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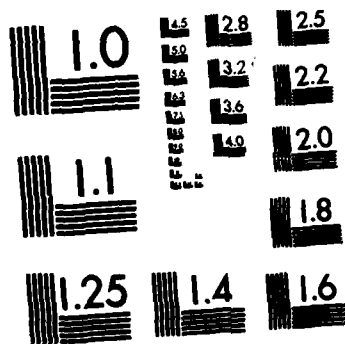
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ADA 124200

MEASURING SLEEP BY WRIST ACTIGRAPH

FINAL REPORT

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June 1, 1981

Supported By

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND

Fort Detrick, Frederick, Maryland 21701

Contract No. DAMD-17-78-C-8040

University of California

La Jolla, California 92093

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ABSTRACT

Future warfare may be exceptionally intense and brief, offering personnel little time for sleep. Fatigue could be a crucial factor in combat performance, especially if troops are airlifted across time zones and subjected to jet lag. Therefore, monitoring sleep loss and facilitating adequate sleep are crucial aspects of military medical planning. To monitor sleep in field conditions, a new technology is needed.

People move constantly when awake but little when asleep. Electronic recognition of activity can thus be used to monitor and determine sleep/wake states. This Final Report summarizes the research and development of a wearable sleep monitoring system. Wrist activity is measured with a piezo-ceramic transducer, monitored and stored by a microprocessor, then transferred to a larger computer for automatic sleep scoring. In prospective validation trials, the automatic measurement of sleep by a prototype device correlated $r=0.97$ with EEG sleep scoring. Full technical specifications are presented for construction of field-deployable sleep monitors which could be worn entirely on the wrist. Deployment of such devices would permit operational objective measurement of sleep loss among our troops.

INTRODUCTION

Sleep loss and combat fatigue are increasing concerns to the modern army. Lapses of attention may be more serious for the soldier who operates smart weapons, vehicles, radar, etc, than they were for the traditional infantryman who carried a pack and dug foxholes. Any future war is likely to be extremely brief and intense, and soldiers using technologically sophisticated weaponry will have little time for sleep. American troops may have to enter combat immediately after being airlifted to remote parts of the world, and plans must be developed to minimize the effects of jet lag on personnel performance.

In order to assess the effects of sleep loss, sleep schedule changes, jet lag, etc, upon operational performance of troops in actual field conditions, a practical method of quantifying sleep is needed which is cost-effective and reliable. Traditional methods of measuring sleep through EEG-EOG-EMG recordings are impractical for actual or simulated combat settings, and subjective monitoring is unreliable (Carskadon et al, 1976). Electrophysiological and observational methods for measuring sleep are also costly, and considerable time is necessary to score EEG records.

In the three years of our contract (DAMD 17-78-C-8040), we have investigated the feasibility of recognizing sleep from measures of wrist activity. We have developed instruments and procedures which allow us to quantify sleep with accuracy comparable to EEG scoring, but with much less expense and inconvenience. In this Final Report, we review and update the research and development reported in previous Annual Reports and include specifications for building sleep monitors suitable for field deployment. The

next step would be to actually build and deploy miniaturized monitors in operational settings. The technical specifications necessary to construct such monitors have been developed, and the monitors could be built today with a suitable engineering investment.

EXPERIMENT 1: SCORING SLEEP FROM WRIST ACTIVITY RECORDINGS

Kupfer et al (1972) and Foster et al (1972a, 1972b) described the use of a telemetric activity recording system for quantifying sleep. Kripke et al (1977) developed a more flexible system for recording wrist activity using a piezo-ceramic activity transducer and Medilog* cassette recorder. Initial pilot results established the value of this analog recording device for quantifying sleep. Kripke et al (1978), using five healthy subjects, obtained a correlation of 0.98 between sleep duration determined from wrist activity and from the EEG. The first experiment to be described here demonstrated the reliability of analog wrist activity recordings for quantifying sleep with a much larger number of recordings and a more diverse group of subjects, including hospital patients with varying degrees and types of insomnia.

Method

The activity transducer was constructed by soldering a small steel nut onto a 5 mm length of spring-like polygraph pen cleaning wire, and clamping the other end of the wire against a piezo-ceramic element (Kripke et al, 1978). The transducer was packaged in a small acrylic box mounted on a watchband. Transducer output was recorded on one channel of a four-channel Medilog cassette recorder. EEG, EOG, and EMG were simultaneously recorded on the other three channels, with timing marks superimposed on the EMG channel. In all, 102 overnight recordings were obtained from 85 subjects, including 39 recordings from 32 hospital patients.

The EEG-EOG-EMG signals (with the time code) were replayed from the cassette to a polygraph at 15 mm/second. Independently, the analog activity recording for the same segment was replayed (with the time code) onto a separate chart at 32 mm/minute. The EEG-EOG-EMG records were scored by one investigator, while activity records were scored independently by a second investigator, blind to the EEG results.

Results and Discussion

Figure 1 shows a representative analog activity recording. Three different sections of the same record (separated by dots) illustrate sleep onset, midsleep, and sleep offset, respectively. Straight lines indicate inactivity while modulations of the line indicate activity. The scorer's sleep/wake determination ('S' or 'W') is noted about the tracings. Periods of sleep and wake can be readily identified by the relative amounts of activity recorded.

The number of minutes for which the activity scorer and the EEG scorer agreed in assigning a score of "wake" or "sleep" was determined for each record. For the entire sample of 102 records, the two scorers agreed on 94.5% of all minutes. Agreement for the 63 non-patient records was 96.3%. The correlation coefficient between the two estimates of Total Sleep Time (TST) was $r=0.90$,

*Ambulatory Monitoring, Inc., 731 Saw Mill River Rd., Ardsley, N.Y. 10502.

indicating that most of the variance in inter-subject TST scored by one method was represented by the other method. The activity scorer's estimate of TST averaged 15.33 minutes greater per night ($t=3.82$, $p<0.0001$). This trend was related to a tendency to underestimate sleep onset latency in activity records. The activity rater scored sleep onset first in 54 records, while the EEG scorer scored sleep onset first in 34 records. The two scorers agreed exactly on sleep onset in the remaining 14 records. On average, sleep was scored four minutes earlier in activity than EEG records.

Figure 2 compares activity scoring (top line) with EEG scoring (bottom line) for ten records (including seven patient records). Thin lines indicate wake. Disagreement is indicated by a dark area below each pair of lines. Typical were the relatively good agreements between sleep/wake scoring for minutes scored from EEG and from activity recordings, as well as the high correlation between TST estimated by both methods and the small absolute error in TST per night. This confirmed the earlier findings and encouraged further development of a sleep monitor system based on activity recording (Mullaney et al, 1980).

EXPERIMENT 2: TRANSDUCER OPTIMIZATION

Although the piezo-ceramic activity transducer developed by Kripke et al (1977) produced excellent recordings and allowed highly accurate sleep/wake scoring in Experiment 1, the possibility that other available activity transducers might be superior was considered. Experiment 2 compared the piezo-ceramic transducer to a commercially available tilt-switch motion transducer* and to a sensitive accelerometer.**

Method

The tilt-switch transducer and a piezo-ceramic transducer were mounted in a 3.7 x 3.5 x 5.6 cm acrylic box and connected to two channels of a Medilog recorder. A 1.35 V battery and a resistive voltage divider were necessary to match the output of the tilt-switches to the input requirements of the recorder. Four subjects wore the pair of transducers on their wrist for a total of six nights. The two channels were played back simultaneously onto polygraph paper at 32 mm/minute. In further experiments, a second piezo-ceramic transducer in a similar box was firmly taped to the accelerometer. The two devices were connected to two channels of the polygraph and were worn by two subjects for several hours each. The duration of these recordings was limited since the accelerometer had to be directly connected to the polygraph.

Results and Discussion

Figure 3 shows a representative example of the performance of the piezo-ceramic and tilt-switch activity transducers. The piezo-ceramic transducer detected movements repeatedly at times when the tilt-switch transducer did not. Apparently, many movements did not change the orientation of the tilt switch array sufficiently to throw any of the switches. In our entire sample, there were no examples where the tilt-switch transducer detected activity not recorded by the piezo-ceramic transducer.

*Vitalog Corporation, 1058 California Avenue, Palo Alto, CA 94306.

**Grass Instruments, Model SPA 1.

Figure 1. Representative analog activity record visually scored in Experiment 1. Activity is seen as modulations of the line, while straight lines indicate inactivity. The scorer's marks ('S' and 'W') are seen on the record. The first three lines show sleep onset, the middle line mid-sleep, and the last three lines show awakening.

Figure 2. Comparison of the scoring of 10 records from analog activity data (top line) and EEG-EOG-EMG data (bottom line). Thick lines indicate sleep, thin lines wake. Disagreement is indicated by a dark space beneath each pair of lines. Seven of the ten records are from patients.

Figure 1

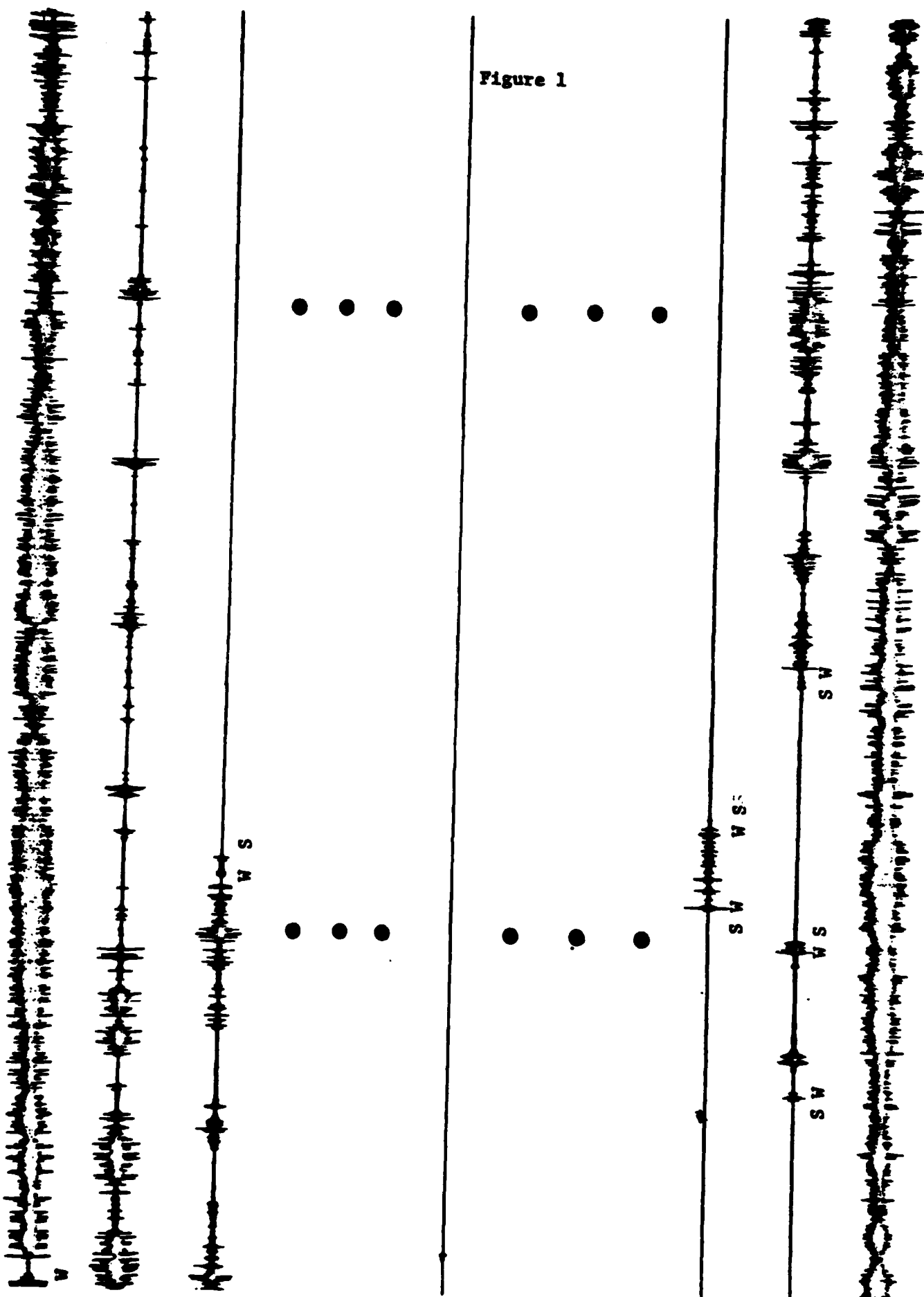
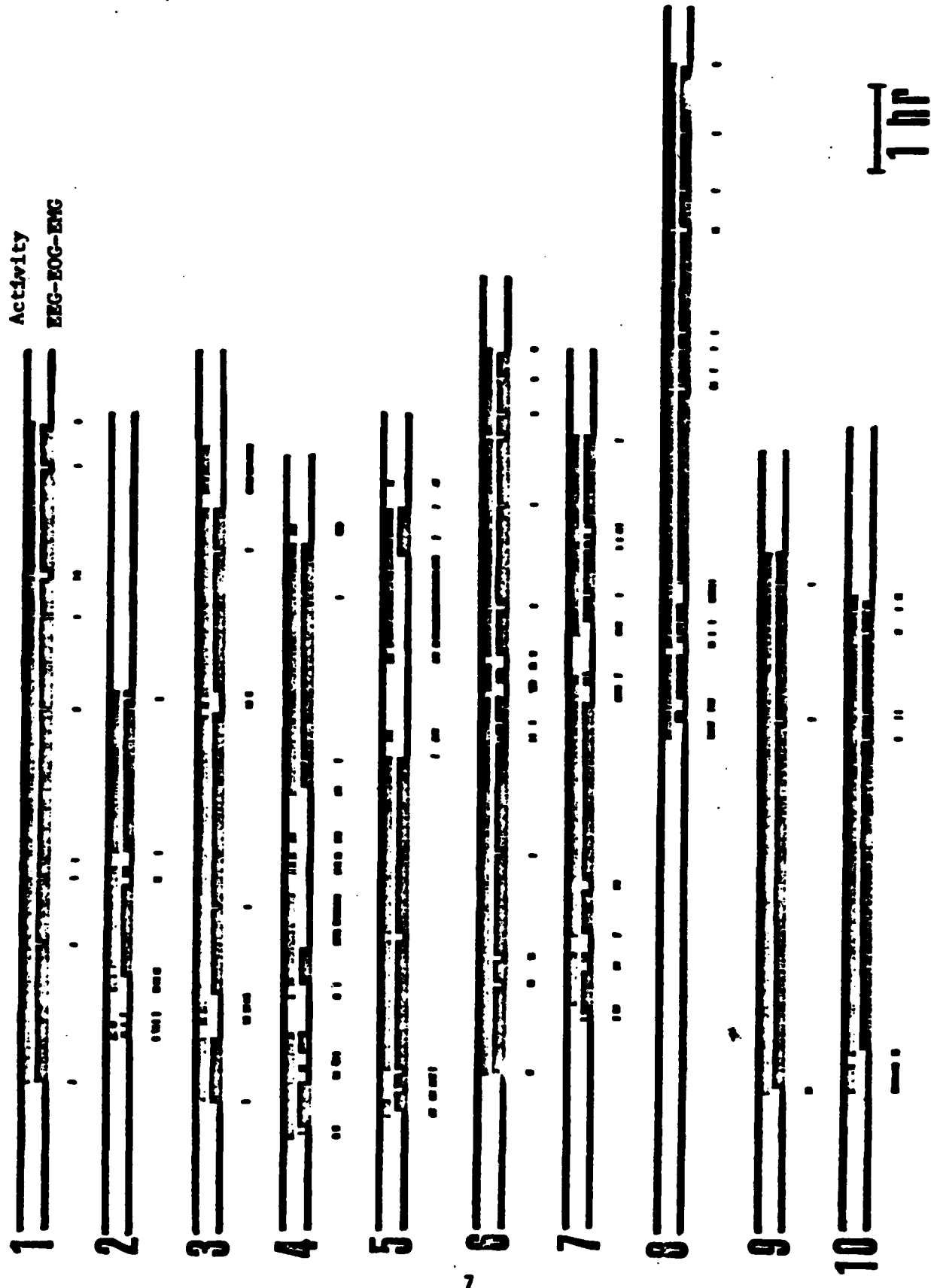


Figure 2



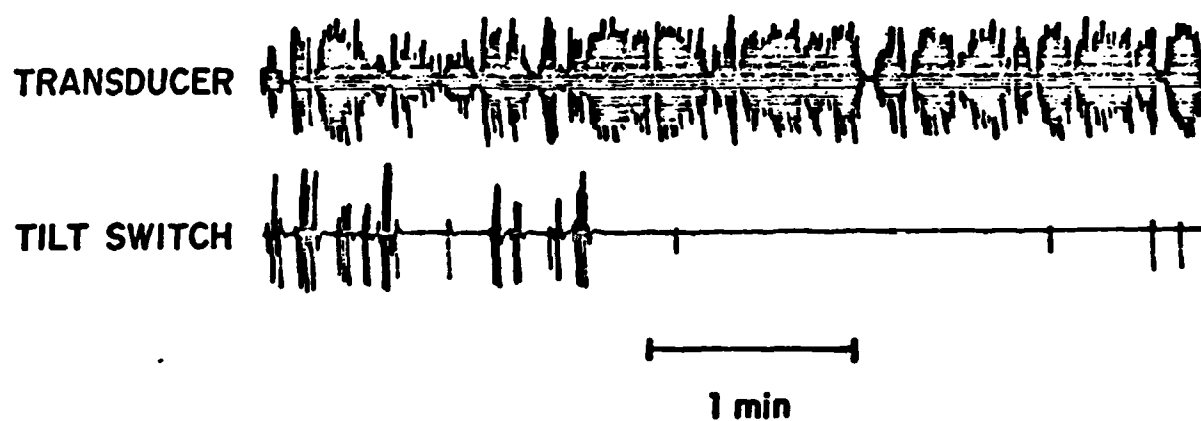


Figure 3. Representative polygraph record of activity recorded simultaneously from piezo-ceramic activity transducer (Channel 1, top) and Vitalog tilt-switch activity transducer (Channel 2). Although the piezo-ceramic transducer measures activity throughout the record, the tilt-switch fails to detect much of this activity.

A representative accelerometer recording is presented in Figure 4. The piezo-ceramic transducer detected all movements detected by the precision accelerometer, but the accelerometer was not sensitive to all movements, presumably due to its uniaxial design.

Thus, the piezo-ceramic transducer compared favorably to alternative designs, yet it is extremely compact, inexpensive and easy to manufacture.

EXPERIMENT 3: TRANSDUCER ORIENTATION

Although the weight is mounted off-center on the spring wire, causing the piezo-ceramic transducer to be excited by accelerations or rotations in any axis, the output voltage was not equalized for each axis. In Experiment 3, transducers were mounted in different axes on the wrist to determine optimal transducer orientation.

Method

Three piezo-ceramic transducers were mounted at three perpendicular orientations within a single 3.7 x 3.5 x 5.6 cm box connected to three channels of a Medilog recorder. Six subjects wore this device on their right wrists for a total of ten nights. The three channels were replayed simultaneously onto polygraph paper at a rate of 32 mm/minute.

Results and Discussion

An example of a recording from the three transducers is presented in Figure 5. This example is representative of the entire sample. Although the recorded activity analog from one transducer was frequently somewhat larger than that from another, there were virtually no instances where movements were not registered by all three transducers, and no clear superiority of orientation could be determined. It was concluded that orientation is not critical for this transducer.

EXPERIMENT 4: TRANSDUCER PLACEMENT

The decision to mount activity transducers on the dominant wrist in previous work was based on the a priori assumption that this location would allow the most sensitive detection of activity. To determine whether mounting on the non-dominant wrist or another area might detect more movements, we simultaneously recorded from both wrists, an ankle, and the forehead. The forehead was chosen with the supposition that all truncal movements would be accompanied by head movement, but respiratory artifacts might be less pronounced on the head than on any site on the body trunk.

Method

Four transducers were mounted in separate boxes (3.5 x 4.4 x 1.7 cm) and connected to the four channels of a Medilog recorder. Nine subjects completed

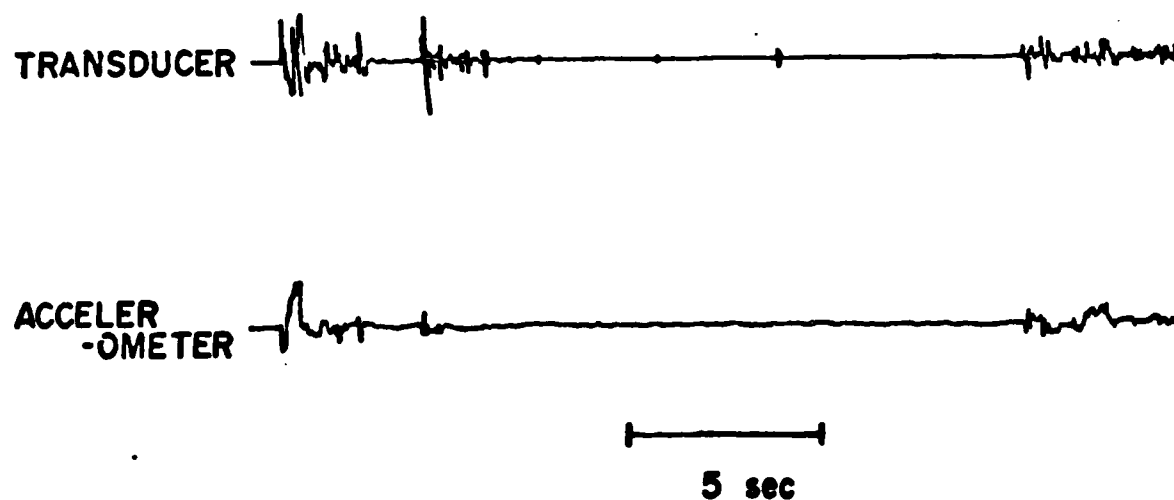


Figure 4. Representative polygraph record of piezo-ceramic transducer (Channel 1, top) and precision accelerometer (Channel 2). Piezo-ceramic transducer detects all activity measured by accelerometer, and some activity missed by accelerometer.

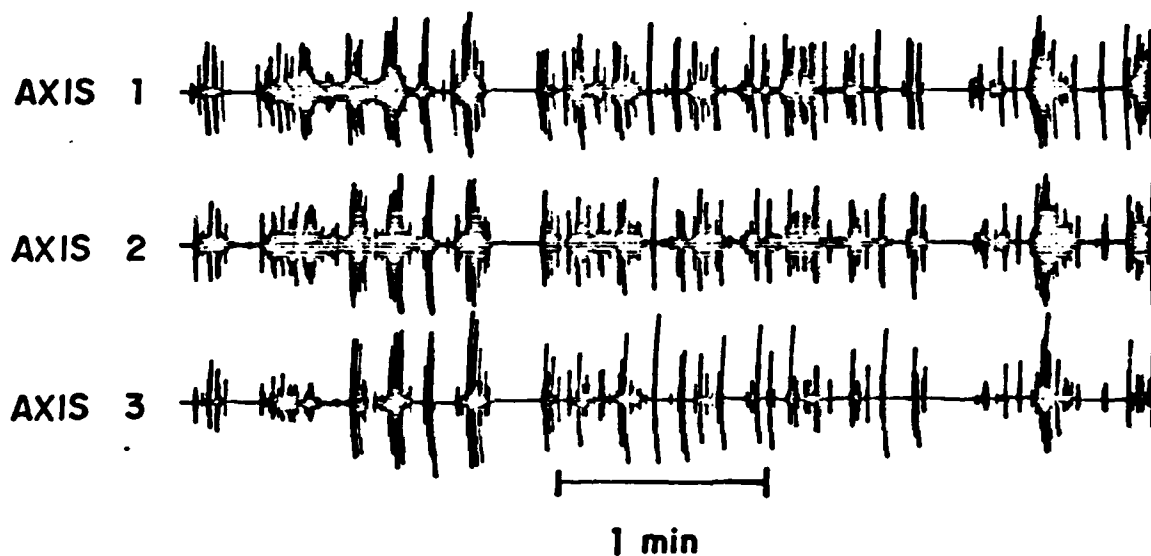


Figure 5. Representative polygraph record of 3 piezo-ceramic transducers mounted at the 3 major axes within a single box and worn on the wrist. Although differences in amplitude occur between the 3 channels, there are no failures to detect activity in any channel.

22 overnight recordings with the transducers worn simultaneously on each wrist, the forehead and an ankle. The assignment of transducers to locations was counterbalanced to control for possible variations in the sensitivity of individual transducers, and the order of polygraphic presentation was also counterbalanced to control for rater bias. The four channels were replayed simultaneously to four channels of the polygraph at 32 mm/minute. The records were then examined by two experienced raters (blind to transducer location) to score each transducer recording for sensitivity to movement and utility for sleep/wake scoring.

Results and Discussion

Figure 6 is part of a typical four-channel recording, showing more movements in the wrists than in either the head or ankle. The raters felt the contrasts between the two wrists were usually very small and of little importance in sleep scoring, and either wrist was preferable to the head or ankle. There was evidence that the left (non-dominant) wrist produced somewhat more activity. The practice of recording wrist activity is supported by these results. The choice of wrists seems unimportant, but the more comfortable non-dominant wrist is probably the better choice.

EXPERIMENT 5: DIGITAL PREPROCESSING

In Experiments 1 to 4, analog activity recordings were collected on cassette tape, replayed to a polygraph, and then scored visually. With this analog system, huge amounts of largely redundant data were collected, much time was expended, both in replaying and scoring recordings, and delicate instruments and trained technicians were required. A much faster and more efficient system would store a measure of activity in a digital memory and make it accessible to a computer for automatic scoring. The first problem in implementing such a system was to find an effective method of expressing a period of continuous activity recording as a single digital value. This experiment compared ten approaches for data compression and digital storage.

Method

Recorded analog activity data were replayed on one channel of a polygraph, and, at the same time, sent through an analog-to-digital converter (ADC) to a Hewlett-Packard 2100 computer. The computer was programmed with ten different data compression algorithms which calculated ten different digital values for each 2-second data epoch. The computer also generated a time code each minute which was written to a second polygraph channel.

The ADC converted the analog signal to a digital value 240 times a second. The 240 Hz conversion rate was chosen to be exactly four times the frequency of 60 Hz electrical noise occasionally recorded (such as that produced by an electric blanket or clock near the bed during the night.) It will be shown that the sum of every four conversions at 240 Hz cancels 60 Hz interference.

A file of seven overnight wrist activity recordings was digitized and transformed into ten alternative digital files corresponding to the ten

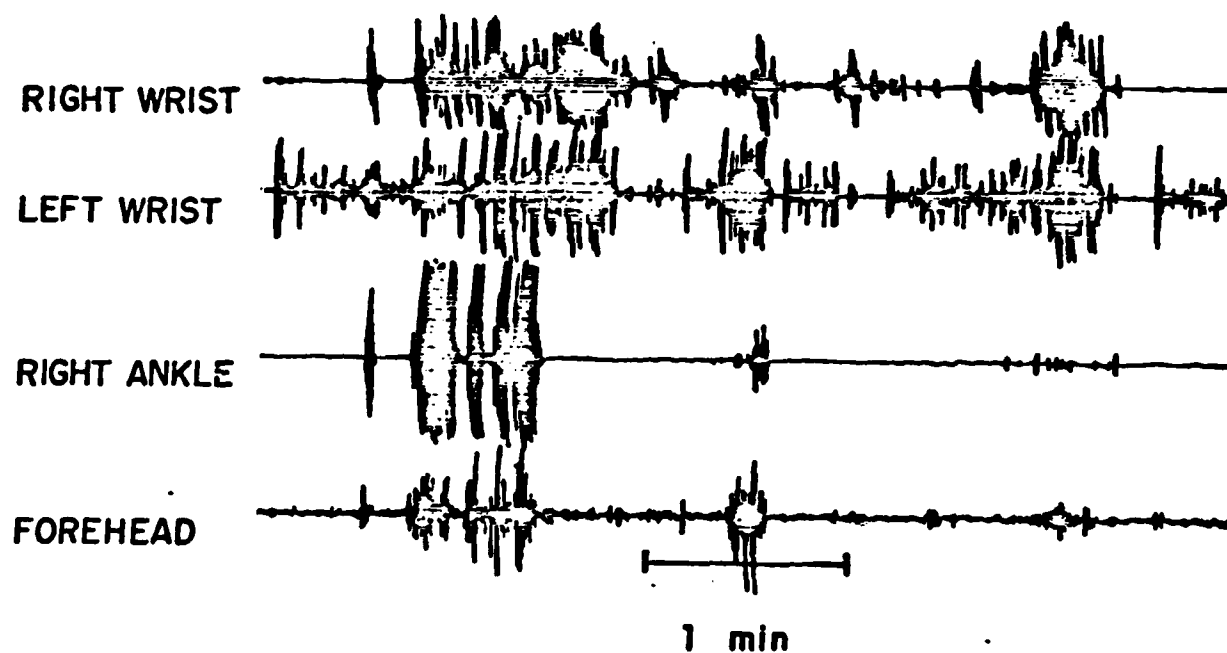


Figure 6. Representative polygraph record of activity detected by piezo-ceramic transducers mounted on the right wrist (Channel 1), left wrist (Channel 2), right ankle (Channel 3), and forehead (Channel 4). Bilateral wrist activity frequently occurs in the absence of head or ankle motion.

algorithms. Portions of the digitized records were displayed on a plotter to compare the ten transformations during different forms of activity. Each of the ten alternative digital files was then scored automatically by the computer using a simple rule in which a minute was scored 'wake' if x of the 30 two-second epoch scores exceeded a threshold of y . Sleep/wake scores for a range of x and y values were compared to the scores assigned by an experienced scorer to the polygraph activity records.

Results and Discussion

Figure 7 shows the plotter display and polygraph write-out of a five-minute portion of a record contaminated with 60 Hz noise from an electric blanket. The ten horizontal traces on the plot represent the ten digital transformations of the analog activity displayed on the polygraph. The vertical lines on the plot separate minutes, which are also marked and labelled with a binary code on the polygraph paper. Of particular interest in this figure is the contrast between traces 1, 3, 5, and 7 and traces 2, 4, 6, and 8 during periods of electric blanket noise. Even-numbered transformations squared conversions prior to summation of each 4 measurements, so all sums were positive and cancellation of 60 Hz noise did not occur. Transformations 1, 3, 5, and 7 summed conversions prior to squaring so cancellation of noise can and did occur. The absence of noise in these latter traces indicates the effectiveness of the simple digital filtering technique.

The potential of each of the ten methods of digital preprocessing was evaluated by calculating the maximum agreement between sleep/wake status computed automatically from each digital file and scored from the polygraph activity record. Table 1 presents the rank order of maximum agreement for each record. Despite some variability, the indication from these data is that transformation 5 was superior to the others. (Transformations 1, 2, and 10 were not tested completely since they were judged inadequate after preliminary evaluations). Transformation 5 summed the absolute difference between the activity score for each 1/60th second and the mean of the five preceding and five subsequent scores.

To summarize the preprocessing algorithm found optimal in this experiment, the analog output of the activity transducer was digitized at 240 Hz, and every four digital activity values was summed to produce a value free of any 60 Hz component. Each of the resulting 120 scores (y) in every two-second epoch were then converted to 120 difference scores, $y(\text{diff}) = 10 * y(i) - [y(i-5) + y(i-4) + y(i-3) + y(i-2) + y(i-1) + y(i+1) + y(i+2) + y(i+3) + y(i+4) + y(i+5)]$, where $y(i)$ is the current 60 Hz sum, $y(i-1)$ the preceding sum, $y(i+1)$ the subsequent sum, etc. The sum of absolute values of these 120 difference scores was the final quantitative expression of activity over a two-second data epoch. Although these algorithms were tested by a retrospective procedure not strictly comparable to prospective scoring, it was encouraging that the median percent agreement obtained for the best algorithm was 91%.

EXPERIMENT 6: SLEEP RECOGNITION

The sleep recognition procedure used in Experiment 5 was an extremely

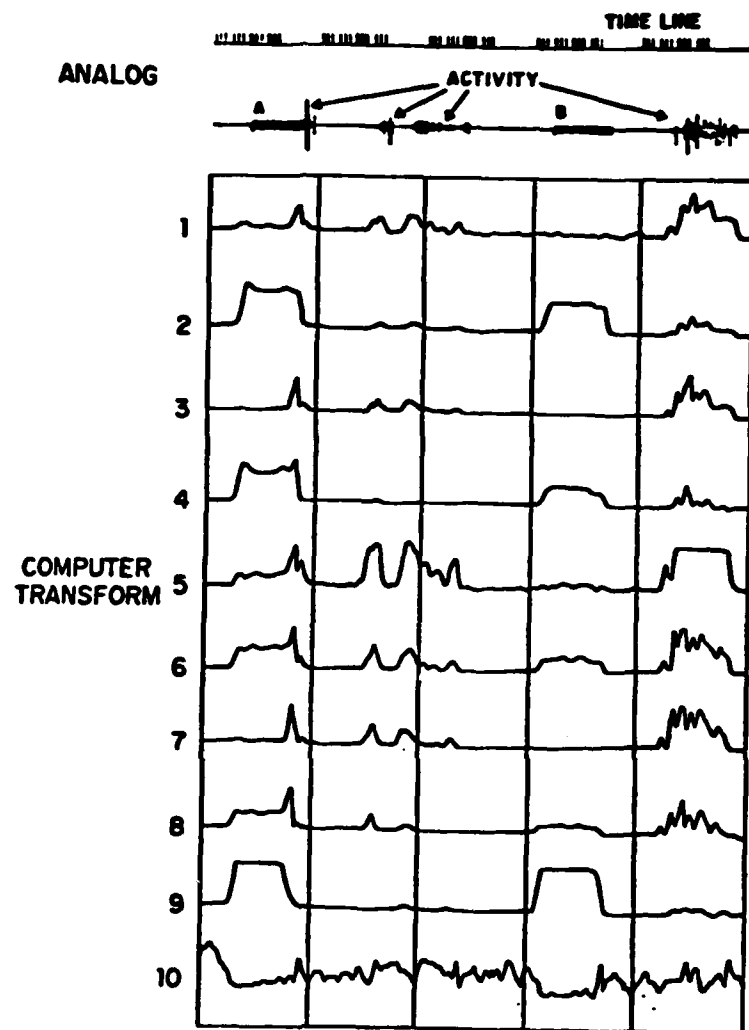


Figure 7. Five-minute portion of analog-polygraph record (top) showing time code and activity mixed with 60 Hz interference from an electric blanket, and plotter display (bottom) showing the ten digital transformations of the same 5-minute segment of activity data. Transformations 1, 3, 5 and 7 effectively filter the 60 Hz noise. A and B are 60 Hz interference.

Table 1.

Rank ordering of agreement scores for 7 of the 10 digital transformations of activity data for each of the 7 records analyzed in Experiment 5.

		<u>Transform Number</u>						
		<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
<u>Record</u> <u>Number</u>	1	5	2	6	3	7	1	4
	2	7	2	1	2	2	2	2
	3	6	5	1	3	2	4	7
	4	7	4	1	5	5	3	1
	5	2	2	6	5	6	2	1
	6	2	2	1	2	6	2	7
	7	3	4	1	4	1	4	7
Mean	4.6	2.9	2.4	3.4	6.6	2.6	4.1	
Median	5	2	1	3	5	2	4	

simple procedure designed to compare preprocessing strategies. Having established an effective preprocessing approach, the next priority was to refine the sleep recognition algorithm for more reliable scoring of sleep.

Method

EEG, EOG, and EMG were recorded from subjects during both wake and sleep, and written onto polygraph paper with a time code. These polygraphic records were then scored for sleep and wake. A wrist activity transducer signal was sampled by the ADC at a conversion rate of 240 Hz. The analog data were preprocessed and stored as described in Experiment 5, but only the optimal transformation (number 5) was used for data analyses. A total of 20 records (13,488 minutes) was analyzed.

Development of the sleep recognition algorithm began with expressions incorporating a weighted sum of combinations of the digital data with potential for discriminating sleep from wake. A minute was scored 'wake' if the weighted sum exceeded a threshold value. For each combination of weights, the agreement between the automatic scoring and EEG scoring was computed, and used as a retrospective measure of the effectiveness of the weighting. The computer varied the weighting of one term at a time iteratively, searching for the combination of weights which produced the highest agreement. Many hundreds of hours of minicomputer time were used to locate the optimal weighting functions.

Seventeen of the 20 records were used in this algorithm development phase. The remaining three records were scored prospectively, ie, each of the three records was scored individually with the single weighting and scale factor found optimal in the development phase. In this prospective test, the laboratory computer simulated the actual deployment of a miniaturized automatic sleep scoring system.

Results and Discussion

One result of the analysis of potential discriminators of sleep and wake was that the most discriminating measure of activity in a minute proved to be the value of the greatest two-second epoch activity amplitude in that minute. For sleep/wake scoring, once the amplitude of the maximal two-second epoch had been entered into the algorithm, no data representing other 2-second epochs from the minute contributed to the discrimination. This unexpected result is extremely fortunate since it allows an entire minute of activity to be summarized by a single value, saving memory space and analysis time.

The optimal sleep recognition algorithm reached after analysis of the 17 records was:

$$D = 0.025 * [.15y(i-4) + .15y(i-3) + .15y(i-2) + .08y(i-1) + .12y(i) + .12y(i+1) + .13y(i+2)]$$

where y represented the value of the maximal two-second epoch score in the current minute, y(i-1) that maximal value for the previous minute, y(i+1) for the subsequent minute, etc. If $D > 1.0$, the minute was scored 'wake', otherwise 'sleep'. The agreement between sleep/wake scored automatically with this algorithm and scored from EEG records was 95.56%. Agreement scores and the

proportion of the record scored as sleep by EEG and by the automatic algorithm for each individual record are shown in Table 2.

The ability of this algorithm to score sleep/wake prospectively was tested with the remaining three records. For these records, only the single expression found optimal in the algorithm development phase was chosen prospectively to automatically score sleep/wake. Agreement with EEG scoring and the proportion of the record scored as sleep by EEG and activity are also shown in Table 2. Overall agreement of these three records with EEG scoring was 96.02%.

Since the records analyzed in this experiment varied greatly in length, and included daytime naps as well as overnight sleep, sleep duration was expressed as the proportion of the record scored as sleep (% Sleep). Table 2 includes % Sleep for each record as scored by EEG and as scored automatically from activity data. The automatic scoring method overestimated % Sleep by an average of 1.89% and 2.33% for the retrospective and prospective sets of records. This corresponds to an overestimation of 12.17 and 19.33 minutes per record, or 27.09 and 33.60 minutes per 24-hour day. Correlation coefficients between % Sleep as scored by activity and EEG were $r=0.9889$ retrospectively and $r=0.9982$ prospectively. Automatic activity estimates of sleep percentage thus conformed closely with EEG estimates.

The primary automatic scoring algorithm developed here as well as the visual scoring of analog activity records in Experiment 1 tended to overestimate sleep duration as scored by EEG. This was due in part to the fact that sleep onset is delayed somewhat after all activity ceases. Other phenomena causing overestimation of sleep time from activity were recognized from inspection of error listings. For example, a few minutes of inactivity surrounded by many minutes of activity usually did not indicate sleep, although it was sometimes scored as sleep by the primary scoring algorithm. These considerations led to the development of a final stage of the sleep recognition algorithm in which corrections of this nature were made.

In this final stage, the sleep/wake score for each minute as determined by the automatic scoring algorithm was subjected to additional corrections. These corrections took the form "after at least x minutes scored wake, the first y minutes scored sleep are rescored wake" and " y or less minutes scored sleep surrounded by at least x minutes scored wake (before and after) are rescored wake." Substituting a range of x and y values into these expressions and rescoring the records scored retrospectively in Experiment 6, a combination of rules emerged which increased still further the similarity between EEG and activity scoring. These rules were: 1) after at least 4 minutes scored wake, the first minute scored sleep by the primary algorithm is rescored wake; 2) after at least 10 minutes scored wake, the first 3 minutes scored sleep by the primary algorithm are re-scored wake; 3) after at least 15 minutes scored wake by the primary algorithm, the first 4 minutes scored sleep are rescored wake; 4) 6 minutes or less scored sleep by the primary algorithm, surrounded by at least 10 minutes before and after scored wake are rescored wake; and 5) 10 minutes or less scored sleep by the primary algorithm, surrounded by at least 20 minutes before and after scored wake, are rescored wake.

This rescoring procedure increased the agreement of the 17 records scored

Table 2.

Record duration, proportion of the record for which EEG and automatically scored activity scores agree, proportion of the record scored as sleep by each technique, and the correlation coefficient (r) between the proportion scored sleep by the two methods. Activity data was digitized by the laboratory computer. Retrospective records (1-17) were those used to derive the scoring parameters, prospective records (18-20) used the parameters derived for the previous records.

<u>Record</u>	<u>Recording Duration (mins)</u>	<u>% Agreement</u>	<u>% Sleep (EEG)</u>	<u>% Sleep (Act.)</u>
1	353	97.17	0.00	2.83
2	574	96.17	45.47	46.86
3	632	95.89	56.80	59.65
4	903	88.82	29.57	34.33
5	660	97.42	54.55	56.21
6	798	95.36	41.73	44.11
7	845	96.80	37.99	40.95
8	1129	96.19	30.65	31.62
9	644	96.89	50.47	51.40
10	553	88.79	56.06	48.10
11	371	96.77	92.72	95.96
12	527	96.96	14.99	16.13
13	226	89.82	93.81	93.36
14	673	91.98	50.67	45.62
15	593	95.78	56.49	59.36
16	829	91.19	40.17	47.77
17	<u>692</u>	<u>94.08</u>	<u>15.17</u>	<u>20.18</u>
Total Retro- spec- tive	11002	94.46	42.09	43.98
r=0.9889				
18	369	93.50	70.19	76.69
19	846	93.62	28.84	31.68
20	<u>1271</u>	<u>98.35</u>	<u>36.82</u>	<u>37.69</u>
Total Pros- pective	2486	96.02	39.06	41.39
r=0.9982				

retrospectively from 94.46 to 94.74. The difference in % Sleep was reduced from 1.89 to 0.81, corresponding to 5.24 minutes per record, or 11.65 minutes per 24-hour day. The correlation coefficient decreased negligibly from .9889 to .9868.

A further test conducted with these data sought to determine the resolution in the stored data necessary to achieve these levels of accuracy. The digital activity value was originally stored on disc as a 16-bit value, ie, a number in the range of 0 to 32767. To investigate the bit resolution requirement, the sleep recognition program was repeated with the same data, but the bit resolution was reduced by dividing the data by powers of 2. There was no decrease in agreement with 4-bit data (0-15), and a decrease on only 0.1% was found with 3-bit data (0-7). This surprising result is important, since it means that data for more minutes can be stored in a given memory capacity. With proper optimization of scaling, 4-bits per minute may be sufficient for reliable sleep/wake scoring. Unfortunately, we have not achieved sufficient experience with the appropriate scale factors to specify which four bits per minute would be most suitable in practice. Certainly 8 bits per minute would be sufficient.

A WEARABLE SLEEP MONITOR SYSTEM

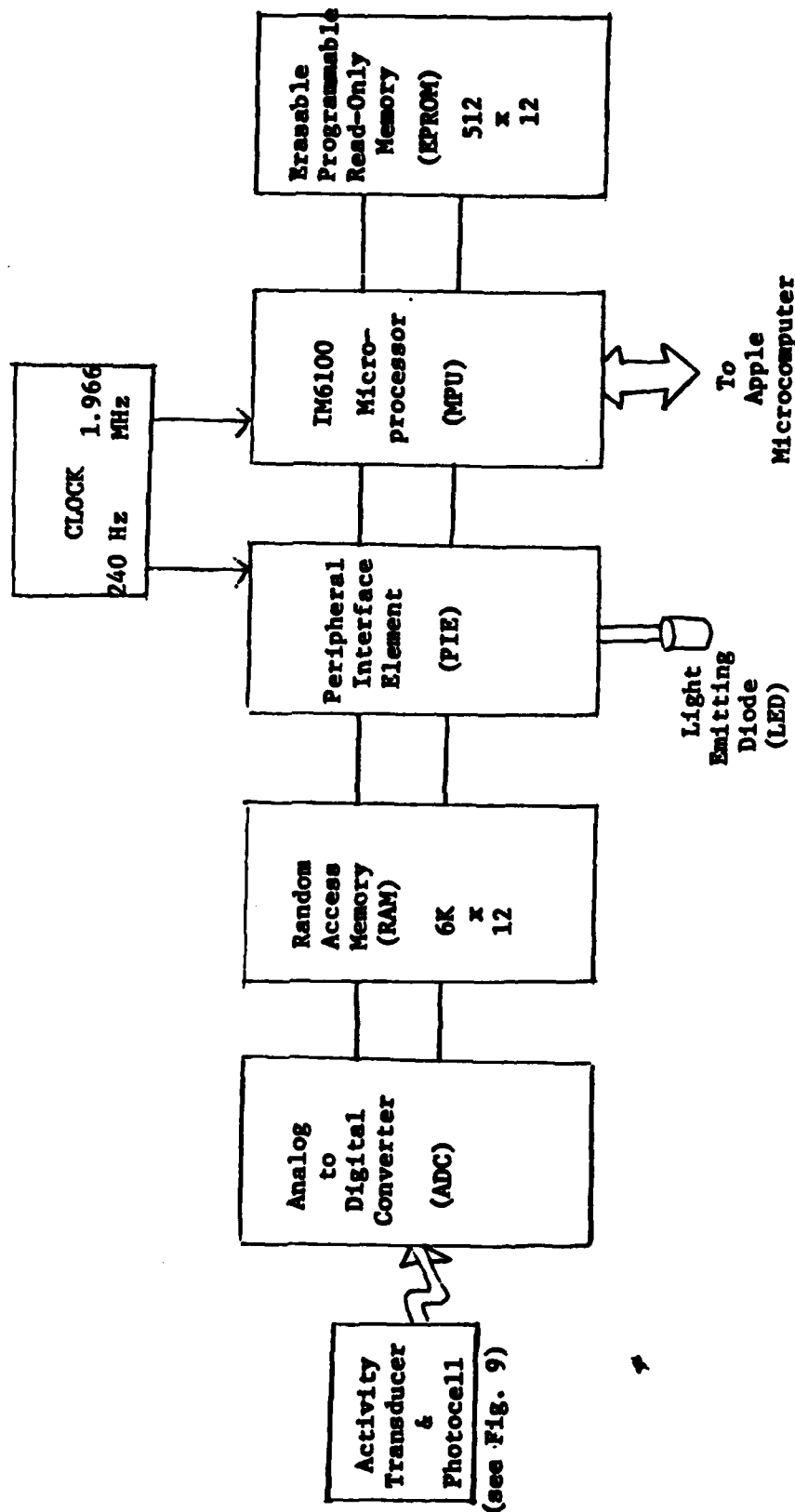
The results summarized to this point were detailed in our previous Annual Reports and have established the feasibility of a sleep monitor system incorporating an activity transducer, digital preprocessor and recorder, and sleep-recognition software. Such a system is capable of quantifying sleep with reasonable accuracy while avoiding the impracticality and expense of polygraphic recording and scoring. Here we describe the implementation of this sleep monitor system in a wearable form.

Digital preprocessing converts the continuous analog signal from the activity transducer to a single digital value for each minute and stores the value in digital memory. To achieve a wearable system, these steps must be accomplished by a digital recorder with the capabilities of a computer, small enough and light enough to be worn comfortably. The monitor must function for days on a battery pack which must also be small and light. To validate these concepts, a wearable monitor was built and tested. Although the prototype was not sufficiently miniaturized for field deployment, it was indeed worn by our test subjects.

To allow validation testing, the Vitalog Corporation* built a package to our specifications incorporating an IM6100 microprocessor, IM6101 programmable interface element (PIE), NSC 809 8-channel analog-to-digital converter (ADC), 6K x 12 random access memory (RAM), crystal clock and a LED indicator light. The entire prototype package, including batteries, is enclosed in a plastic case 15 x 9 x 5-1/2 cm and weighs 480 g. It is about the size of a 35 mm camera and was worn by subjects on a belt around the waist. We built an external activity transducer and connected it to the ADC through a cable. A plug was also provided through which the memory could be accessed by an external Apple II computer. All electronic components were CMOS for minimal power consumption. A block diagram is included (Fig 8).

*Vitalog Corporation, 1058 California Avenue, Palo Alto, CA 94306.

Figure 8. Block diagram of wearable components of sleep monitor system. Activity (and illumination) is detected by the external transducer and transmitted to the ADC. 240 Hz clock pulses generate interrupts which cause the program to activate the ADC, process the digital conversion, and store the results in RAM each minute. An external Apple microcomputer can be connected to the microprocessor to read the data from RAM for permanent storage and sleep scoring. Time information is transmitted through a LED. Communication between the MPU, the ADC and RAM is via data bus and control lines organized by the PIE, which also handles interrupt signals, the wait state, and LED output. Communication with the Apple is handled by an EPROM monitor.



In the following sections, the major components of our prototype and their functions are described in more detail. The actual integrated circuit types and manufacturers are listed only for illustration, as similar systems could be designed with CMOS microprocessors of other manufacture.

IM6100 Microprocessor

Overall control of data collection, processing, and storage was accomplished by the IM6100 microprocessor. The IM6100 is a fully programmable 12-bit microprocessor which is functionally equivalent to a PDP-8/e minicomputer, and it recognizes the PDP-8e instruction set. Internal state timing is generated by a crystal which also produces a 240 Hz interrupt signal. A simple accumulator oriented instruction set proved adequate. An 8-bit microprocessor would have been adequate.

An extremely useful feature of the IM6100 is a wait state, in which program execution is suspended but not halted while power consumption is greatly reduced. Battery drain for the entire package (exclusive of the external transducer which contains its own battery) was measured at 8.5 mA (6V) with the processor running continuously, compared with 3.4 mA when halted. By entering the wait state after processing each ADC conversion, battery drain could be reduced to 5.2 mA. At a drain of 5.2 mA, the battery charge was sufficient to operate the monitor program continuously for 180 hours. By entering the halt mode after shorter recording session, the data could be preserved in the digital memory for even longer periods.

IM6101 Programmable Interface Element

The IM6101 PIE handles all communication between the IM6100, the ADC, and LED indicator light, and an external computer, and controls the wait state. Designed for interfacing peripheral devices to the IM6100, the IM6101 allows efficient interaction with these different classes of I/O without the need for additional external logic, and greatly facilitates interrupt processing. In our realization, the LED indicator was used to signal time codes by which segments of EEG records could be synchronized with the digital scoring results.

Analog to Digital Converter (ADC)

The ADC converts a voltage in the range of 0 to +5V to an 8-bit digital value (0-255). Up to eight channels of analog data could be sampled by the ADC multiplexer under program control.

External Activity Transducer and Amplifier

As noted above, the ADC converts voltage in the range¹ of 0 to +5V with a resolution of 8 bits. Thus, ground level is converted to '0', and +5V to '255'. Maximum resolution is obtained when input voltage covers as much of this range as possible. Since the piezo-ceramic transducer generates only a few millivolts, and alternately produces positive and negative voltage, amplification and level-shifting circuitry powered by a small 5.6V battery was necessary to match the requirements of the ADC. The circuit shown in Figure 9 amplifies the signal from the piezo-ceramic element and shifts it positively so that it alternates

about the level of a center tap in the battery (nominally 2.8V). The signal is amplified so that it covers the full range of 0 to +5V when the transducer is shaken vigorously. This amplified signal is led to the ADC along with the center tap voltage, which serves as a reference. The difference between the signal and reference voltage represents the signed amplitude of the transducer output. A photocell is also mounted in the external transducer package and connected through a resistive bridge to a third channel of the ADC. The voltage level of this photocell circuit serves as a measure of illumination. This can be used as an objective measure of bedtime (defined by "lights out") and can provide some information on the subject's environment.

The Monitor Program

The monitor program (Appendix 1) is loaded from an Apple II microcomputer. After clearing the data memory, the program causes the processor to enter the power-down wait state. On each 240 Hz clock interrupt request, the program determines whether the transducer reference voltage is at ground level, meaning that the switch in the external transducer is off. When the switch is first turned on, increasing the reference level to about 2.8V, the monitor program enters the main data collection, preprocessing and recording routines. In this state, each 240 Hz interrupt request causes the program to read the signal and reference value of the transducer from the ADC, compute the difference (ie, the signed amplitude of the signal relative to its resting level), and sum this value. After each four interrupts, the sum of the preceding four conversions is entered into a differencing function. The sum of every four conversions at 240 Hz represents the 60 Hz digital filter developed in Experiment 5. The differencing function is equivalent to algorithm 5 described in Experiment 5. Specifically, the input to the differencing function is multiplied by 10, and the sum of the preceding and following 5 inputs are subtracted from this product. Then the absolute values of 120 such transformations are summed to form a 2-second epoch score. The largest epoch score for each minute is stored sequentially in memory.

Also, each minute, a voltage indicating the illumination level from the photocell is digitized and stored, and a time code is signaled through the LED. The time code permits external monitoring of the system operation and coordination with polygraphic recording. The monitor program fills 448 12-bit memory locations, leaving 5696 locations available for data storage. This allows us to store two 12-bit data values (activity and illumination) each minute for 47 hours and 28 minutes. Since 4-bit resolution might be adequate, up to 6 times this duration or about 12 days data might theoretically be stored, were the illumination data sacrificed and were battery changes feasible.

SLEEP RECOGNITION SOFTWARE

Having measured, processed, and recorded activity data, the remaining task for a sleep monitor system is to interpret the activity information as sleep or wake. In our prototype system, the contents of the recorder memory were sent to an Apple II microcomputer, which stored the data on discs. The data were then transferred to a more powerful Hewlett-Packard 1000 system for automatic sleep scoring. Automatic scoring used the sleep recognition algorithm which was

developed in Experiment 6.

Fourteen digital activity records totalling 12,739 minutes were collected from healthy male college students participating in experiments in which EEG, EOG, and EMG were being recorded. Time codes from the monitor via the LED were written on the polygraph record each minute. Since the physical parameters of the transducer-amplifier-ADC differed somewhat from those used previously, the parameters of the sleep recognition algorithm were recalibrated using the method described in Experiment 6, the computer deriving the optimal sleep recognition algorithm. For these recordings, the parameters producing the best agreement with EEG scoring were:

$$D = .036 \times [.07y((i-5) + .08y(i-4) + .10y(i-3) + .11y(i-2) + .12y(i-1) + .14y(i) + .09y(i+1) + .09y(i+2) + .09y(i+3) + .10y(i+4)]$$

where $y(i)$ represents the greatest 2-second epoch score in minute i , etc, and $D > 1.0$ is scored wake. The results of this primary scoring algorithm were then subjected to the rescoring algorithm described in Experiment 6, in which corrections for sleep onset latency and brief periods of inactivity were made. Results are summarized in Table 3. Overall minute-by-minute agreement was 93.88%. The activity estimate of % Sleep exceeded the EEG estimate by an average of 1.03%, corresponding to 9.35 minutes per record, or 14.81 minutes per 24-hour day. The correlation coefficient between the two estimates of % Sleep was $r=0.9724$.

An additional 14 records totalling 22,514 minutes were scored prospectively using the parameters found optimal in the calibration phase. Twelve subjects were healthy male college students, while two (subjects 12 and 13) were patients with sleep complaints undergoing clinical sleep evaluations. The patient records were included to test the system on highly disturbed sleep records. As seen in Table 4, overall agreement with EEG scoring was 93.04%. The activity estimate of % Sleep exceeded the EEG estimate by an average of 1.20%, corresponding to 19.29 minutes per record or 17.27 minutes per 24-hour day. The correlation coefficient was $r=0.9692$.

Figure 10 illustrates the scoring of one of the activity records in the prospective series (record 6). The 48-hour record is divided into four 12-hour segments in this figure, and hours are marked along the bottom of each segment. The top trace in each segment plots the maximal activity value for each minute. Below this is the result of EEG scoring of the record (solid indicates wake, light indicates sleep), and below this is the result of automatic scoring of the activity data. The lowest trace in each segment illustrates the agreement between EEG and activity scoring (solid indicates agreement).

ASSESSMENT OF VALIDATION

The results of our prospective validation of the automatic scoring system are comparable to those obtained when the parameters were optimized retrospectively. These results indicate the performance we would expect in an operational application. The wearable sleep monitor system measures sleep with approximately the same precision as the experimental laboratory system developed in Experiments 5 and 6, and visual scoring of analog activity records in

Table 3.

Record durations, proportion of the record for which EEG and automatically scored activity scores agree, proportion of the record scored as sleep by each technique, and correlation coefficient between the proportion scored sleep by the two methods. Activity data was collected with the wearable monitor. Scoring parameters were derived retrospectively by analysis of these data.

<u>Record</u>	<u>Recording Duration (minutes)</u>	<u>% Agreement</u>	<u>% Sleep (EEG)</u>	<u>% Sleep (Activity)</u>
1	357	91.04	85.71	99.68
2	2838	95.81	18.68	19.84
3	1463	98.63	24.27	24.13
4	2839	98.20	20.61	21.91
5	452	90.27	97.35	92.04
6	335	95.22	97.61	97.01
7	456	80.70	88.16	75.88
8	491	90.63	91.85	87.37
9	493	90.06	90.06	82.56
10	478	91.84	96.03	95.82
11	474	85.02	82.70	96.41
12	494	83.40	81.58	92.51
13	1091	93.13	55.47	36.66
14	478	89.96	89.33	98.12
Total	12739	93.88	46.38	47.41

$r=0.9724$

Figure 10. A 48-hour activity record collected with the wearable monitor (divided into four 12-hour segments). Hours are marked along the bottom of each segment. The top trace in each segment plots the digital activity value for each minute. Below this is the EEG score (wake is solid, sleep is light) and below this the automatic activity score. The lower trace illustrates agreement between EEG and activity scoring (solid is agreement).

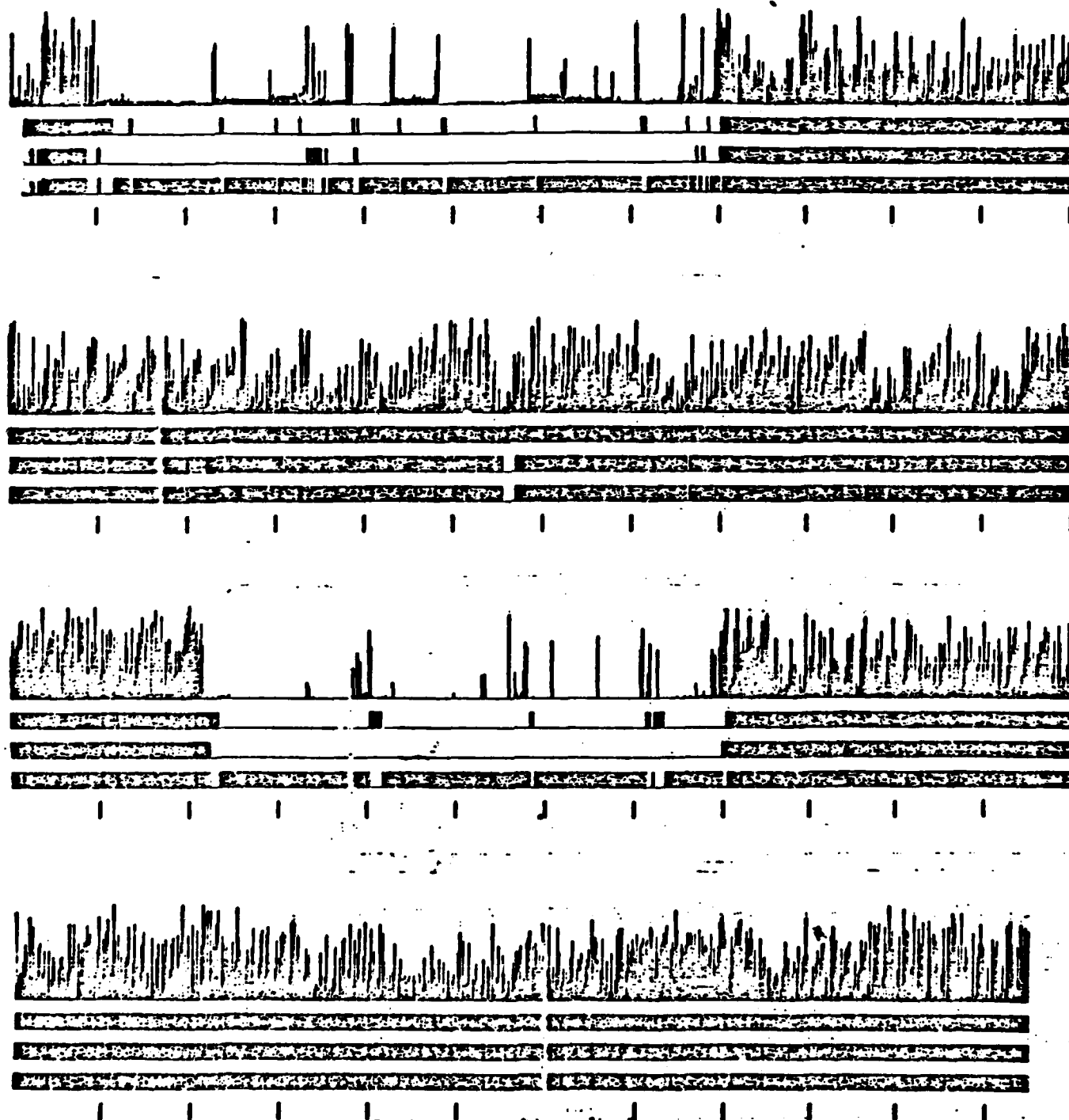


Table 4.

Record durations, proportion of the record for which EEG and automatically scored activity scores agree, proportion of the record scored as sleep by each technique, and correlation coefficient between the proportion scored sleep by the two methods. Activity data was collected with the wearable monitor. Scoring was prospective, using parameters derived from previous data.

<u>Record</u>	<u>Recording Duration (minutes)</u>	<u>% Agreement</u>	<u>% Sleep (EEG)</u>	<u>% Sleep (Activity)</u>
1	469	95.31	94.46	93.60
2	459	76.25	92.37	71.68
3	495	93.74	93.33	93.94
4	1302	97.00	26.57	26.80
5	2838	96.16	24.07	24.95
6	2838	97.08	25.19	26.71
7	2838	87.14	10.47	23.33
8	2593	93.21	25.92	25.38
9	2675	93.61	36.11	35.33
10	1335	93.41	34.23	29.21
11	2261	95.98	40.82	41.84
12	625	80.96	66.88	74.40
13	484	85.12	84.50	89.05
14	1302	92.93	38.56	33.95
Total	22514	93.04	34.28	35.48

$r=0.9692$

Experiment 1. The overall accuracy is more than adequate for practical utilization.

Throughout the research and development phase of this project, our goal has been to maximize the minute-by-minute agreement between EEG and activity scoring of sleep. We feel that the 90%+ agreement we have obtained in every phase of our research is very good, and it is unlikely that any alternative activity-based scoring system could reach substantially higher agreement. One reason for this is that EEG scoring is itself an estimate. Although rules have been formulated to assist in the standardization of EEG sleep scoring, scoring is nevertheless a matter of interpretation. Two raters scoring the same EEG record seldom agree 100% of the time (Mullaney et al, 1980). Some of the activity system's discrepancies with EEG estimates are certainly due to unreliability in the standard EEG scoring methods.

A second factor reducing the agreement of EEG and activity scoring in the present studies involves errors of resolution which occur in reducing the continuous processes of sleep and wake to discrete epochs. EEG recordings are usually scored in 20-30 second epochs. In our activity scoring system, the epoch was one minute. Our criterion for assigning a score of wake or sleep to a minute required that at least 50% (30 sec) be in that state. The EEG and activity methods had somewhat different responses to minutes containing brief awakenings. A final problem involved the inescapable fact that people sometimes do not move at all during times when they are awake.

Most investigators would probably assume that EEG scoring corresponds more accurately to behavioral and functional sleep than does activity scoring. While we have no objective comparisons of EEG and activity scoring as indicators of behavioral sleep, we suspect that where the EEG and activity scores were discrepant, on some occasions, behavioral criteria would favor the activity scoring. Nevertheless, reliability data indicates that the agreement between EEG and activity estimates of TST are only slightly less than agreement of two scorers rating the same EEG record. A more important issue is the well-known subject-to-subject and night-to-night variability which is observed in sleep recordings. In general, the increased quantity of data which could be gained for a given expense by automated wrist activity scoring would more than compensate in increased precision for any loss of accuracy as compared to EEG scoring.

Even if the EEG method is slightly more accurate in estimating sleep time, other factors such as simplicity and practicality make activity scoring more desirable for many purposes. The activity transducer is more comfortable and convenient for the subject, who can sleep outside the laboratory if desired, free from electrodes. The adaptability of the activity scoring method to naturalistic settings also increases its value as a measurement approach.

Although our current prototype activity scoring device is rather large and fragile for field conditions, we are certain that a device of equivalent capability could be miniaturized so that it could be worn entirely on the wrist. A wrist-mounted device could be built for military specifications of durability.

HARDWARE SPECIFICATIONS OF A WRIST-WEARABLE SLEEP MONITOR

Essentially all of the design, software, and procedural requirements have now been developed so that a miniaturized wrist-wearable sleep monitor can be built suitable for military settings. Although the actual construction, testing, and deployment of such a device is beyond the scope of this contract, we present below technical requirements for such a device. We believe a fully wrist-wearable device can be built with sufficient durability and reliability for military settings, and an appropriate read-out device can be constructed. Either current flat-pack or chip carrier technology would be adequate for miniaturization, the major problem being conservation of power and battery life.

The miniaturized sleep monitor should contain the following components or their equivalent:

1. Low-power microprocessor, processing at least 100,000 instructions per second, 8 bit word width or more.
2. Crystal-controlled hardware interrupts at 240 Hz or some multiple (1200 Hz recommended).
3. 8-K bytes of RAM memory or more.
4. A piezo-ceramic activity transducer as described in Figure 9, with appropriate buffer amplifier circuit and level shifter.
5. A single-channel A/D converter sensitive to positive and negative voltages or 2-channel positive-only A/D converter, 8-bit resolution or better and conversion rate faster than 240 Hz.
6. A facility for loading programs down into the microprocessor and restarting the microprocessor, either using a ROM controlled peripheral interface element or using direct control of the memory bus to load memory, eg, communication through DMA.
7. A facility for halting processor operations and unloading memory to an external controller, either through a peripheral interface element controlled by ROM or through DMA.
8. Total system power consumption and battery supply must allow operation for at least 48 hours with facility for rapid battery change. Power consumption of less than 3 millamps is recommended. Longer battery life is highly desirable.

The following design features are recommended but not required:

1. Program down-loading and data dump could be accomplished through optical coupling, using a self-clocking system. Two LEDs and two photocells (LED receivers) should be sufficient to implement 2-way communication. The LEDs could be controlled by I/O lines, for example, controlled through a peripheral interface element, and the software implementing this control could be housed in ROM. The photocells should have an opaque cover when not in use.
2. The unit should have a waterproof seal for all elements except the battery element should. The battery compartment should also have a waterproof gasket.
3. Parallel battery leads should be provided so that a fresh or recharged battery can be connected before a partially discharged battery is disconnected, to implement continuous operation.

4. Design of the circuit with an 8-channel multiplex analog digital converter would be useful to allow for future design expansions and implementations.
5. Inclusion of an ambient-light photocell with a window through the case, amplifier circuit, and ADC channel would be useful for sensing subject light exposure, eg, when the subject goes to bed. A sensitivity range of 1-5,000 lux or up to 50,000 lux if possible is desired.
6. If an 8-channel ADC is implemented, 3 thermistor bridges with amplifiers could be included. An external plug could allow one external thermistor to be connected. Thermistors on the top and bottom of the case could be used to detect when the instrument is taken off the wearer.
7. If the microprocessor had a low-power halt mode and could be restarted by interrupts, this capability could be used to reduce power consumption.
8. Ideally, the case should be cigarette-pack size or smaller, eg, 2x5x8 cm maximum. In our experience, a very broad leather or plastic wrist band as wide as the case is most comfortable.
9. A 4-digit LCD display controlled by the microprocessor would be extremely useful for clock and warning functions.
10. If the monitor will communicate with its external controller through DMA, the external interface must be designed. We would favor building an interface to a field-portable microprocessor such as an Apple II computer. The complete sleep scoring, readout, and display functions could be performed by a microprocessor comparable to an Apple II (16K byte 6502 processor with keyboard and display).

SOFTWARE SPECIFICATION

The logical steps necessary for sleep scoring are outlined in the preceding text and are specified exactly in the accompanying program (Appendix 1).

The software will need to be adapted for the exact configuration of wrist-wearable sleep monitor which is built, and a scaling parameter will need to be determined empirically. Operational requirements for data reporting and display will also require certain modifications of our current programs.

Now that the basic principles have been established, the hardware/software requirements for a readout device are not great. A portable microprocessor comparable to a 16K Apple II with one 5-1/4 inch disc would be sufficient for field requirements, and could easily be programmed once the report configuration desired is specified.

SUMMARY

Experiment 1 tested the idea that sleep/wake can be recognized from activity data. One hundred and two analog recordings of EEG-EOG-EMG and wrist activity were collected on cassette tape. Polygraph write-outs of the EEG-EOG-EMG channels and the activity channel were scored for sleep by

independent raters. The raters agreed 94.5% of the time, indicating that wrist activity data provides nearly the same information as electrophysiological measures for recognizing sleep.

The adequacy of the piezo-ceramic activity transducer used in Experiment 1, and its orientation and placement were investigated in Experiments 2 through 4. In Experiment 2, the transducer was compared with a tilt-switch transducer and a sensitive accelerometer and was found to be superior. Experiment 3 found the transducer to be essentially omni-directional, thus making its orientation unimportant. The suitability of the wrists for placement of the transducer was confirmed in Experiment 4.

While more efficient than EEG scoring, the analog activity recordings collected in the preceding experiments required much time for playback and interpretation by a trained scorer. A practical sleep monitor system would quantify the activity data and make it available to a computer for automatic scoring. Experiment 5 derived an algorithm for reducing two seconds of activity to a single value. The optimal algorithm also effectively eliminated any 60 Hz interference.

Experiment 6 investigated methods of interpreting the digital activity value for each two-second data epoch as sleep or wake. It was found that the largest two-second epoch score in each minute best represented activity in that minute. A given minute was scored wake if a weighted sum of this score for the given minute and for the immediately preceding and following minutes exceeded a threshold. For the 17 activity records with which these rules were derived, automatic scoring agreed with hand EEG scoring 94.46% of the 11,002 minutes. A further three records scored prospectively with the same parameters agreed 96.02% of the time with EEG scoring.

A prototype sleep monitor system was developed. The system consists of a wrist-mounted piezo-ceramic transducer, microprocessor-controlled data compression and storage device worn on the belt, and sleep recognition software in an external computer. The unit is capable of recording wrist activity digitally for several days on a single battery charge while subjects go about their normal routine. Fourteen subjects' records were used to retrospectively derive the optimal sleep recognition algorithm for this system. Of the 12,739 minutes recorded, 93.88% were scored the same by automatic scoring and by hand EEG scoring. An additional group of 14 records were scored prospectively using the same parameters, and 93.04% of the minutes were scored the same by automatic and by hand EEG techniques. The proportion of the record scored as sleep automatically from activity and from EEG differed by 1.03% and 1.20% in the two groups, and the correlation coefficients between the two estimates of sleep across subjects were .9724 and .9692.

The electronic components of this sleep monitor system could be miniaturized with current technology into a package worn entirely on the wrist. A miniature wrist-mounted sleep monitor system would make large-scale sleep measurement feasible under field conditions.

We are extremely pleased with the success of this technical development and hope our designs can be operationally applied.

ACKNOWLEDGMENT

This research was supported in part by the Veterans Administration, by ONR N00014-79-C-0317, and by Research Scientist Development Award 1 K01 MH00117 (to DFK) from the National Institute of Mental Health. William Mason, M.A. and Nobuyuki Okudaira, M.D., Ph.D. assisted in the research.

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- Mullaney, D.J., Kripke, D.F., and Messin, S. Wrist-actigraphic estimation of sleep time. Sleep, 3(1): 83-92, 1980 (supported in part by the DAMD).

APPENDIX 1

Monitor program used to control data collection, processing, and storage for wearable sleep monitor.

```

0001 /ACTICORD
0002
0003
0004 /RECORDS OUTPUT OF ACTIGRAPH TRANSDUCER AND PHOTOCELL
0005 /RESOLUTION=1 MINUTE, DURATION=47HR,20MIN
0006 /TIME CODE EACH MINUTE THRU L.E.D.
0007
0008 /AUTHOR: JOHN WEBSTER
0009
0010
0011
0012
0013
0014 STORE = JMS I STORE
0015
0016 /PAGE #
0017
0018 *#
0019
0020 000 0000 RTNADR, # /INTRPT RETURN ADDR
0021 001 5026 INTRPT, JMP INTSRV /INTRPT PNTR
0022
0023
0024 /AUTOINDEX REGISTERS
0025 *13
0026 013 0000 A13, # /RESERVED FOR A/D. . .
0027 014 0000 A14, # /BUFFER POINTER
0028 015 0000 A15, # /RESERVED FOR DIFF. . .
0029 016 0000 A16, # /SCORE POINTERS
0030 017 0000 DATAP, # /DATA STORE POINTER
0031
0032
0033 /INTERRUPT SERVICE ROUTINE
0034 *26
0035 026 3106 INTSRV, DCA ACSAVE /SAVE REGISTERS
0036 027 7004 RAL
0037 030 3107 DCA LKSAVE
0038 031 6504 RCRA
0039 032 3110 DCA CRASAV
0040 033 4044 JMS GETACT /GET ACTIVITY SCORE
0041 034 1110 TAD CRASAV /RESTORE REGISTERS
0042 035 6505 WCRA
0043 036 6007 CAF
0044 037 1107 TAD LKSAVE
0045 040 7010 RAR
0046 041 1106 TAD ACSAVE
0047 042 6001 ION /ENABLE INTRPT
0048 043 5400 JMP I RTNADR
0049
0050
0051 /ACTIVITY SCORE SET-UP
0052 044 7402 GETACT, HLT
0053 045 1113 TAD AWORD /SET UP PIE FOR A /D
0054 046 6505 WCRA
0055 047 7201 CLA IAC /START WITH CH.1 (BIAS)
0056 050 4066 JMS A2D
0057 051 7041 CIA
0058 052 3121 DCA BIAS /NEGATE AND SAVE
0059 053 4066 JMS A2D /THEN CH.# (ACT)
0060 054 1121 TAD BIAS - /FIND DIFFERENCE
0061 055 3413 DCA I A13 /PACK INTO BUFFER
0062 056 1013 TAD A13 /RESET BUFFER PNTR. . .
0063 057 1114 TAD STKEND /IF AT END (EOB)
0064 060 7640 SZA CLA 36

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8865 861 5864
8866 862 1111
8867 863 3813
8868 864 5444
8869
8870
8871
8872
8873 866 7482
8874 867 6581
8875 878 7388
8876 871 1115
8877 872 3116
8878 873 6511
8879 874 6513
8880 875 7418
8881 876 5873
8882 877 2116
8883 183 5874
8884 181 6588
8885 182 8117
8886 183 5466
8887
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8889
8890 184 8888
8891 185 8888
8892 186 8888
8893 187 8888
8894 118 8888
8895 111 8547
8896 112 8888
8897 113 8281
8898 114 7221
8899 115 7766
8900 116 8888
8901 117 8377
8902 128 7772
8903 121 8388
8904 122 4228
8905 123 8677
8906 124 8888
8907 125 8888
8908 126 8888
8909 127 7775
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8911 131 8888
8912 132 7773
8913 133 8888
8914 134 8888
8915 135 8888
8916 136 7742
8917 137 8888
8918 148 8888
8919 141 8888
8920 142 7618
8921 143 8888
8922 144 8888
8923 145 7774
8924 146 8888
8925 147 8177
8926 158 7788
8927 181 8388
8928 182 8688

```

```

JMP .+3
TAD STKBEG
DCA A13
JMP I READAD

```

/ANALOG TO DIGITAL CONVERSION

*66

```

A2D, HLT
WRITE1 /CHAN. SELECT
CLA CLL
TAD MCNT /SET UP BACKUP CNTR
DCA MCNTR
WRITE2 /START CONVERSION
SKIP2 /DONE (EOC)?
SKP
JMP DONE
ISZ MCNTR /NO, INCR. BACKUP
JMP .-4
DONE, READ1 /YES
AND X377 /MASK GARBAGE &
JMP I A2D /EXIT

```

/CONSTANTS AND VARIABLES

```

MAXEP, 8 /ACCUMULATES MAXIMAL EPOCH SCORE
LITE, 8 /HOLDS LITE LEVEL VALUE
ACSAVE, 8 /SAVES AC DURING INTRPT
LKSAVE, 8 /SAVES LINK DURING INTRPT
CRASAV, 8 /SAVES CRA DURING INTRPT
STKBEG, 547 /POINTS TO ACT SCORE BUFFER
ERROR, 8
AVORD, 281 /INITIAL CRA VALUE
STKEND, 7221 /-END OF ACT SCORE BUFFER
MCNT, 7766 /TIME DELAY FOR A/D
MCNTR, 8 /COUNTER FOR TIME DELAY
X377, 377 /USED TO MASK A/D CONV
M6, -6
BIAS, 8 /HOLDS TRANS. BIAS VALUE
BWORD, 4228 /INITIAL CRB VALUE
CATBEG, 677 /POINTS TO START OF RECORDER MEM.
FLDFLG, 8 /INDICATES MEMORY FIELD (8 OR 1)
MINCNT, 8 /MINUTE COUNT
TCODE, 8 /TIME CODE
M3, -3
GRPS, 8 /COUNTER FOR TIME CODE
OCNTR, 8 /
M5, -5 /
TCNTR, 8 /
CODE1, 8 /TIME CODE '8' OR '1'
TFLAG, 8 /TIME CODE FLAG
M38, -38
MINDIV, 8 /MINUTE DIVIDER
EPSUM, 8 /ACCUMULATES EPOCH SUM
DFSUM, 8 /ACCUMULATES DIFSCR SUMS
M128, -128
EPDIV, 8 /EPOCH DIVIDER
SUM4, 8 /ACCUMULATES SUM TO 4
M4, -4
CNT4, 8 /COUNTS 4
X177, 177 /MASK FOR DIFSCR
X7788, 7788
DATWRD, 8 /HOLDS DATA PRIOR TO STORE
CODETS, CODET /POINTS TO TIME CODE RTN

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#129	153	8488	DFSC,	DIFSCR	/POINTS TO DIFSCR RTN
#130	154	8888	CRATMP,	S	/TEMP CRA STORE
#131	155	1888	FLD1,	1888	/WCRA TO GET FIELD 1
#132	156	2881	MEMLIN,	2881	/- END OF FIELD
#133	157	7776	M2,	-2	
#134	158	7766	M18,	-18	
#135	161	7688	T288,	7688	
#136	162	4888	O4888,	4888	/WCRA TO WAIT
#137	163	8888	LATEST,	S	/HOLDS MOST RECENT SUM4
#138	164	8557	BUFLOC,	557	/POINTS TO DIFSCR BUFFER
#139	165	8888	BUFN,	S	/BUFFER LOC
#140	166	8888	MINUS,	S	
#141	167	8888	OFLOW,	S	
#142	178	8888	PRDCT,	S	
#143	171	8648	STORE,	STORES	/POINTS TO STORE RTN
#144	172	8888	DIFOUT,	S	
#145	173	8888	BUMP,	S	
#146	174	7765	M11,	-11	
#147	175	7778	M8,	-8	
#148	176	7777	M1,	-1	
#149	177	8877	X77,	77	

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#191

#192

/PAGE 1

/START-UP

*288

START,

CAF

TAD

WCRA

CLA CLL

TAD

WCRB

CLA CLL

TAD

DCA

DCA

STORE

SKP

JMP

CLA IAC

JMS

TAD

SMA CLA

JMP

RCRA

TAD

WCRA

JMP

TAD

WCRA

NOP

CLA CLL

TAD

AWORD

BWORD

DATBEG

DATAP

DATWRD

.-2

A2D

M188

GO

O4888

WAIT

AWORD

DATBEG

/SET UP PIE

/ZERO MEMORY

/WAIT FOR 'ON'

/IS SWITCH ON?

/NO, WAIT

/YES, INIT & GO

WAIT,

GO,

0193	233	3017		DCA	DATAP	
0194	234	3124		DCA	FLDFLG	
0195	235	3125		DCA	MINCNT	
0196	236	1111		TAD	STKBEG	
0197	237	3013		DCA	A13	
0198	240	1111		TAD	STKBEG	
0199	241	3014		DCA	A14	
0200	242	1125	MINIT.	TAD	MINCNT	/ENTER EACH MINUTE
0201	243	3126		DCA	TCODE	/LOAD TIME CODE
0202	244	1145		TAD	M4	
0203	245	3130		DCA	GRPS	
0204	246	1145		TAD	M4	
0205	247	3131		DCA	OCNTR	
0206	250	1176		TAD	M1	
0207	251	3133		DCA	TCNTR	
0208	252	1176		TAD	M1	
0209	253	3134		DCA	CODE1	
0210	254	2135		ISZ	TFLAG	/SET TIME CODE FLAG
0211	255	2125		ISZ	MINCNT	
0212	256	1136		TAD	M30	
0213	257	3137		DCA	MINDIV	
0214	260	3104		DCA	MAXEP	
0215	261	3105		DCA	MINTOT	
0216	262	3140	EPOCH,	DCA	EPSUM	/ENTER EACH EPOCH
0217	263	3141		DCA	DFSUM	
0218	264	1142		TAD	M120	
0219	265	3143		DCA	EPDIV	
0220	266	3144	FOUR,	DCA	SUM4	/ENTER EACH FOUR A/D'S
0221	267	1145		TAD	M4	
0222	270	3146		DCA	CNT4	
0223	271	1135		TAD	TFLAG	
0224	272	7640		SZA CLA		
0225	273	4552		JMS 1	CODETS	
0226	274	6001		ION		
0227	275	7300	EACH,	CLA CLL		/ENTER EACH A/D
0228	276	1013		TAD	A13	
0229	277	7041		CIA		
0230	300	1014		TAD	A14	
0231	301	7440		SZA		/IS A/D BUFFER EMPTY?
0232	302	5315		JMP	NEW	
0233	303	6504		RCRA		/YES, ENTER WAIT STATE
0234	304	7421		MQL		
0235	305	7501		MOA		
0236	306	1162		TAD	04000	
0237	307	6505		WCRA		
0238	310	7701		ACL		
0239	311	6505		WCRA		
0240	312	7000		NOP		
0241	313	7000		NOP		
0242	314	5275		JMP	EACH	
0243	315	7300		CLA CLL		/NO, READ NEXT VALUE
0244	316	1414		TAD 1	A14	
0245	317	1144		TAD	SUM4	/AND SUM TO 4
0246	320	3144		DCA	SUM4	
0247	321	1014		TAD	A14	/RESET BUFFER IF AT END
0248	322	1114		TAD	STKEND	
0249	323	7640		SZA CLA		
0250	324	5327		JMP	.+3	
0251	325	1111		TAD	STKBEG	
0252	326	3014		DCA	A14	
0253	327	2146		ISZ	CNT4	/SUMMED 4 YET?
0254	330	5275		JMP	EACH	/NO
0255	331	1144		TAD	SUM4	/YES, FIND DIFF. SCR.
0256	332	4553		JMS 1	DFSCR	

#257 333 7188
 #258 334 1141
 #259 335 7438
 #260 336 7248
 #261 337 3141
 #262 348 2143
 #263 341 5266
 #264 342 1141
 #265 343 7118
 #266 344 7841
 #267 345 1184
 #268 346 7788
 #269 347 5353
 #270 350 1141
 #271 351 7118
 #272 352 3184
 #273 353 2137
 #274 354 5262
 #275 355 6882
 #276 356 1363
 #277 357 4866
 #278 368 3151
 #279 361 6881
 #280 362 5367
 #281 363 8882
 #282 364 7888
 #283 365 7888
 #284 366 7888
 #285 367 4571
 #286 378 7482
 #287 371 1184
 #288 372 3151
 #289 373 4571
 #290 374 7482
 #291 375 5242
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CLL
 TAD DFSUM /ADD TO DFSUM
 SZL
 STA
 DCA DFSUM /TRUNCATE IF TOO LARGE
 ISZ EPDIV /IS IT AN EPOCH YET?
 JMP FOUR /NO
 TAD DFSUM /YES, FIND MAXIMAL. . .
 CLL RAR /EPOCH EACH MINUTE
 CIA
 TAD MAXEP
 SMA CLA /IS THIS IT?
 JMP .+4 /NO
 TAD DFSUM /YES, REPLACE OLD
 CLL RAR
 DCA MAXEP
 ISZ MINDIV /IS IT A MINUTE YET?
 JMP EPOCH /NO
 IOF /YES, READ LITE LEVEL
 TAD .+5 /FROM A/D, CH.2
 JMS A2D
 DCA DATWRD
 ION
 JMP .+5
 2
 NOP
 NOP
 NOP
 STORE /AND STORE IN RECORDER
 HLT /MEMORY
 TAD MAXEP /NOW GET MAXIMAL EPOCH
 DCA DATWRD /AND STORE IT IN NEXT
 STORE /MEMORY LOCATION
 HLT
 JMP MINIT

8321
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 8328 488 7482
 8329 481 3183
 8330 482 1164
 8331 483 3816
 8332 484 1174
 8333 485 3165
 8334 486 3348
 8335 487 3341
 8336 418 7388
 8337 411 1416
 8338 412 7518
 8339 413 5223
 8340 414 1348
 8341 415 3348
 8342 416 7438
 8343 417 7881
 8344 428 1341
 8345 421 3341
 8346 422 5231
 8347 423 1348
 8348 424 3348
 8349 425 7428
 8350 426 7248
 8351 427 1341
 8352 438 3341
 8353 431 2165
 8354 432 5218
 8355 433 1174
 8356 434 3165
 8357 435 3342
 8358 436 3343
 8359 437 7888
 8360 448 7388
 8361 441 1365
 8362 442 7518
 8363 443 5253
 8364 444 1342
 8365 445 3342
 8366 446 7438
 8367 447 7881
 8368 458 1343
 8369 451 3343
 8370 452 5261
 8371 453 1342
 8372 454 3342
 8373 455 7428
 8374 456 7248
 8375 457 1343
 8376 458 3343
 8377 461 2165
 8378 462 3248
 8379 463 7188
 8380 464 1348
 8381 465 7841
 8382 466 3348
 8383 467 7438
 8384 478 7881

/PAGE 2

/COMPUTE DIFFERENCE SCORE

*488

DIFSCR.

SUM.

NEG.

NEXT.

LX18.

LNEG.

LNXT.

HLT

DCA

TAD

DCA

TAD

DCA

DCA

DCA

CLA CLL

TAD I

SPA

JMP

TAD

DCA

SZL

IAC

TAD

DCA

JMP

TAD

DCA

SNL

STA

TAD

DCA

ISZ

JMP

TAD

DCA

DCA

DCA

NOP

CLA CLL

TAD

SPA

JMP

TAD

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SZL

IAC

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DCA

JMP

TAD

DCA

SNL

STA

TAD

DCA

ISZ

JMP

CLL

TAD

CIA

DCA

SZL

IAC

LATEST

BUFLOC

A16

M11

BUFN

MINLO

MINHI

A16

NEG

MINLO

MINLO

MINHI

MINHI

NEXT

MINLO

MINLO

MINHI

MINHI

BUFN

SUM

M11

BUFN

PRDLO

PRDHI

/STORE MOST RECENT SUM

/SET UP BUFF PNTRS

/CLEAR DP ADDER

/SUM: LAST 11 SUM4'S

/MOV CURR VAL

/BY 11

#385 471 1341
 #386 472 7841
 #387 473 3341
 #388 474 7188
 #389 475 1342
 #390 476 1348
 #391 477 3342
 #392 588 7438
 #393 581 7881
 #394 582 1343
 #395 583 1341
 #396 584 3343
 #397 585 1164
 #398 586 3816
 #399 587 1164
 #400 518 3815
 #401 511 1174
 #402 512 3165
 #403 513 1415
 #404 514 3173
 #405 515 1163
 #406 516 3416
 #407 517 1173
 #408 528 3163
 #409 521 2165
 #410 522 5313
 #411 523 1342
 #412 524 7518
 #413 525 7841
 #414 526 7882
 #415 527 7884
 #416 538 8147
 #417 531 5688
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 #422 548 8888
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 #438 568 8888
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 #444 566 8888
 #445 567 8888
 #446 578 8888
 #447 571 8888
 #448 572 8888

SHUFL,

/

*548
 MINLO,
 MINHI,
 PRDLO,
 PRDHI,
 SCNT,

STACK,

BUFR,

TAD MINHI
 CIA
 DCA MINHI
 CLL
 TAD PRDLO
 TAD MINLO
 DCA PRDLO
 SZL
 IAC
 TAD PRDHI
 TAD MINHI
 DCA PRDHI
 TAD BUFLOC
 TAD A16
 TAD BUFLOC
 DCA A15
 TAD M11
 TAD BUFN
 TAD I A15
 DCA BUMP
 TAD LATEST
 DCA I A16
 TAD BUMP
 DCA LATEST
 ISZ BUFN
 JMP SHUFL
 TAD PRDLO
 SPA
 CIA
 BSW
 RAL
 AND X177
 JMP I DFSCR

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 8493 603 1160
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 8495 605 2131
 8496 606 5215
 8497 607 1145
 8498 610 3151
 8499 611 2130
 8500 612 7410
 8501 613 3135
 8502 614 5225
 8503 615 6506
 8504 616 1126
 8505 617 7104
 8506 620 3126
 8507 621 7420
 8508 622 1127
 8509 623 1176
 8510 624 3134
 8511 625 1134
 8512 626 7500

/PAGE 3

/GENERATE TIME CODE (OCTAL MINUTES)

*600

CODET,	HLT	/ENTER EACH 4 A/D'S IF TFLAG SET
	ISZ	TCNTR /TIME FOR ANOTHER DIGIT?
	JMP	TOUT /NO
	TAD	M10
	DCA	TCNTR
	ISZ	OCNTR /YES, START OCTAL GROUP?
	JMP	FLASH /NO, OUTPUT DIGIT
	TAD	M4 /YES, SKIP DIGIT
	DCA	OCNTR
	ISZ	GRPS /4 OCTAL GROUPS YET?
	SKP	
	DCA	TFLAG /YES, CLEAR TFLAG
	JMP	TOUT
FLASH,	STLITE	/LITE ON
	TAD	TCODE
	CLL RAL	/GET NEXT MSB
	DCA	TCODE
	SZL	/BINARY 1 OR 0?
	TAD	M4 /1:HOLD LITE 5 UNITS
	TAD	M1 /0:HOLD LITE 1 UNIT
	DCA	CODE1
TOUT,	TAD	CODE1 /HOLD LITE ON?
	SMA	

0513	627	6507	CLLITE		/NO, CLEAR IT
0514	630	7001	JAC		/YES
0515	631	3134	DCA	CODE1	
0516	632	6600	JMP	I CODET	
0517					
0518					
0519			/STORE DATA		
0520			*640		
0521	640	7402	STORES,	HLT	
0522	641	6504		RCRA	/SAVE CRA
0523	642	3154		DCA	CRATMP
0524	643	1124		TAD	FLDFLG
0525	644	7650		SNA CLA	/WHICH FIELD?
0526	645	5251		JMP	.+4
0527	646	1155		TAD	FLD1
0528	647	6505		WCRA	/IF FLD 1 CHANGE FLDS
0529	650	7300		CLA CLL	
0530	651	1151		TAD	DATWRD
0531	652	3417		DCA I	DATAP
0532	653	1154		TAD	CRATMP
0533	654	6505		WCRA	/RESTORE CRA
0534	655	7300		CLA CLL	
0535	656	1017		TAD	DATAP
0536	657	1156		TAD	MEMLIM
0537	658	7650		SNA CLA	
0538	661	5264		JMP	.+3
0539	662	2240		ISZ	STORES
0540	663	5640		JMP I	STORES
0541	664	1124		TAD	FLDFLG
0542	665	7440		SZA	/NO, RETURN +1
0543	666	5640		JMP I	STORES
0544	667	2124		ISZ	FLDFLG
0545	670	7240		STA	/FLD 0, SWITCH TO FLD 1
0546	671	3017		DCA	DATAP
0547	672	2240		ISZ	STORES
0548	673	5640		JMP I	STORES
0549					/RTRN +1
0550					
0551			/RECORDER MEMORY		
0552					
0553			/MAXIMAL EPOCH ACTIVITY SCORE AND		
0554			/LITE LEVEL FOR EACH MINUTE ARE		
0555			/STORED IN ALTERNATE MEMORY LOCS		
0556			/FROM LOC. 700 TO 5777 (FLD 0)		
0557			/AND 10000 TO 15777 (FLD 1)		
0558					
0559			*700		
0560					
0561					
0562					
0563			SSS		

END

FILMED

3-83

DTIC