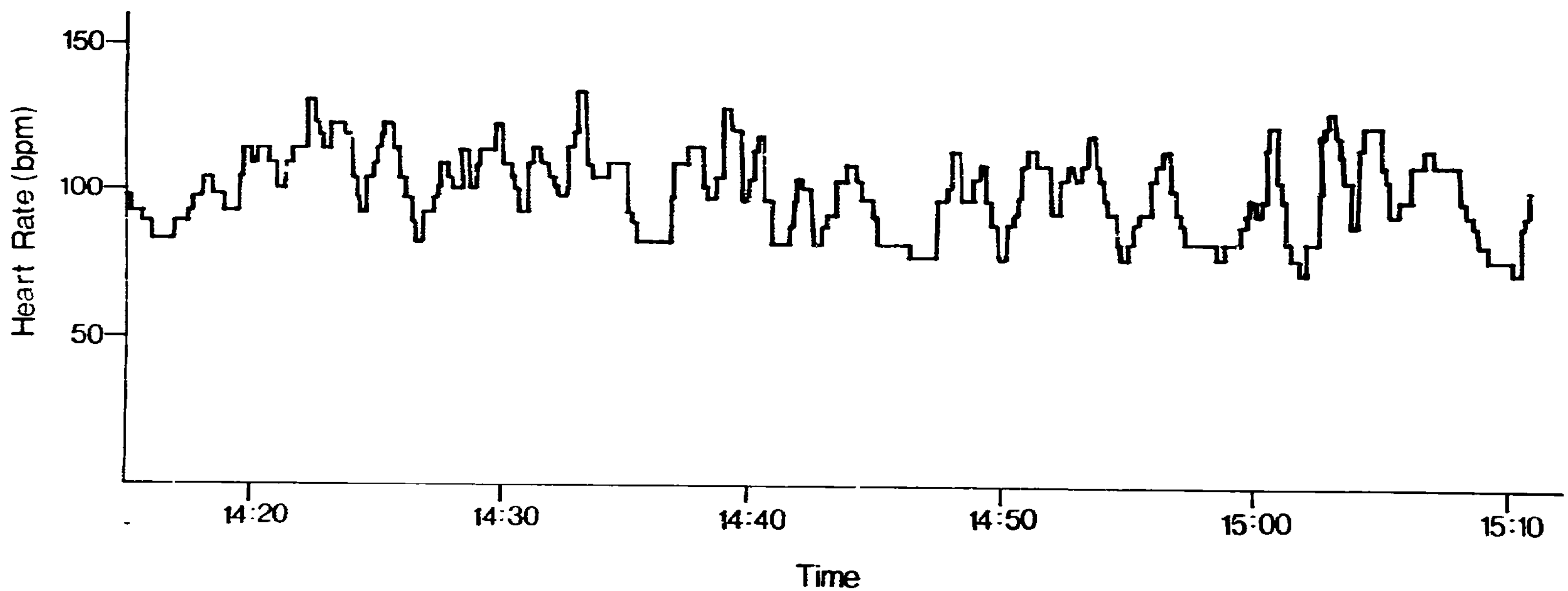

Figure 4

Classification of combat engineer tasks into light medium or heavy work on the basis of heart rate