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FREQUENCY ANALYSIS OF KOROTKOV BLOOD PRESSURE SOUNDS USING THE FOURIER TRANSFORM

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FOREWORD

This report was prepared at the Systems Research Laboratories, Inc., Dayton, Ohio, under Air Force contract AF 41(609)-2753 and task No. 793003. The report was submitted for publication on 29 November 1965.

The data-collection phase of this study represents a cooperative effort between the USAF School of Aerospace Medicine and Systems Research Laboratories, Inc.

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This report has been reviewed and is approved.

Harold V. Ellingson

HAROLD V. ELLINGSON
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Commander

ABSTRACT

The purpose of this investigation was to determine the frequency content of the sound signals (Korotkov sounds) obtained from the microphone located in the arm cuff of an automatic blood pressure measuring instrument. Korotkov sound recordings were made for five subjects in five experimental situations: rest, postexercise, passive tilting, centrifuge rides, and flights in NF-100 aircraft. The frequency analysis was performed by using a digital computer to obtain the Fourier transforms of the sound signals. The Fourier transforms were displayed on the computer oscilloscope and photographed. The photographs were then arranged in a number of rectangular arrays for convenient comparison of the frequency content of the Korotkov sounds as related to the several types of Korotkov sounds, experimental situations, and subjects.

Initial study of the 240 average Fourier transforms contained in these arrays indicates no readily observable common characteristics except that most of the sound energy is almost always located below 50 cps.

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I. INTRODUCTION

Data collection and computer technics were employed in analyzing the Korotkov sounds of five subjects under several noise and stress conditions. An underlying purpose of this investigation was to determine what sound characteristics, if any, were common to all subjects under all the noise and stress conditions imposed and, by so doing, to help develop an optimum design for an electronic device by which Korotkov sounds can be recognized.

A technic has been developed for automatically measuring blood pressure in a noisy environment such as that which occurs in flight. This technic employs an arm pressure cuff, which is automatically inflated and deflated in a preprogramed manner. A sensitive microphone is located under the cuff to detect the pulse sounds (called Korotkov sounds) which occur as the blood pulses through the brachial artery. The cuff pressure is decreased from above systolic pressure to below diastolic pressure at a rate of 5 mm./sec. The duration of this deflation period is approximately 30 seconds and the period between successive inflations is approximately 1 minute.

Korotkov sounds are complex sound pulses which occur at a repetition rate equal to the pulse rate during the time the cuff pressure is less than the systolic pressure and greater than the diastolic pressure. The occurrence of each Korotkov sound causes the cuff pressure to be read and recorded. The first and last cuff pressures recorded, corresponding to the first and last Korotkov sounds, are the systolic and diastolic pressures, respectively. When the technic is employed in an aircraft, both the Korotkov sound signal and a signal proportional to the pressure in the arm cuff are telemetered to a ground station.

A necessary requirement for the successful use of this technic for measuring blood pressure is that the sounds used for initiating cuff-pressure readings are truly Korotkov sounds rather than extraneous noise. Two factors, however, make accurate recognition difficult. The first is environmental noise, which is especially troublesome under aircraft flight conditions, and the second is the changing nature of the Korotkov sounds themselves. A Korotkov sound, like many physiologic phenomena, is typified by a complex waveform. This waveform may change in period, amplitude, and spectral content from individual to individual and for the same individual when undergoing stress.

Ware and Kahn (1) reported a device for measuring blood pressure as described above. By using band-pass filters with center frequencies at 40 cps and 150 cps they found that valid Korotkov sounds could be recognized by an electronic coincidence technic. A similar device developed by Systems Research Laboratories in 1964 also employs the coincidence technic but places the filter center frequencies at 40 cps and 100 cps.

A brief survey is given of papers dealing with the qualitative characteristics of Korotkov sounds.

As a qualitative description, the work of Collins et al. (2) is noteworthy. Collins divided the train of Korotkov sound pulses which occur between systole and diastole into 4 audible phases and a fifth silent phase. As the pressure in the cuff was released, just enough to permit a jet of blood to pass the restrictive point, a "sharp light thud" was detected. This sound could be heard over a range of about 10 mm. Hg and was termed a phase 1 sound. As the pressure in the cuff continued to decrease, the sounds changed in quality and intensity. Collins described these phase 2 sounds as soft but rather inconsistent murmurs which persisted over a pressure range of 10 mm. Hg. Loud, long, and clear sounds characterized phase 3. This type of sound persisted for 15 to 22 mm. Hg in the normal individual. Muffled and dull sounds were observed during phase 4, which was associated with a pressure spread of 11 mm. Hg. The largest change in the intensity of the Korotkov sounds occurred at the transition from phase 3 to phase 4.

Many attempts have been made to quantify characteristics of Korotkov sounds. One of the first concerted attempts (1914) was made by Hooker and Southworth (3), who used a carbon-button microphone and a Lippman capillary electrometer. They measured 15 cps as the predominant frequency. In 1925, Bramwell and Hickson (4) used a Frank capsule and recorded sounds under the cuff. They recorded frequencies as high as 100 to 150 cps, but they did not detect an appreciable difference in the 4 phases. The following year, Korns (5) used a membrane manometer and observed frequencies in the range of 40 to 256 cps. In 1943, Groedel and Miller (6) used a heart-sound pickup with a photographic recording instrument to find prominent frequencies in the range of 45 to 60 cps. The following year, Rappaport and Luisada (7) utilized a pressure-equalized microphone as a pickup and a photographic ECG instrument as a recorder. Their findings show 25 to 55 cps as the predominant frequency range.

One of the more current quantitative descriptions of the Korotkov sounds was presented in 1963 by Geddes et al. (8). According to Geddes, phase 1 sounds have principal frequencies in the 40 to 55 cps range. The frequency and intensity decrease somewhat during phase 2. With the arrival of phase 3 sounds, the frequency and intensity increase quite rapidly. The principal frequencies lie in the 60 to 70 cps range and the intensity is about twice that observed at the transition from phase 1 to phase 2. With the occurrence of phase 4 sounds, the amplitude and frequency drop rapidly. The amplitude goes to zero or near zero and the frequency components drop to 25 to 35 cps. It must be noted, however, that the frequency response of the recording instrument utilized by Geddes fell off appreciably above 70 cps.

In addition to revealing a divergence of opinions as to the spectral content of Korotkov sounds, this research has revealed no previous studies of Korotkov sounds under conditions of high environmental noise and subject stress.

II. ANALYTIC METHODS

The Fourier transform is the analytic tool which was employed to perform the frequency analysis of the Korotkov sounds. The power-spectrum technic is probably the most widely applied sophisticated signal analysis technic employed by medical researchers and was employed at the outset of this study. It was soon abandoned, however, because the nature of the Korotkov sound signals made the technic unapplicable.

The power-spectrum approach is profitably applied when the signal consists of recurring phenomena plus additive random noise. The autocorrelation step in the power-spectrum technic then serves to negate the random components of the signal. The Fourier transform of the resultant autocorrelation function yields the relative power density of the periodic components of the original signal. The noise-abatement feature of this technic makes it attractive for the purpose of our study; Korotkov sounds are not amenable to this method, however, because they are transient and changeable in form and do not necessarily recur at a fixed rate. This variation in rate was caused by the slight but significant short-term changes in arterial pulse rate and was thus the major reason for rejecting the power-spectrum approach. Unless the sounds are stationary, the autocorrelation step cannot reveal any transient period components (such as damped sinusoidal vibrations) that might occur in several successive Korotkov sounds.

In the approach employed in this study, the autocorrelation step was eliminated and the Fourier transform was applied directly to individual Korotkov sounds. This approach exposes the frequency distribution of the sound energy of individual sounds without regard to stationary sounds or presumed similarities between adjacent sounds. This makes it possible, for instance, to compare the frequency distributions of the 4 Korotkov sound phases, phase 1 sounds of the same subject obtained during several different situations, and different subjects obtained during the same situation.

Direct application of the Fourier transform has one drawback—it includes no provision for distinguishing the signal from noise. This is only a minor problem in experimental situations which produce sound-signal levels that are high compared to the baseline noise level. In situations such as centrifuge rides and flights in NF-100 aircraft, however, the potentially high-noise level can make discrimination between signal and noise quite difficult. This difficulty was avoided for the most part by limiting the range of the frequency analysis to a maximum of 160 cps. Since most of the energy in a Korotkov sound can be expected to occur in the low audio-frequency range, restricting the frequency analysis to the region where the signal-to-noise ratio is highest maximizes the probability that the frequency distribution obtained is largely composed of sound energy.

Extending the frequency cutoff to the higher audio range, say 2000 cps, presents two choices:

1. A large band of frequency information may be collected in which noise and signal are indistinguishable.

2. A new analysis approach may be adopted which would rely on the summation of the Fourier transforms of many Korotkov sounds to cause any low-amplitude, high-frequency sound components to rise above the level of the random noise. At least one investigation (12) involved an approach similar to the latter choice to obtain information about the high-frequency content of Korotkov sounds. When the objective is to reveal the significant frequency similarities, however, or dissimilarities which occur for several subjects in several experimental situations, more valuable information can be derived by analyzing individual Korotkov sounds and concentrating this analysis on the narrow frequency range containing the major portion of the sound energy.

III. EQUIPMENT AND METHODS

Experimental situations

Each of five volunteers was subjected to five different experimental situations: rest, exercise, passive tilting, centrifuge rides, and flights in NF-100 aircraft. In each instance, pressure-cuff inflations were performed and tape recordings were made of cuff pressure, Korotkov sounds, voice, ECG, respiration, and G level (when appropriate).

Since the "rest" and "exercise" situations were pursued in close succession, the cuff inflation profiles for both experimental situations are shown joined (fig. 1a). During the "rest" situation the pressure cuff was inflated twenty times for each subject. The first ten inflations were performed with the subject seated and relaxed; the last ten were performed with the subject seated but tensing the arm wearing the cuff. During the "exercise" situation each subject exercised three times by running in place for 20 seconds. Cuff inflations were not attempted during the exercise periods because motion artifact was high; instead, they were performed between exercise periods with the subject seated. Three consecutive inflations followed each exercise period.

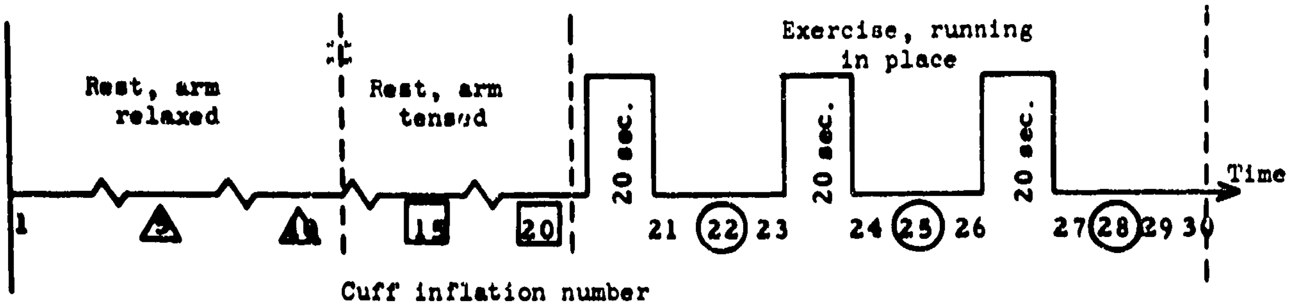

Figure 1a. Rest/exercise profile.

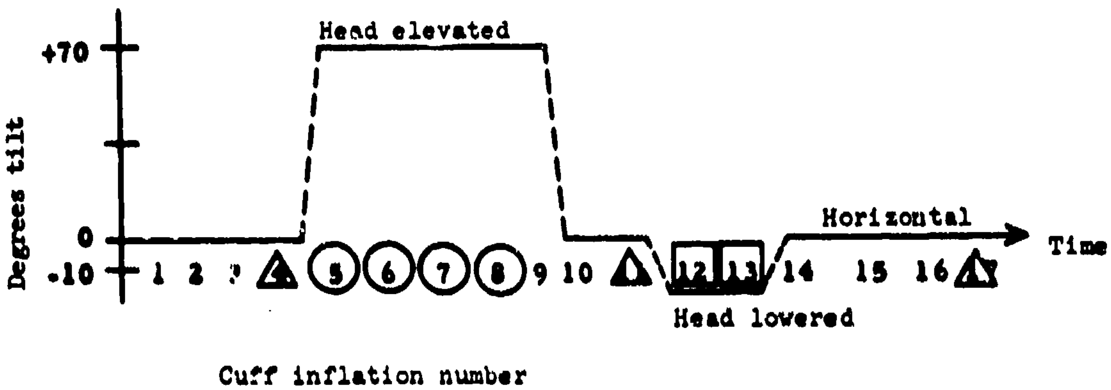

Figure 1b. Passive tilting profile.

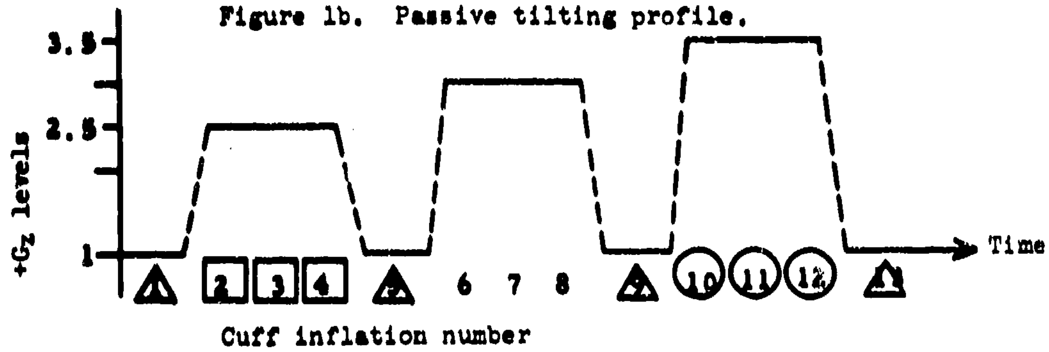

Figure 1c. Centrifuge profile.

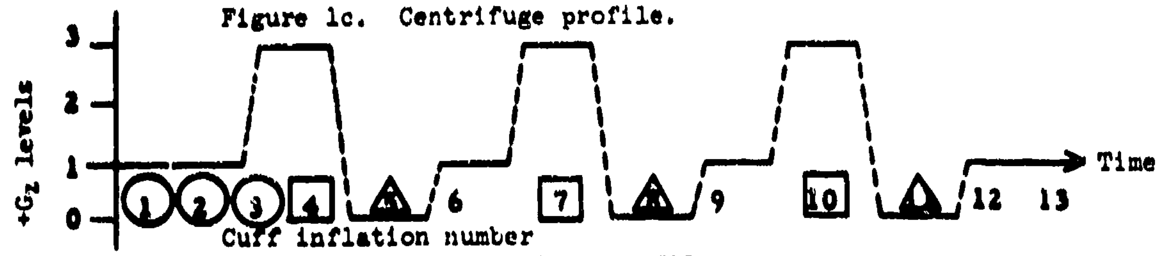

Figure 1d. NF-100 flight profile.

FIGURE 1

Maneuver profiles employed in the four experimental situations during which cuff inflations were performed and Korotkov sounds recorded. Inflation numbers circumscribed with symbols are those that were selected as representative of each maneuver. Fourier transforms obtained from sounds with similar symbols were averaged.

The experimental profile for the "passive tilting" situation is shown in figure 1b. The first four cuff inflations were performed with the subject lying horizontally on a tilt table. Then the subject was tilted head up 70°, and five inflations were performed. Subsequently, the subject was returned to horizontal for two inflations before being tilted head down 10° for two inflations. The seventeen-inflation profile was completed with five more inflations in the horizontal position.

The experimental profile for the centrifuge rides (fig. 1c) consisted of three consecutive runs at 2.5 G, 3.0 G, and 3.5 G, respectively. G's were applied in the $+G_z$ (longitudinal) direction. Three inflations were performed at each G level, and one inflation was performed at the 1 G level while the subject was being rested between runs. Each run lasted approximately 3 minutes. Three inflations prior to the first centrifuge ride and two inflations following the last ride completed the thirteen-inflation profile.

The experimental profile for flights in NF-100 aircraft is shown in figure 1d. Following three inflations during level flight (1 G), a maneuver sequence of 3 G, zero G, 1 G was pursued three times in succession. One inflation was performed at each G level in the sequence. The 3 G levels were obtained in spiral diving turns lasting approximately 1 minute each; zero G levels were obtained by the parabolic arc method and lasted approximately one-half minute each. Two inflations during level flight completed the thirteen-inflation profile.

Data collection

Although multiple data signals were tape recorded (cuff pressure, Korotkov sounds, voice, respiration, and G level when appropriate); only the Korotkov sounds were to be analyzed in this study. The cuff pressure and voice signals were employed as convenient "keys" for identifying the location of the Korotkov sound data on the recordings.

The Korotkov sound signals were obtained from a microphone located in the pressure cuff of an automatic blood pressure measuring instrument similar to that described in reference 9. Proper use of the instrument requires that care be taken when placing the pressure cuff and microphone. The procedure involved locating the microphone over the brachial artery about 3 inches above the elbow and locating the pressure cuff over the microphone so that the microphone was located about one fourth the cuff width from the bottom of the cuff. Then, with the subject's arm relaxed, the cuff tension was adjusted so that small sound signals were detected when the cuff pressure was above systolic. Subjects with large biceps were instructed to minimize arm flexure because an increase in bicep diameter might push the cuff down from its optimum location.

For all the experimental situations except the centrifuge rides the data signals were conditioned, telemetered, and recorded in the following manner. They were amplified by Mennen Greatbach (model 621A) amplifiers and converted to FM by Bendix model TOE-305 subcarrier oscillators. These FM signals then were multiplexed and transmitted on a carrier frequency of 232.9 Mc./sec. After demodulation at the telemetry ground station, the data signals were recorded in the FM mode on a Sangamo model 4700 tape recorder operated at 3¾ in./sec. This recorder has an FM center frequency of 6.75 kc./sec. and a double bandwidth of 1250 cps. Since this recorder can record and play back simultaneously, proper recording was verified by observing the data written simultaneously on an Offner strip chart recorder. The upper 3 dB frequency of the Korotkov sound channel was limited to 160 cps by loading the Mennen Greatbach amplifier with a 0.1 μf. capacitor. Also, the subcarrier discriminator for the Korotkov sound channel was provided with a filter to limit the upper 3 dB frequency to 160 cps.

Data from the centrifuge experiments were not telemetered; instead, they were transmitted via slip rings and signal leads. The data signals were amplified by Taber model 202G-4 amplifiers and recorded in the FM mode on a

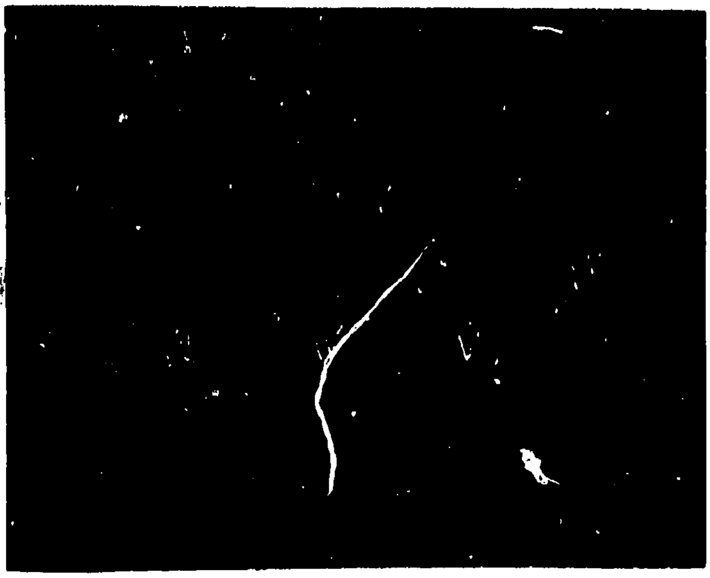

FIGURE 2

Computer cathode-ray tube display of typical 19-second segment of Korotkov sound record. Record starts at upper left and is continuously displayed in 2.5-second segments per line. Movable edit line is shown in position for extracting an individual sound.

Pemco portable instrumentation recorder operated at 1⅞-in./sec. The FM center frequency of this tape recorder is 3.37 kc./sec. and the double bandwidth is 625 cps. Prior to recording, the Korotkov sound signal was filtered by an SRL model 221A Vap filter operated in the low-pass mode where the band-pass filter is 5 to 640 cps. At the completion of each centrifuge experiment the tape recorded data were played back into an Offner strip-chart recorder to verify the quality of the recordings.

Data handling

Several data-handling steps were required to reduce the tape-recorded sound data to a form suitable for application of the Fourier transform by a digital computer. The first step involved converting the analog tape recordings to a digital format. The facilities used to accomplish this step included: (1) an Ampex FR 1200 tape recorder to play back the analog tapes, (2) a Philbrick operational amplifier to act as a buffer stage between the recorder and the A/D converter, (3) a Raytheon AD-50A analog-to-digital converter, and (4) a PDP-1 digital computer (Digital Equipment Corp.) programed to collect the digitized Korotkov sound signals. The input to the Philbrick amplifier was a.c. coupled (1.5 cps low-frequency cutoff) to eliminate any d.c. component from the tape-recorder output.

The digital computer was programed to collect 19-second segments of digitized sound signals at a rate of 400 samples per second on manual command from the operator. (This number was selected because it is near the minimum rate required to resolve frequency components as high as 160 cps—the high-frequency cutoff of the recorded sound data. The sampled interval of 19 seconds was chosen as that was sufficient time for the cuff pressure to decrease from above systolic to below diastolic.) By monitoring the cuff-pressure channel with an oscilloscope connected to the recorder output, the operator selected portions of the sound-channel analog record which contained Korotkov sounds. When the oscilloscope indicated that a cuff inflation profile was beginning (fig. 1), the operator depressed a switch on the computer console and the following 19-second segment of the sound-channel record was automatically collected in digital format and stored on magnetic tape.

The second data-handling step extracted individual Korotkov sounds from the 19-second record containing all the Korotkov sounds which occurred during an inflation. This was accomplished by first displaying the 19-second digitized sound record on the computer's cathode-ray tube (fig. 2). Then the operator visually located 4 sounds that were representative of Korotkov sounds of phases 1, 2, 3, and 4, respectively, and extracted each from the record by superimposing a movable edit line before the beginning of each sound. The computer program then suitably labeled each individual Korotkov sound and enscribed it on digital magnetic tape in a format compatible with the IBM 7094 computer which was to calculate the Fourier transforms.

In addition to the editing technic, which reduced the number of Korotkov sounds to only 4 from each inflation, the mass of recorded data was reduced further by selecting representative inflations from the multi-inflation profiles followed in the several experimental situations. Inflations chosen as representative of each of the maneuvers which occurred in each experimental situation are identified in the experimental profiles (fig. 1).

Following these two data handling steps, which enabled selection and preparation of the Korotkov sounds, the Fourier transforms of each sound were computed by an IBM 7094 computer.

Results display format

A digital tape containing the Fourier transform depiction of the frequency distribution of each Korotkov sound was returned from the 7094 computer facility to the PDP-1 computer facility so that the transforms could be displayed on the computer cathode-ray tube and photographed. Figure 3 indicates the graphic form of this display technic by illustrating how the Fourier transform describes the frequency distribution of a sinusoidal signal.

IV. RESULTS

The accumulation of analog Korotkov sound data was recorded during 365 pressure-cuff inflations, encompassing five subjects, four experimental situations for each subject, and three maneuvers in each situation. This large amount of data was made more manageable by selecting 4 sounds, representative of the 4 Korotkov sound phases, from the 30-odd sounds which occurred during each inflation. The data were decreased further by choosing the Korotkov sounds from only 2 to 4 representative inflations from the groups of 6 to 8 inflations performed on each subject during each maneuver. In this manner, the data were reduced to 4 sounds each from 175 inflations—700 individual Korotkov sounds. The Fourier transforms of these 700 sounds were then computed and individually normalized by assigning the largest frequency component in each transform the arbitrary magnitude of 10.0.

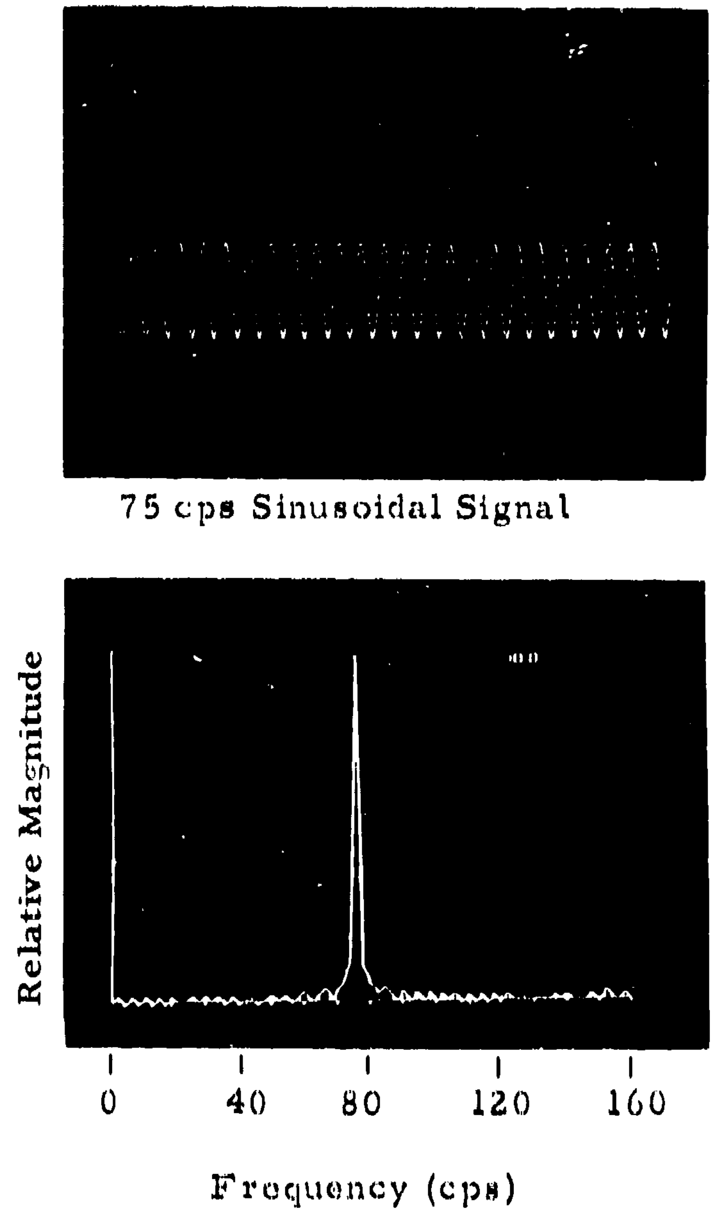

FIGURE 3

Illustration of technics for obtaining and displaying the frequency distribution of a Korotkov sound. Upper trace is a digitized 75 cps sinusoidal signal; lower trace is the magnitude versus frequency plot for this signal obtained with the Fourier transform. Both traces are photographs of the computer cathode-ray tube display.

This number of normalized Fourier transforms then was reduced from 700 to 240 by averaging the Fourier transforms obtained from repetitious inflations—e.g., the three phase 1 Korotkov sounds for subject 1 during the 3.5 G maneuver on the centrifuge. The decision to average the transforms of similarly generated Korotkov sounds represents a compromise between two desirable but conflicting ends. On the one hand, it was desirable to retain individual transforms of every Korotkov sound to reveal any variations which might have occurred within the groups of like sounds obtained from any one subject in any one situation. On the other hand, the total accumulation of frequency-distribution data had to be limited to a reasonable amount if human analysts were to be able to read it and derive meaningful information from it. It was also desirable to average transforms obtained under identical experimental conditions to negate the influence of random noise.

Attempts were not made to decrease the number of Fourier transforms below 240, because to do so would require destroying one or more of the three parameters the data were intended to reflect—Korotkov sound phases, subjects, and experimental maneuvers. For 4 sound phases, five subjects, and twelve different maneuvers (three in each of four experimental situations), the minimum number of Fourier transforms is, necessarily, $4 \times 5 \times 12 = 240$.

Rectangular arrays of photographs of the individual Fourier transforms were constructed to display the data in a manner which would facilitate assessment of the effects of each of the three experimental parameters. The 240 photographs have been arranged twice, so that a comparison of 4 Korotkov sound phases as they appeared for each experimental maneuver (vertical columns of photographs) and the effects the three maneuvers had on each of the 4 Korotkov sound phases (horizontal rows of photographs). The third experimental parameter, subject number, is the "running" parameter (page-to-page) for the twenty pages required to display figures 5 to 24.

The second form of arranging the 240 Fourier transform photographs is shown in figures 25 to 40. This arrangement makes it easier to compare different subjects during the same experimental maneuver. The transform photographs for the five subjects are arranged in vertical columns for each of the three maneuvers. In the sixteen pages required for this alternate form of data display, the Korotkov

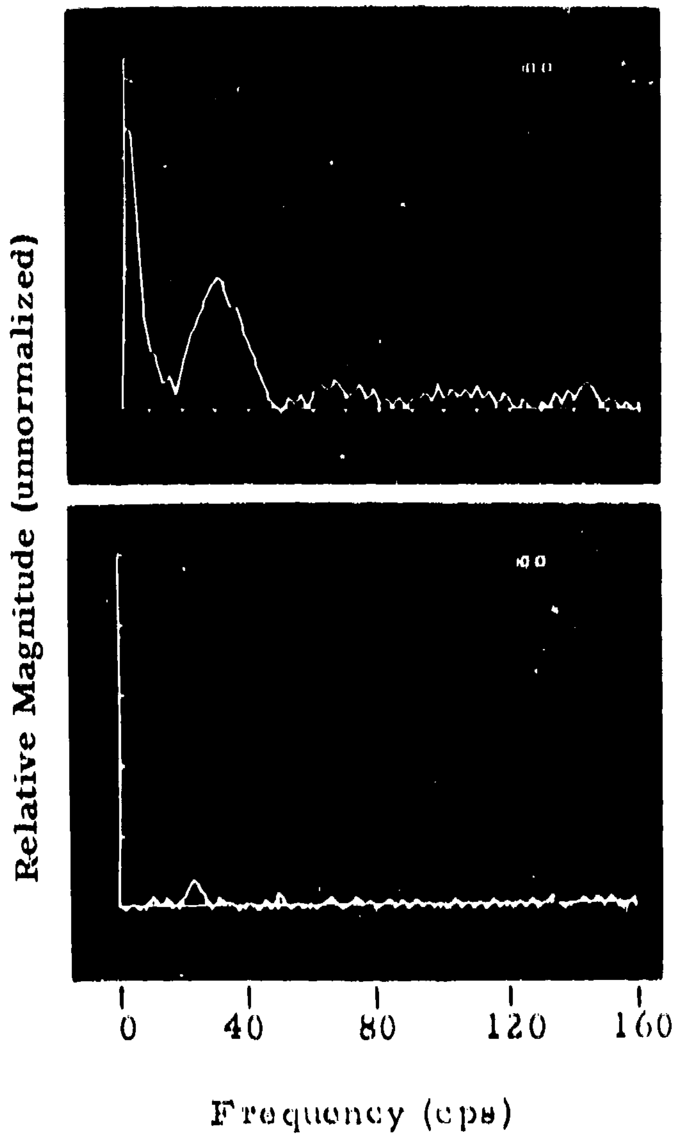

FIGURE 4

Unnormalized frequency distributions of a Korotkov sound (upper trace) and its following "baseline" (lower trace). The low noise level exemplified was characteristic of recordings made during "passive tilting" maneuvers.

sound-phase number takes on the role of the page-to-page parameter.

The same magnitude versus frequency information contained in the 240 photographs was also provided in tabular form to permit more exacting examination of the data. The 240 pages of computer printout required were included as a separately bound appendix.

The data obtained during the "passive tilting" and "rest/exercise" experimental situations were least affected by additive random noise. Although an exacting determination of how much noise was present could not be made, an indication was obtained by applying the Fourier transform to sections of "baseline"—the microphone output during the quiescent period following a cuff inflation. Figure 4 contains unnormalized Fourier transforms of a phase 3 Korotkov sound and the baseline following the inflation during which the sound occurred. This particular example, taken from the data obtained during "passive tilting," is typical of most of the data obtained during "passive tilting" and "rest/exercise." It will be noted that for subjects 2 and 5, however, during "rest/exercise" large 60-cycle components were present (and also the 120 cps harmonic).

Data from the NF-100 flights are quite similar in quality to that obtained during passive tilting (with the exception of the data for subject 5), but the centrifuge data are generally poorer in quality. For this experimental situation only the data from subject 5 appear to be relatively unblemished by noise.

V. CONCLUSIONS

Although careful study will be required to reveal all the characteristics of this Korotkov sound data (figs. 5 to 40), initial study has produced several general conclusions:

1. Except for the dissimilarities caused by differences in the noise environment, the frequency distribution for all the experimental situations are quite similar.

2. No prominent differences are consistently apparent when comparisons are made among the several experimental maneuvers or among the several subjects.

3. Most of the sound energy is generally located below 50 cps with the most prominent peaks occurring below 20 cps.

4. For phases 1 and 4 sounds the sound energy is often heavily localized below 20 cps, whereas for phase 2 and, especially, phase 3 sounds the energy tends to be more broadly distributed in the 0 to 50 cps range.

The prominent frequencies noted in these conclusions do not closely agree with those found by other investigators. Most others found some prominent frequencies above 50 cps (refer to Introduction). The chief reason for this discrepancy constitutes a significant feature of the computational methods used in this study.

Prominent frequency components higher than about 50 cps are not discernible in the Fourier transform photographs because the amplitudes of higher components are so small that they are indistinguishable from random noise. If each photograph was an average of a large number of sounds, however, rather than just 2 to 4 sounds, the frequency distribution of the noise would become "flatter," and low-level signal frequencies would become more identifiable. To confirm this hypothesis, a small statistical study was performed on a select group of Fourier transforms from the "passive tilting" situation. Although the low-frequency components were still most prominent, noticeable amounts of sound energy were located at 46 cps, 104 cps, and 150 cps. These frequencies coincide closely with the three frequencies which Ware and Kahn (1) employed in their indirect blood pressure instrument—namely, 40 cps, 90 cps, and 150 cps.

Hence, the data in this study can be employed to indicate which of the Korotkov sound characteristics are discernible in individual sounds. By additional statistical manipulations, the data may also indicate what general characteristics are discernible by averaging large groups of sounds. For a study designed to determine diagnostic feasibility, the wide-band characteristics attainable by averaging would be more suitable. When reliable recognition of the occurrence of Korotkov sounds is the objective, however, data which express the characteristics of individual sounds are more valuable. Any device designed to recognize Korotkov sounds must do so on an individual sound, real time basis; the device cannot respond to the average components of a sequence

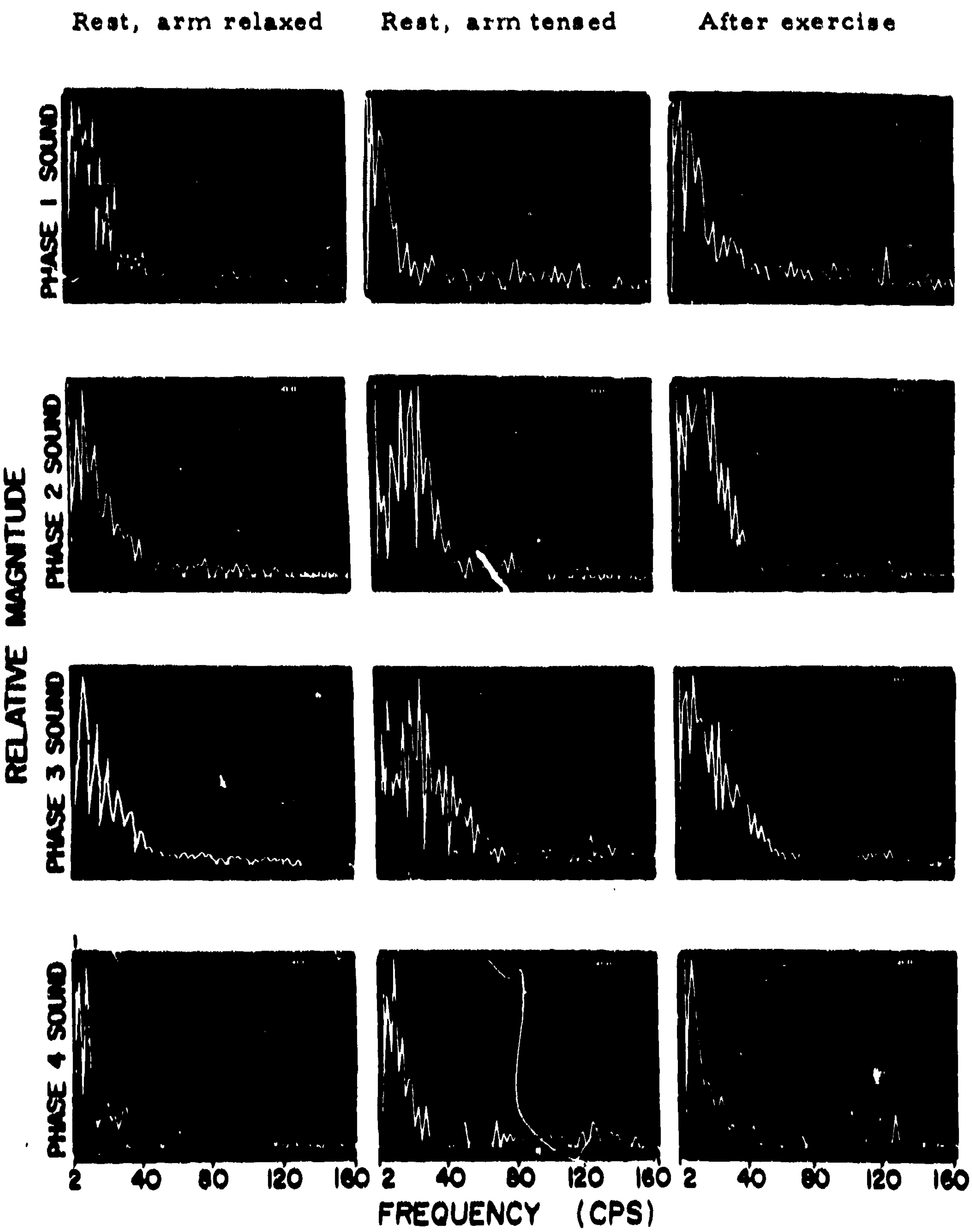

FIGURE 5

Normalized average Fourier transforms of Korotkov sounds of subject 1 obtained during three rest/exercise maneuvers.

Figures 5 to 24: *Vertical columns allow sound phase-to-sound phase comparison of the frequency distribution of the sound energy for each maneuver; horizontal rows allow maneuver-to-maneuver comparison for each of the four sound phases.*

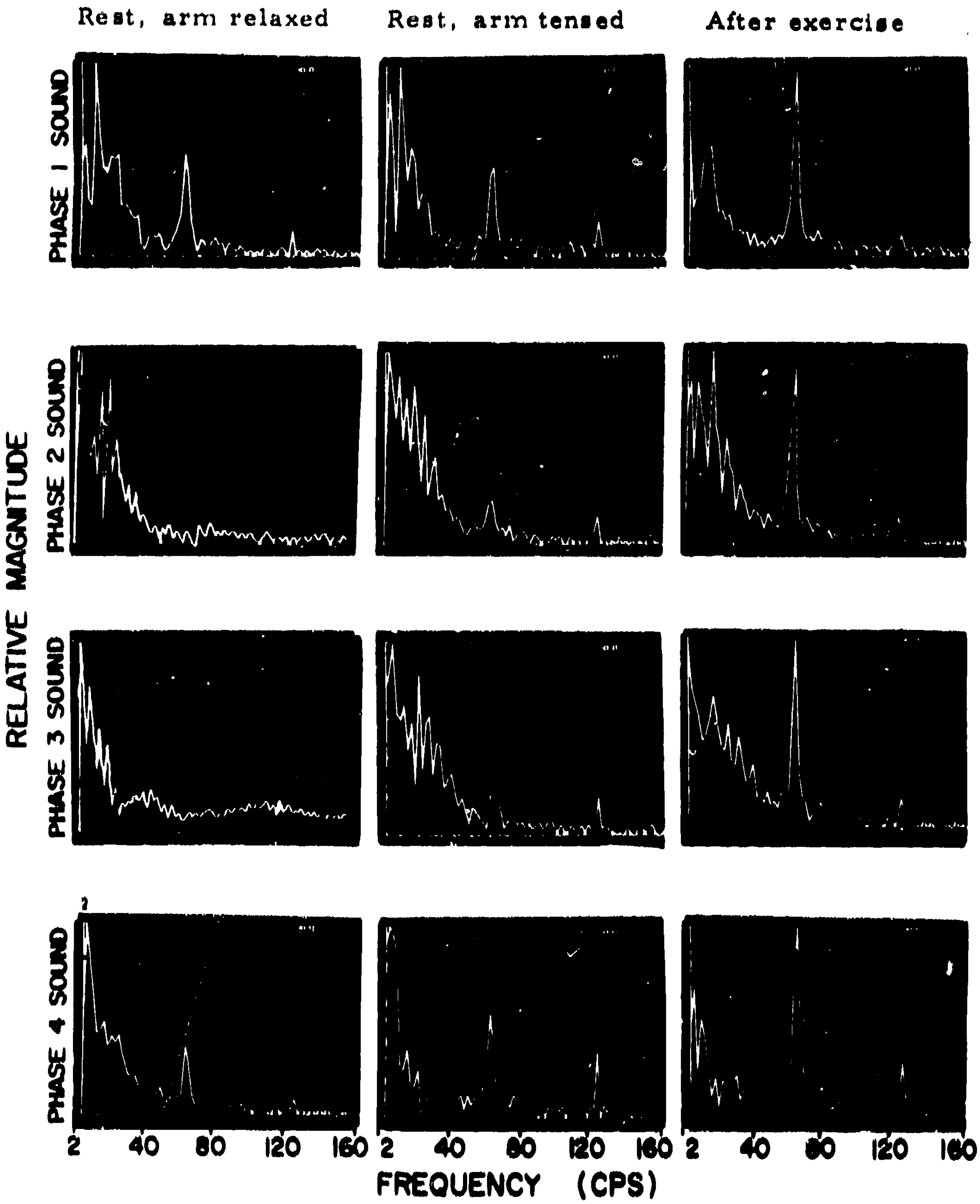

FIGURE 6

Normalized average Fourier transforms of Korotkov sounds of subject 8 obtained during three rest/exercise maneuvers.

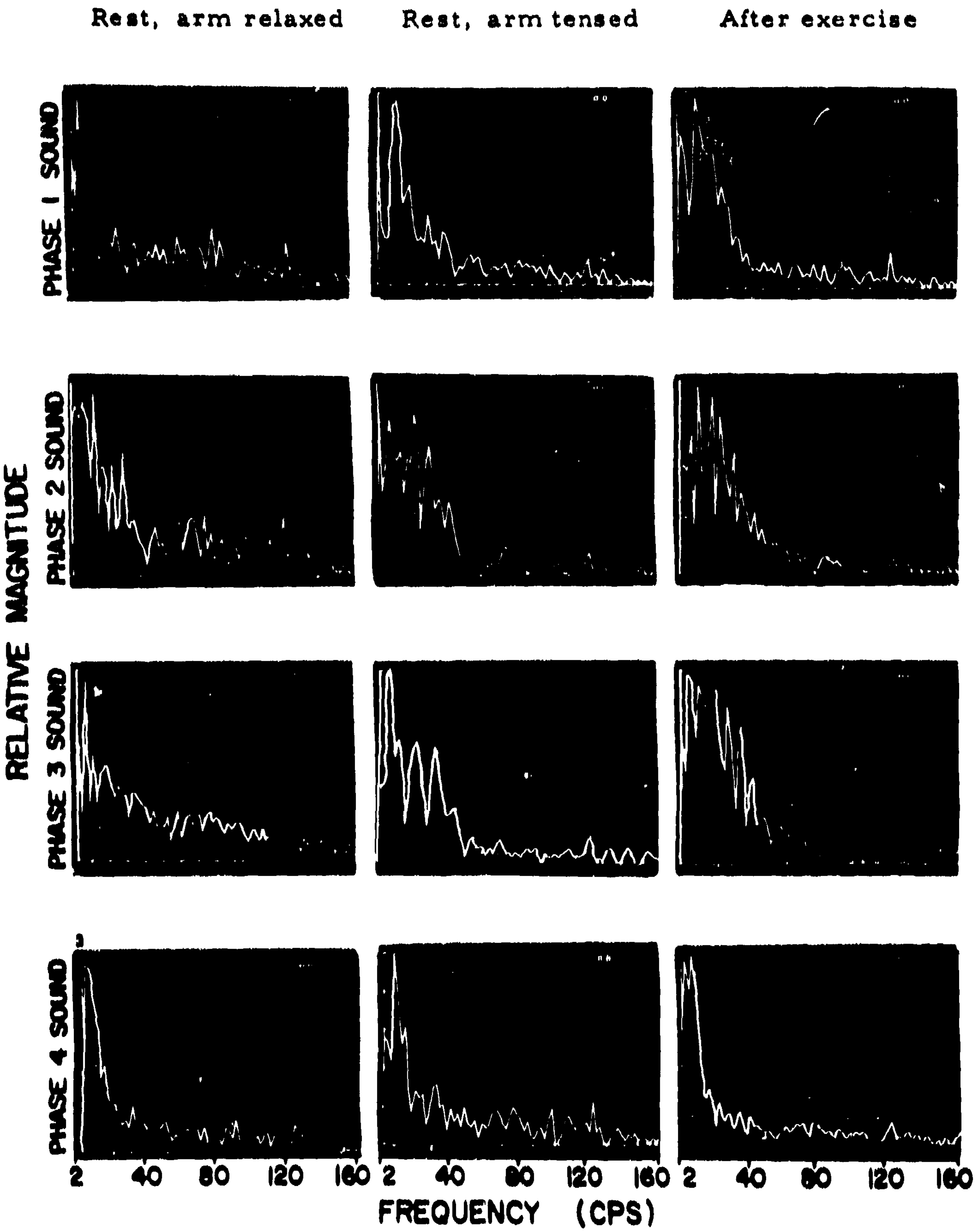

FIGURE 7

Normalized average Fourier transforms of Korotkov sounds of subject 8 obtained during three rest/exercise maneuvers.

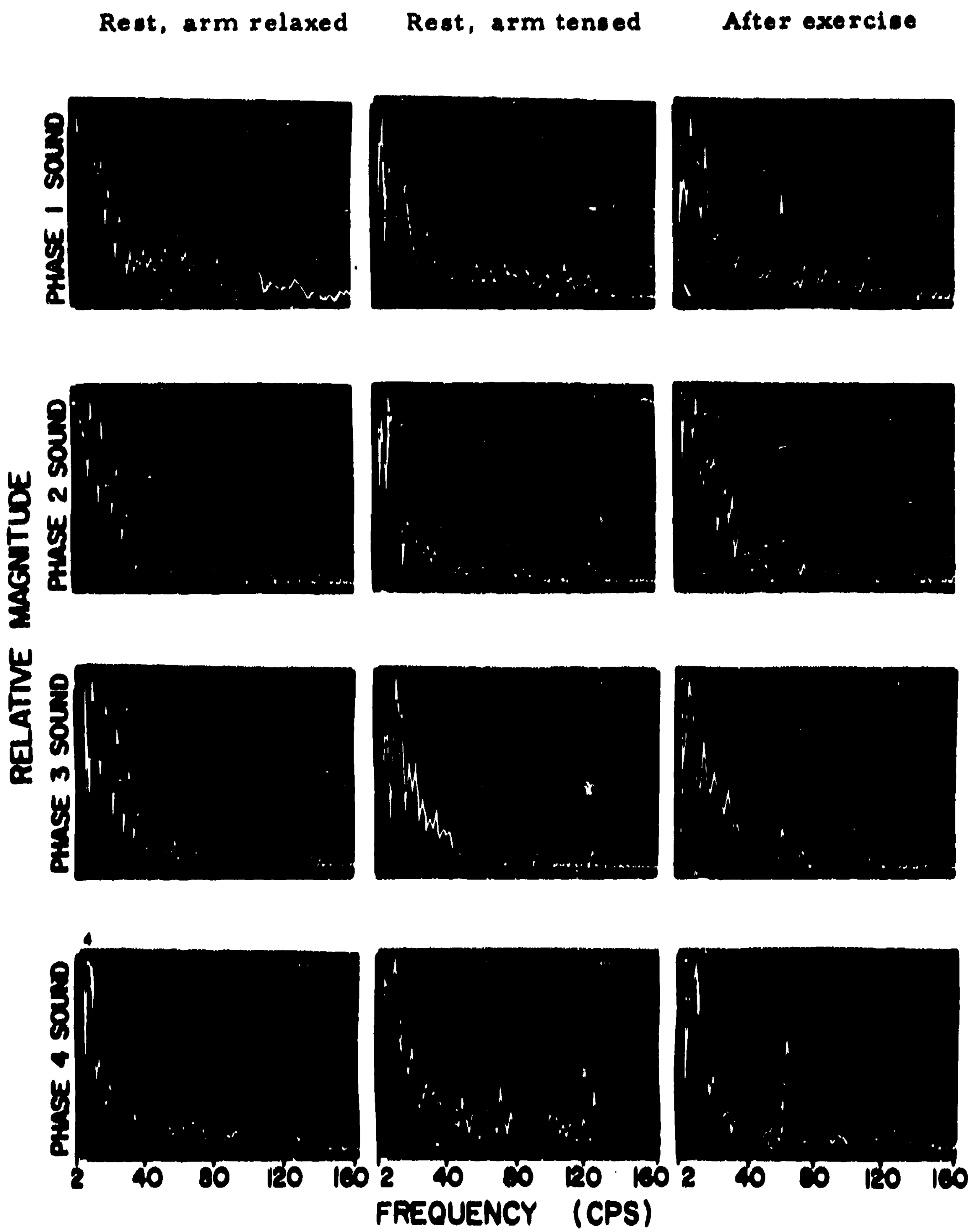

FIGURE 8

Normalized average Fourier transforms of Korotkov sounds of subject 4 obtained during three rest/exercise maneuvers.

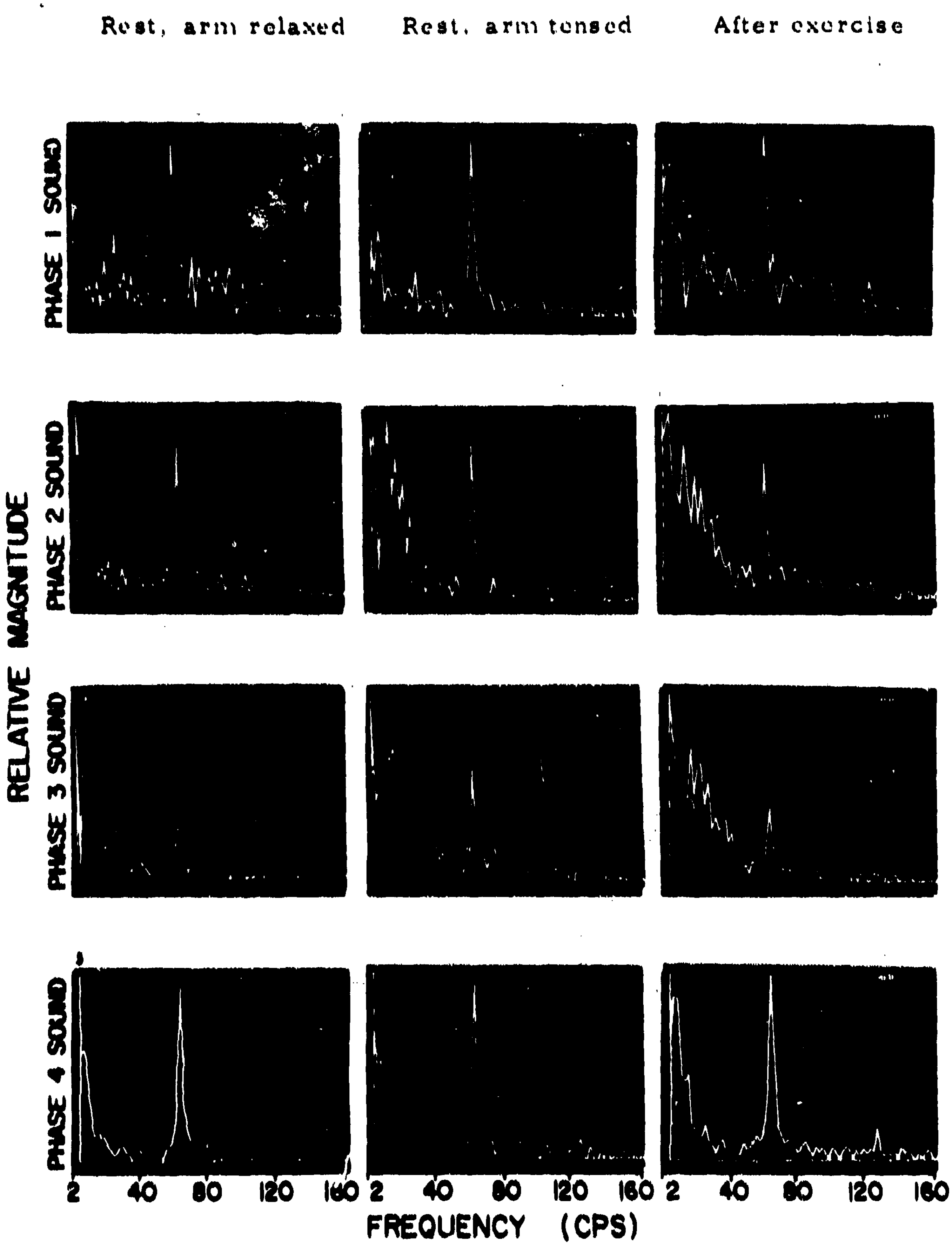

FIGURE 9

Normalized average Fourier transforms of Korotkov sounds of subject 5 obtained during three rest/exercise maneuvers.

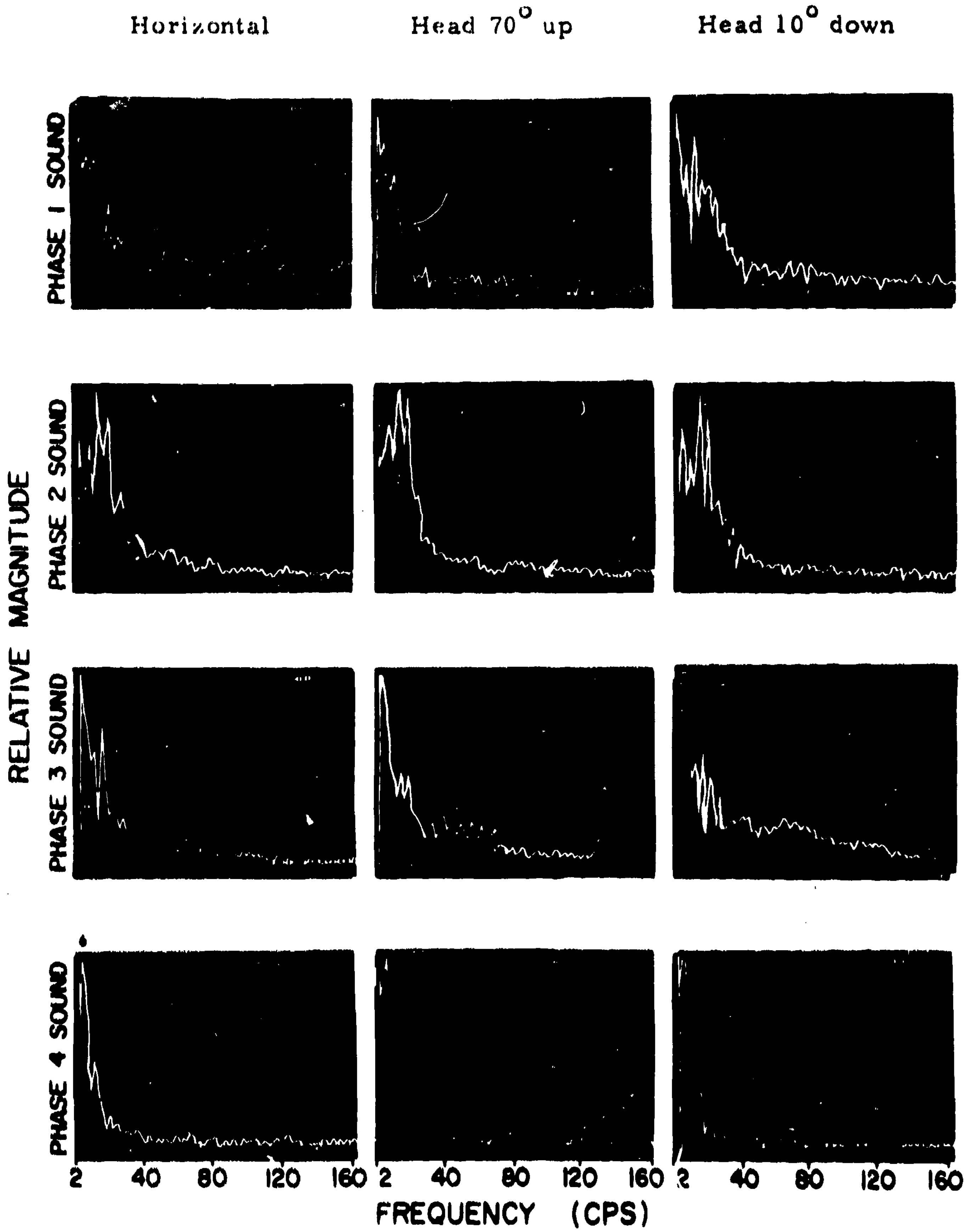

FIGURE 10

Normalized average Fourier transforms of Korotkov sounds of subject 1 obtained during three tilt-table maneuvers.

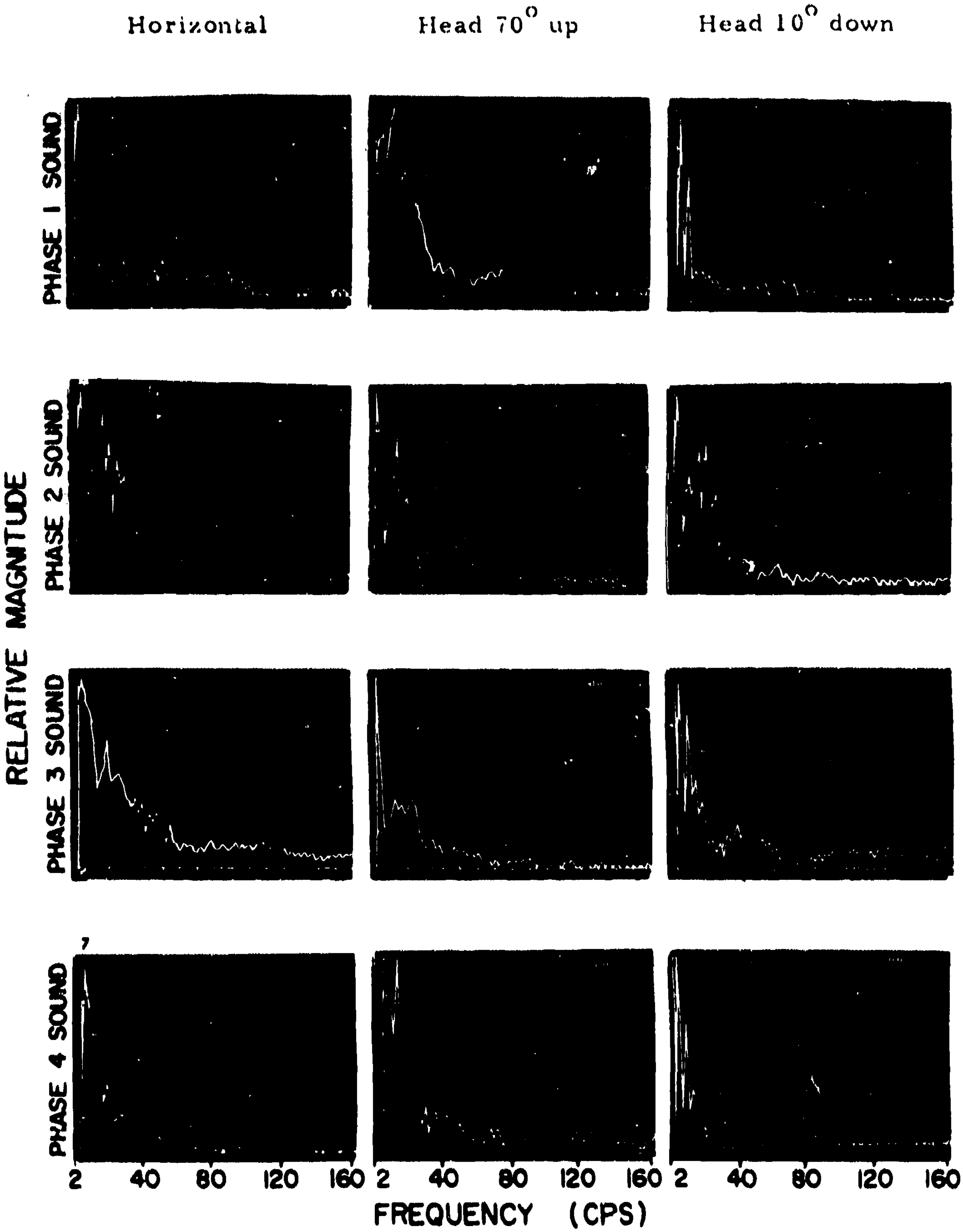

FIGURE 11

Normalized average Fourier transforms of Korotkov sounds of subject 2 obtained during three tilt-table maneuvers.

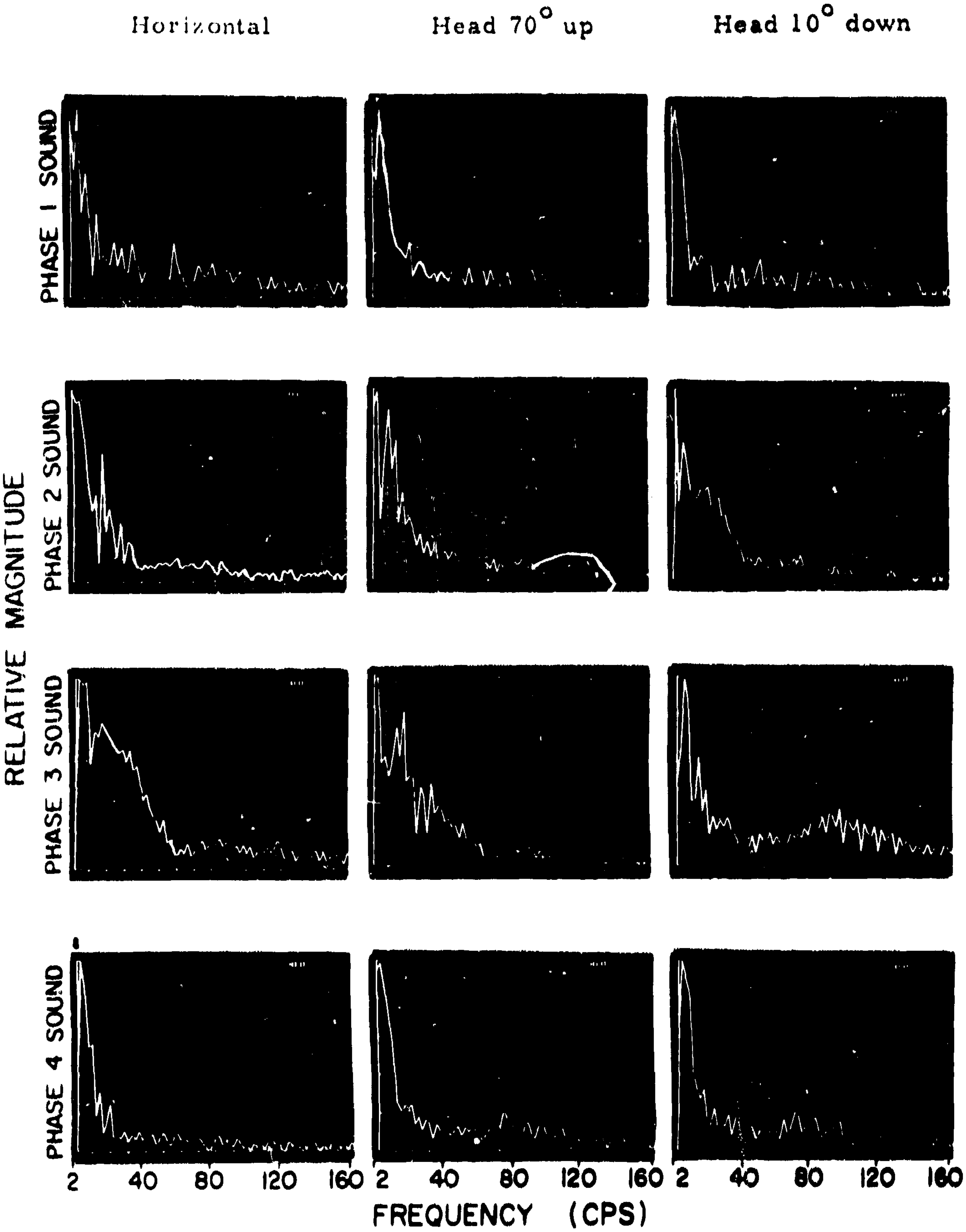

FIGURE 12

Normalized average Fourier transforms of Korotkov sounds of subject 3 obtained during three tilt-table maneuvers.

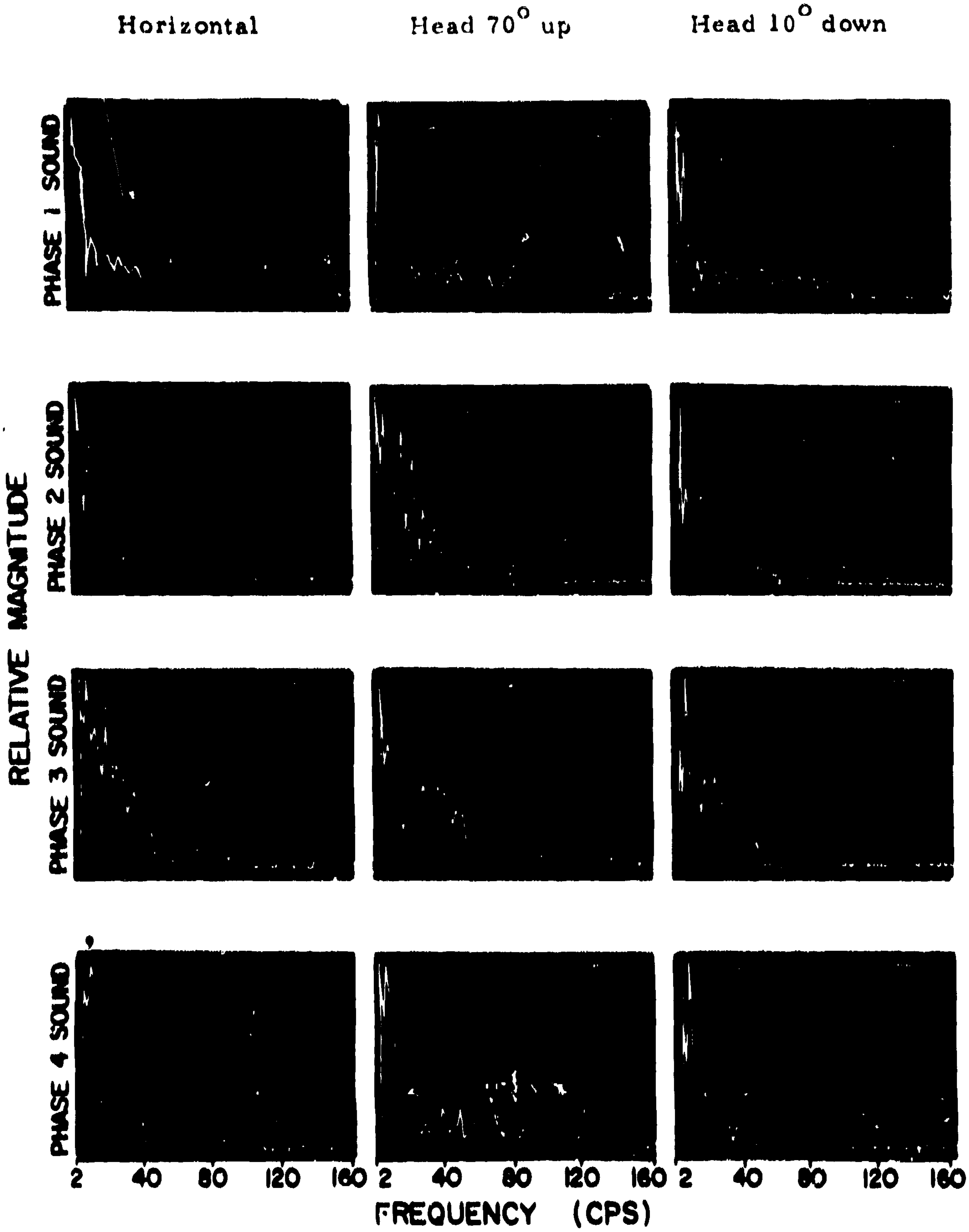

FIGURE 13

Normalized average Fourier transforms of Korotkov sounds of subject 4 obtained during three tilt-table maneuvers.

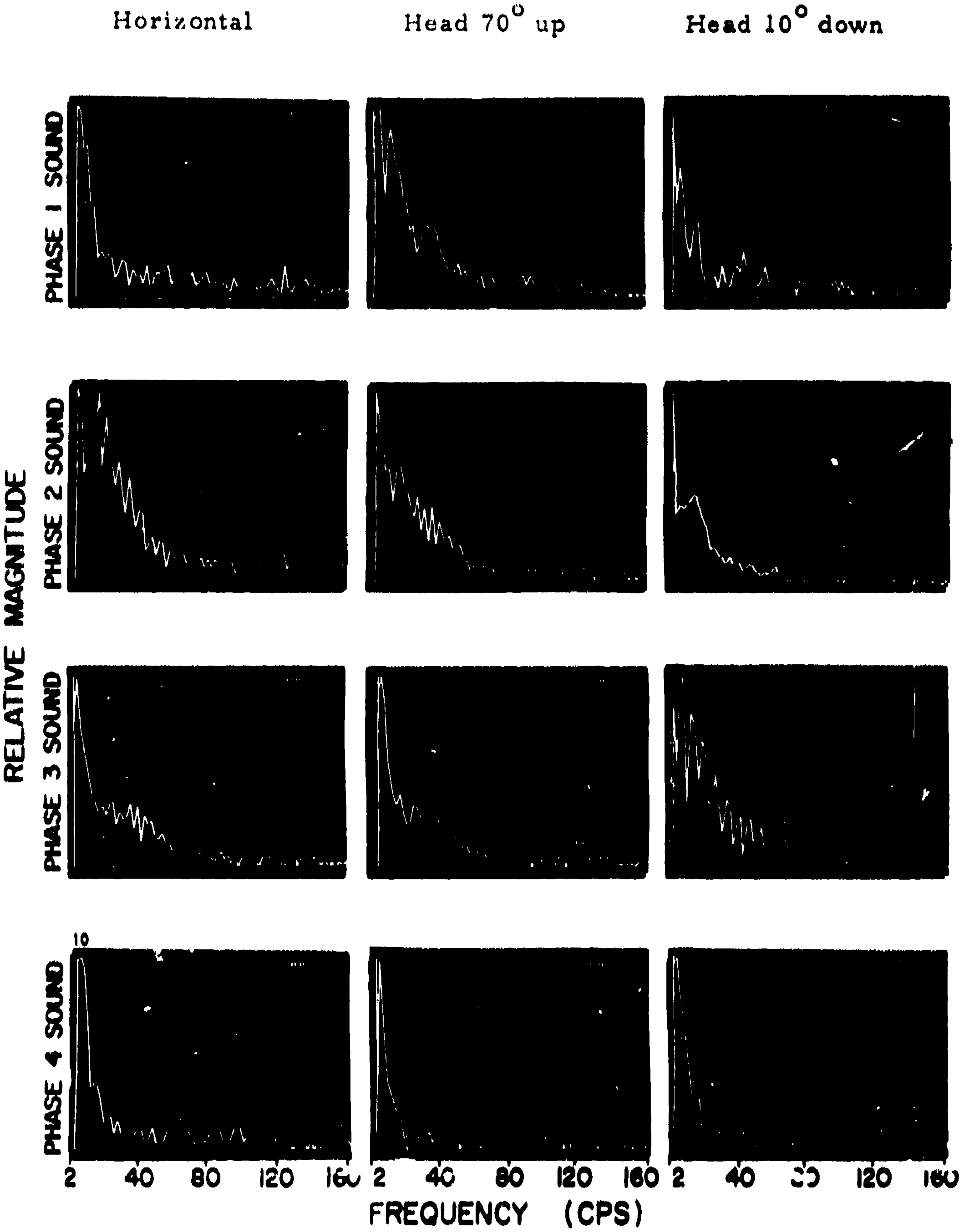

FIGURE 14

Normalized average Fourier transforms of Korotkov sounds of subject 5 obtained during three tilt-table maneuvers.

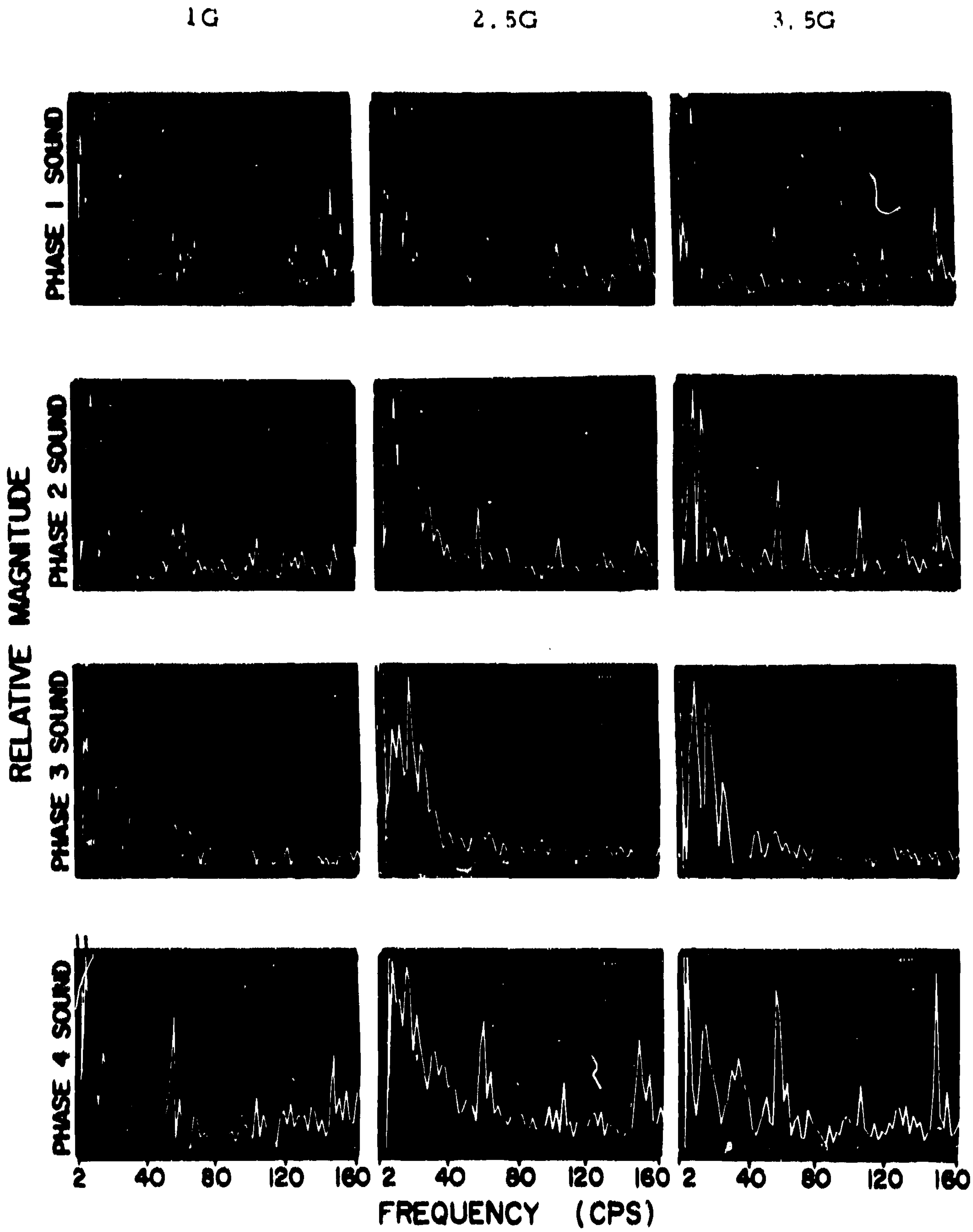

FIGURE 15

Normalized average Fourier transforms of Korotkov sounds of subject 1 obtained during three centrifuge maneuvers.

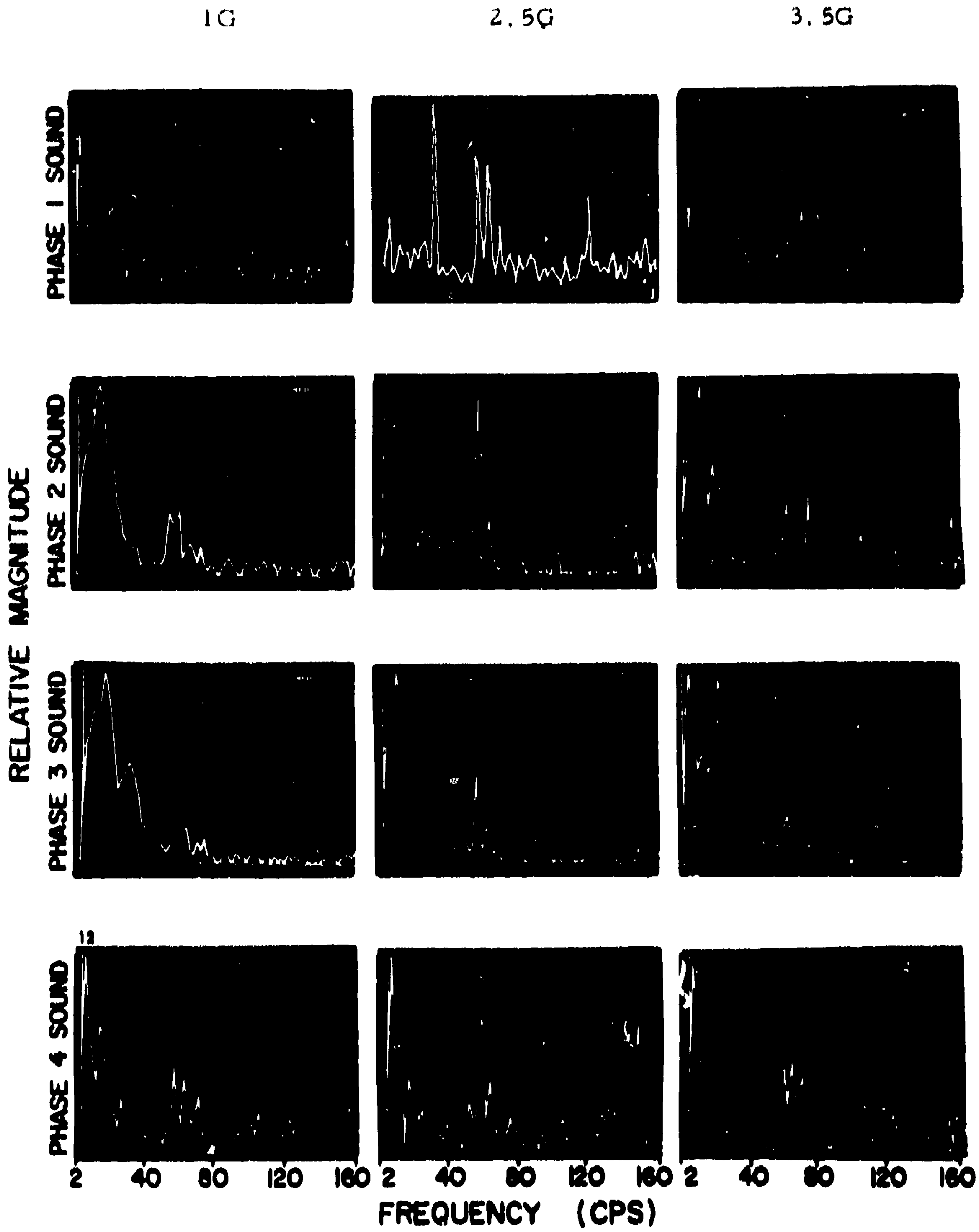

FIGURE 16

Normalized average Fourier transforms of Korotkov sounds of subject 2 obtained during three centrifuge maneuvers.

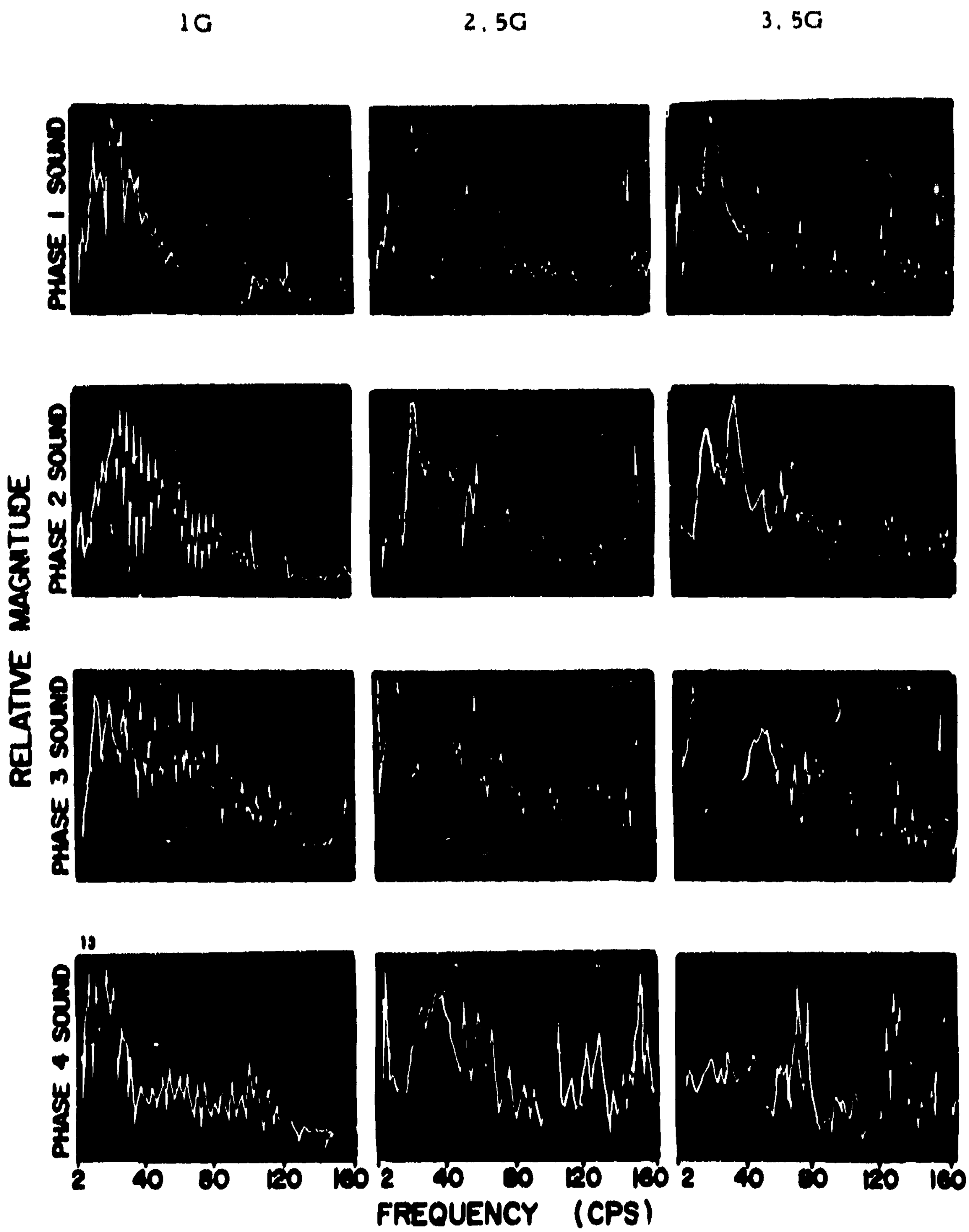

FIGURE 17

Normalized average Fourier transforms of Korotkov sounds of subject 3 obtained during three centrifuge maneuvers.

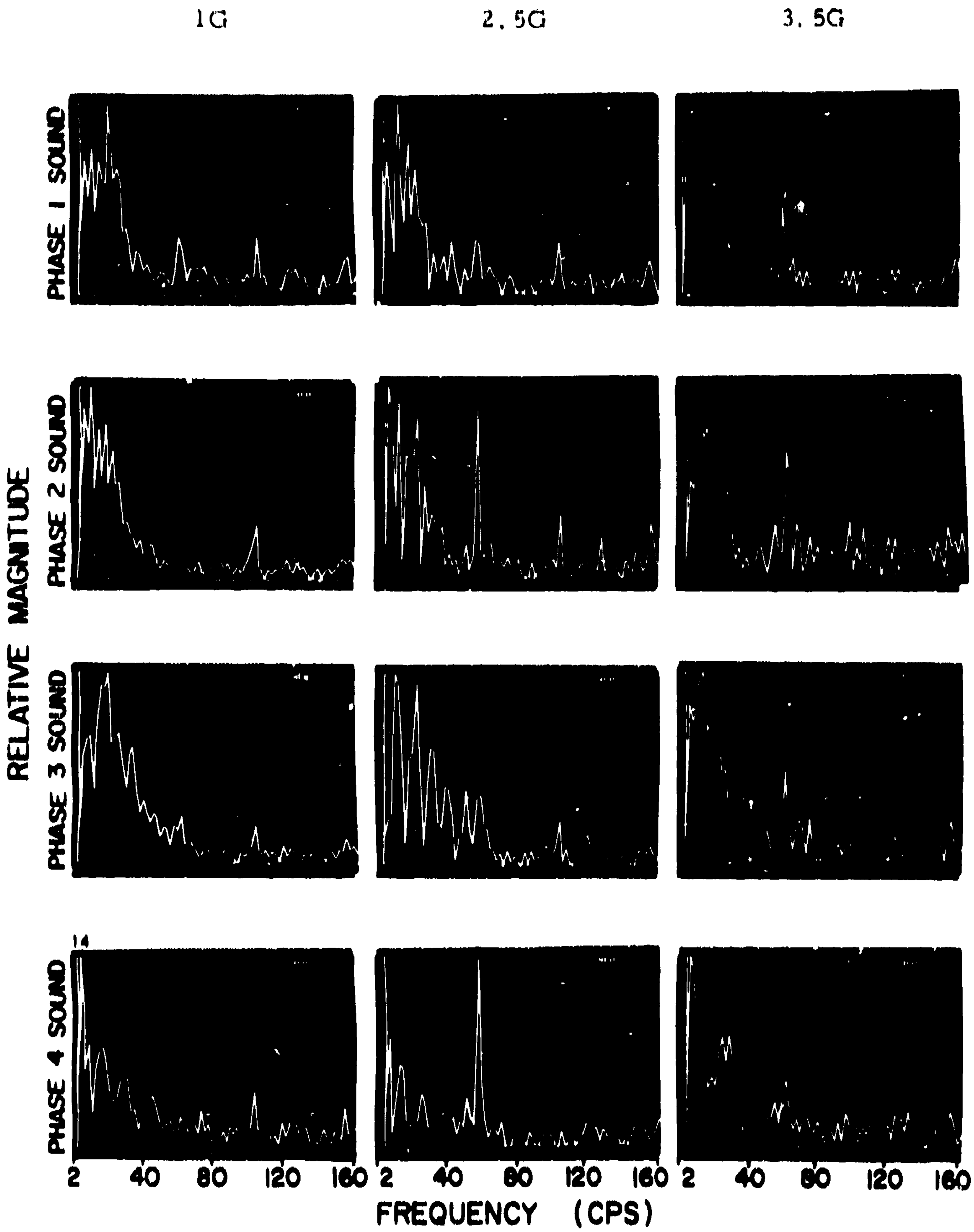

FIGURE 18

Normalized average Fourier transforms of Korotkov sounds of subject 4 obtained during three centrifuge maneuvers.

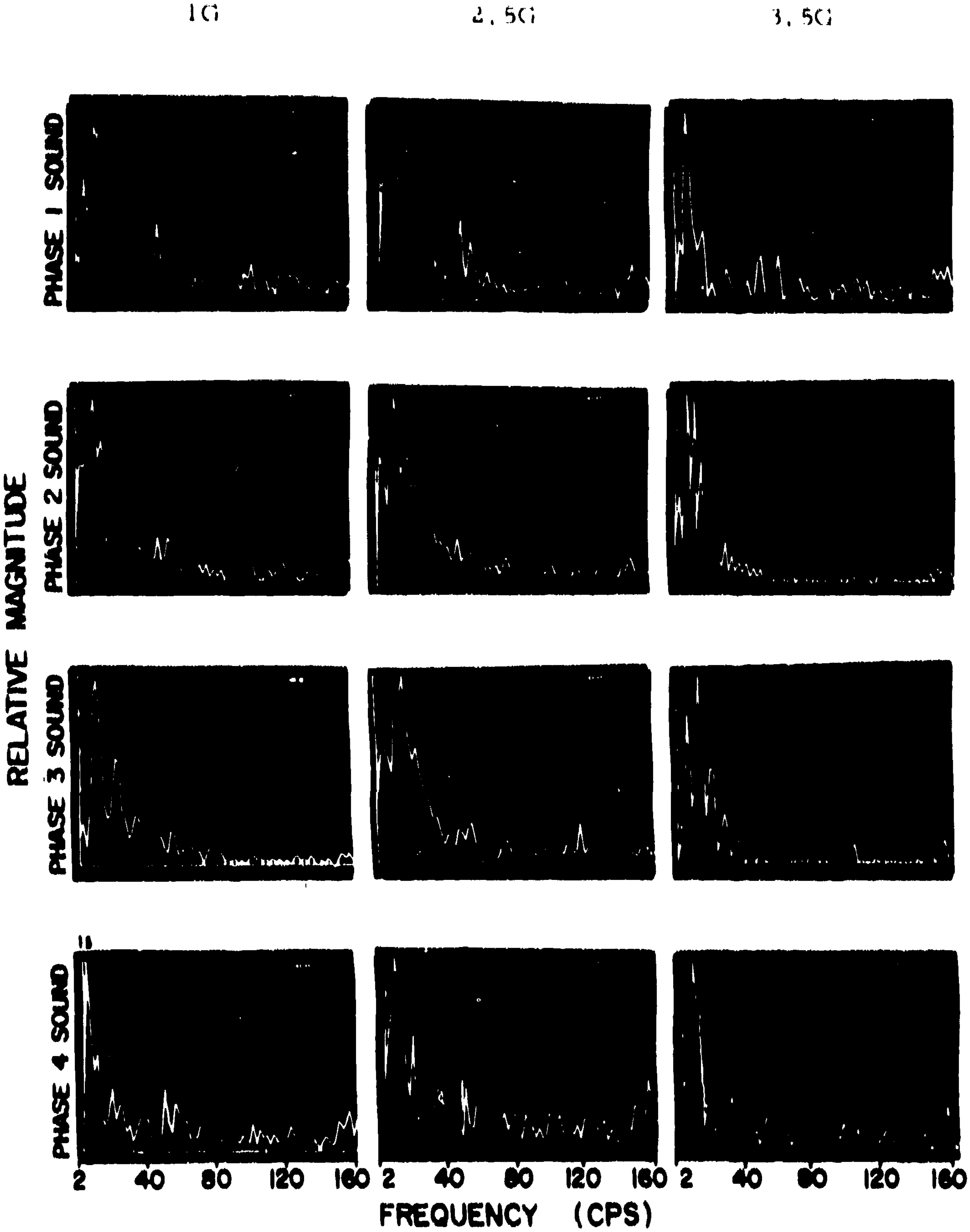

FIGURE 10

Normalized average Fourier transforms of Korotkov sounds of subject 5 obtained during three centrifuge maneuvers.

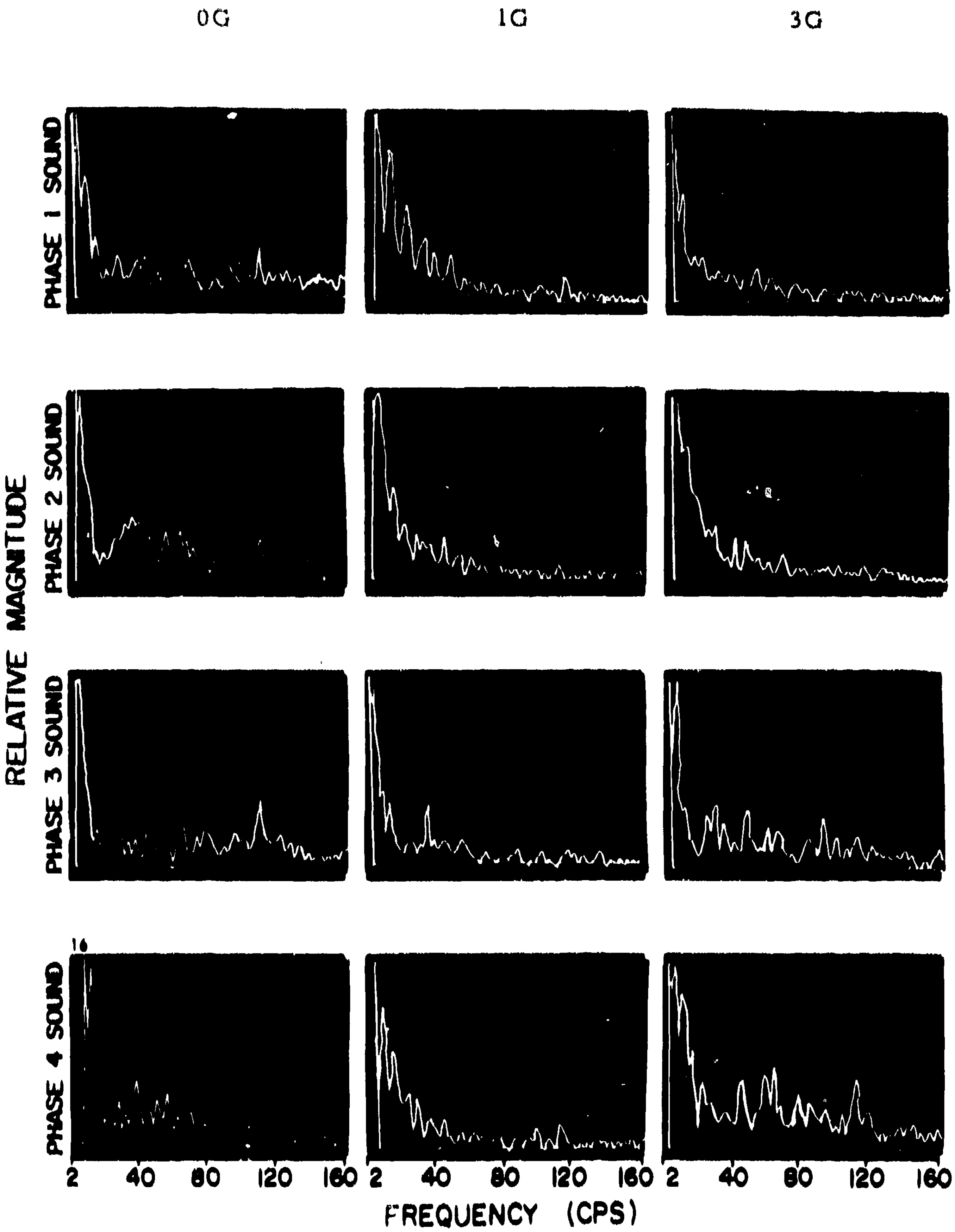

FIGURE 20

Normalized average Fourier transforms of Korotkov sounds of subject 1 obtained during three flight maneuvers in NF-100 aircraft.

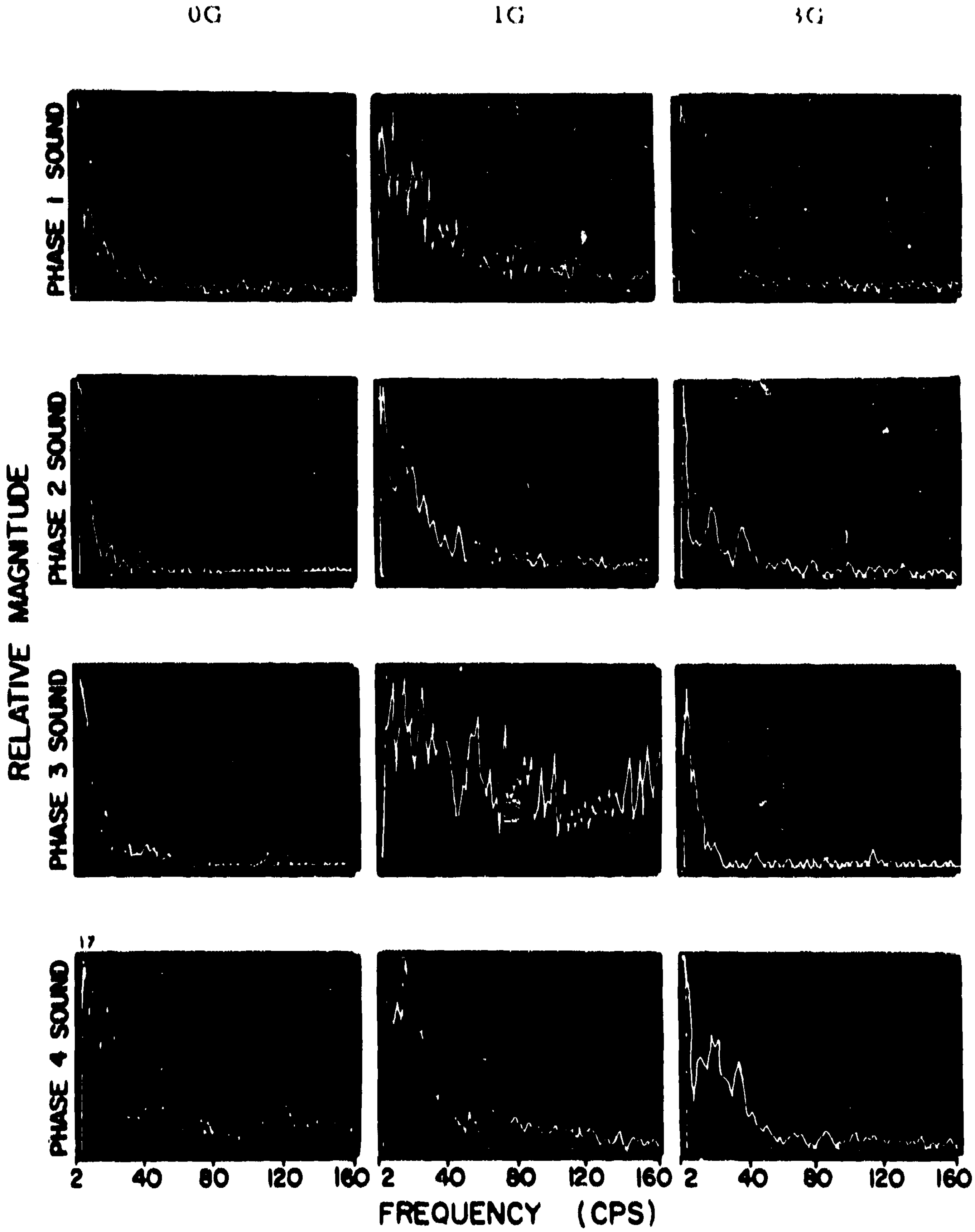

FIGURE 21

Normalized average Fourier transforms of Korotkov sounds of subject 2 obtained during three flight maneuvers in NF-100 aircraft.

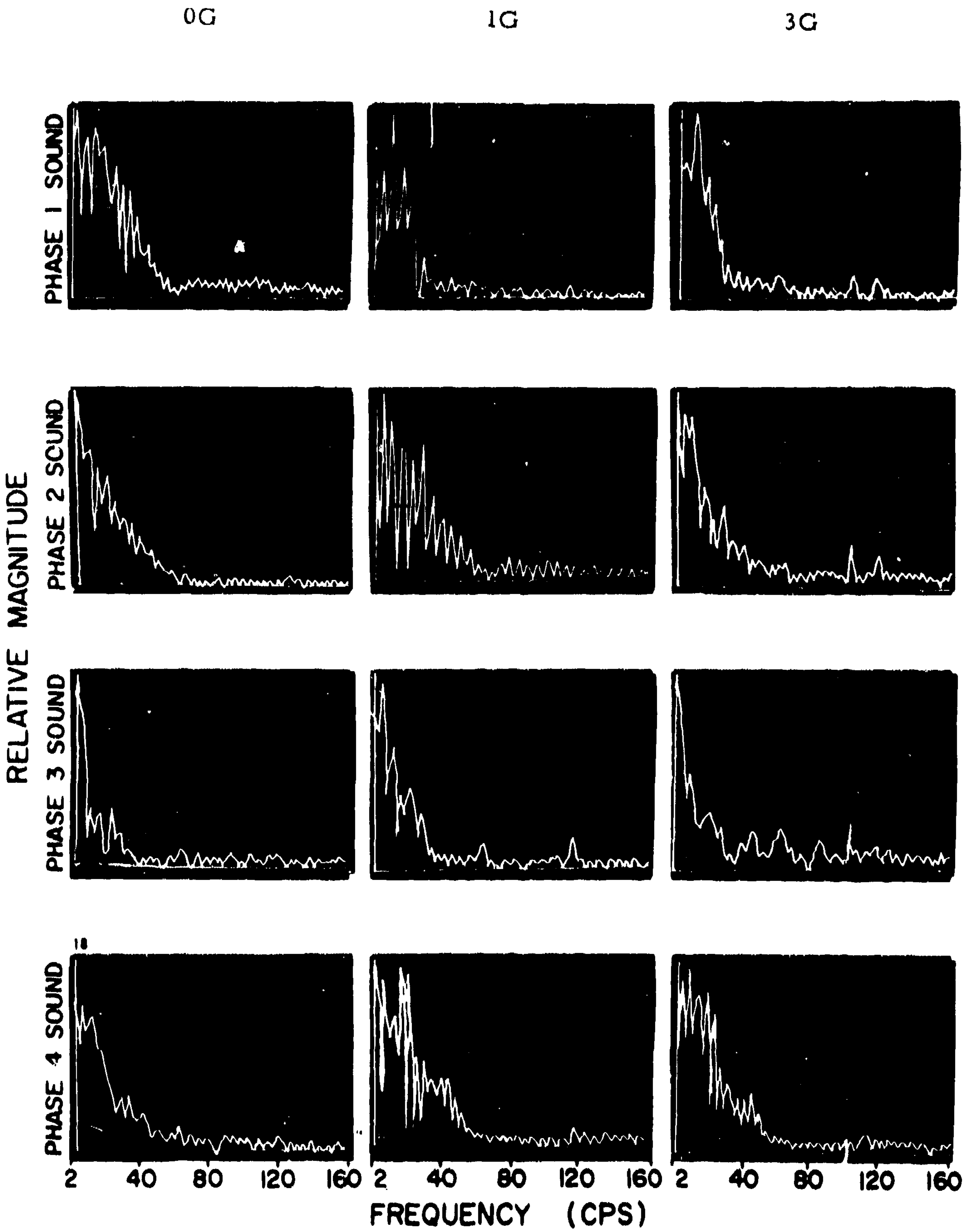

FIGURE 22

Normalized average Fourier transforms of Korotkov sounds of subject 3 obtained during three flight maneuvers in NF-100 aircraft.

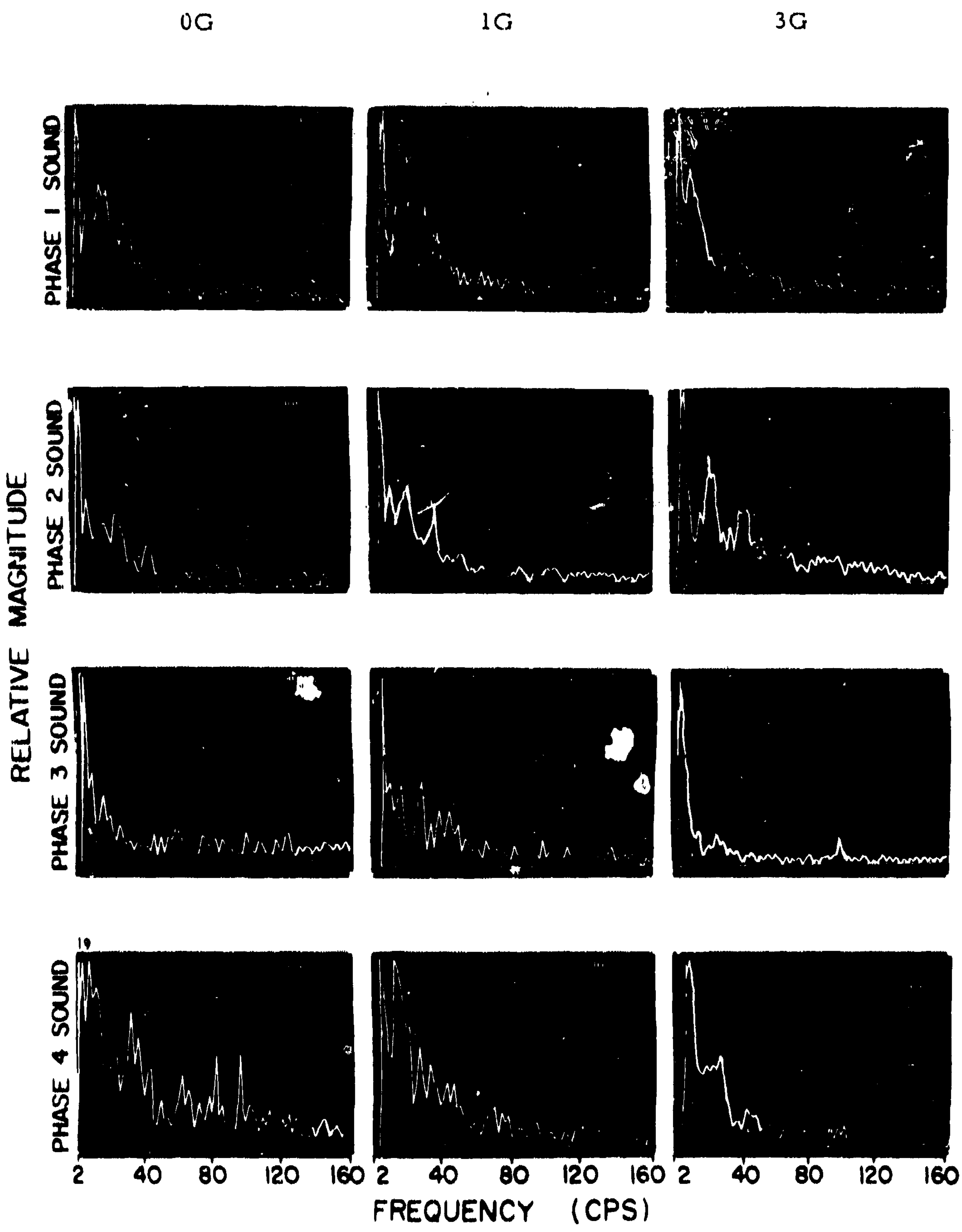

FIGURE 23

Normalized average Fourier transforms of Korotkov sounds of subject 4 obtained during three flight maneuvers in NF-100 aircraft.

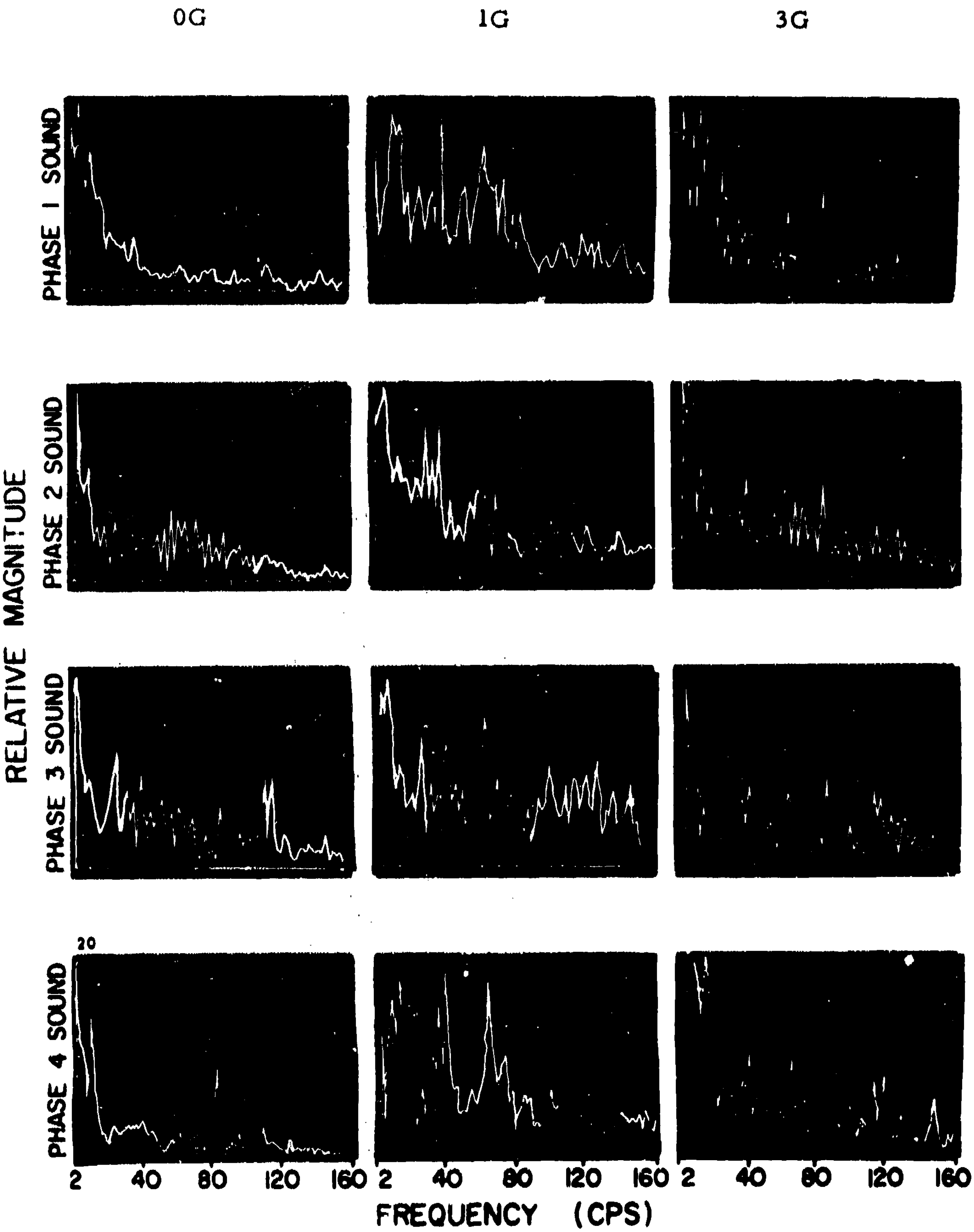

FIGURE 24

Normalized average Fourier transforms of Korotkov sounds of subject 5 obtained during three flight maneuvers in NF-100 aircraft.

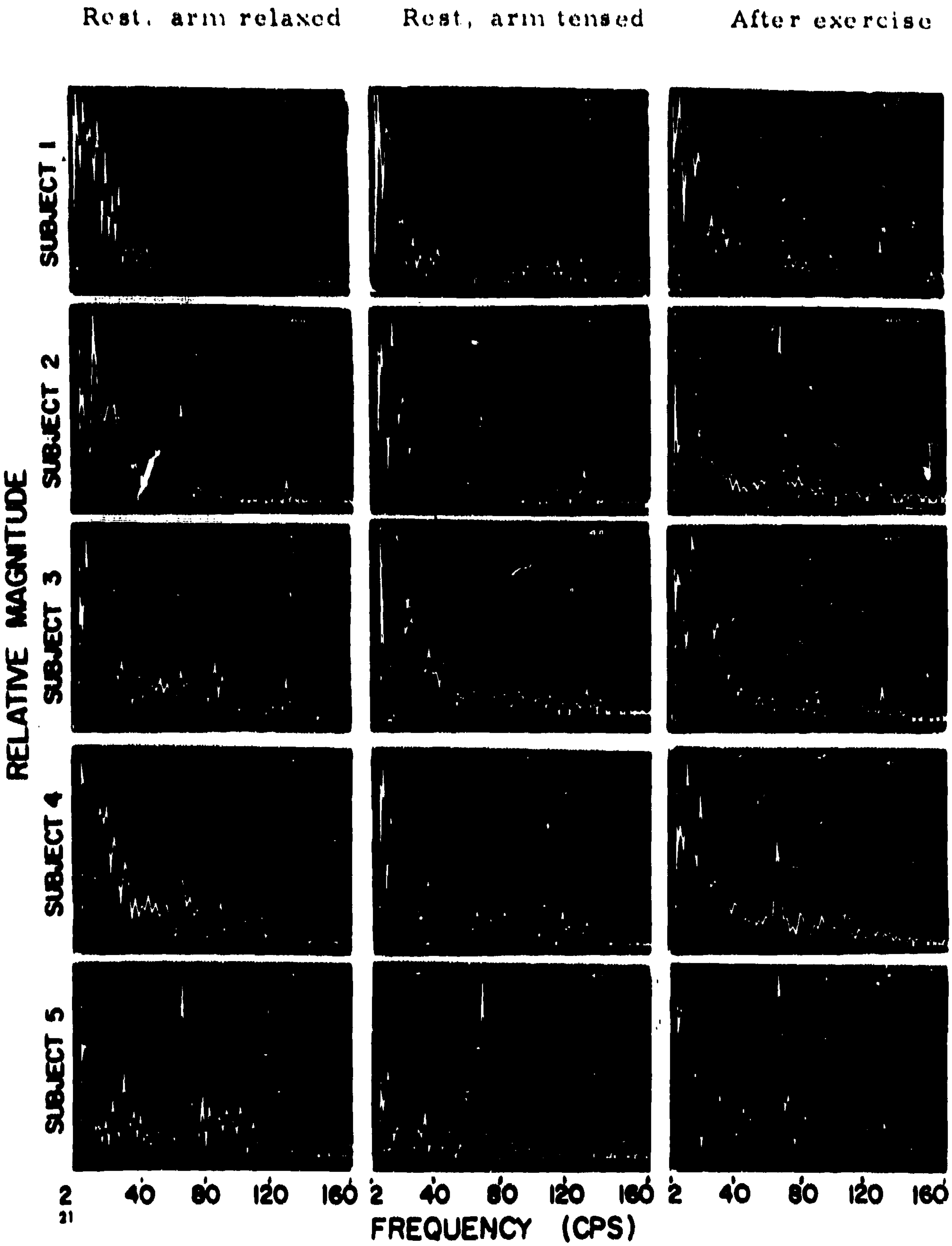

FIGURE 25

Normalized average Fourier transforms of phase 1 Korotkov sounds of five subjects obtained during three rest/exercise maneuvers.

Figures 25 to 40: *Vertical columns allow subject-to-subject comparison of the frequency distribution of the sound energy for each maneuver; horizontal rows allow maneuver-to-maneuver comparison for each of the five subjects.*

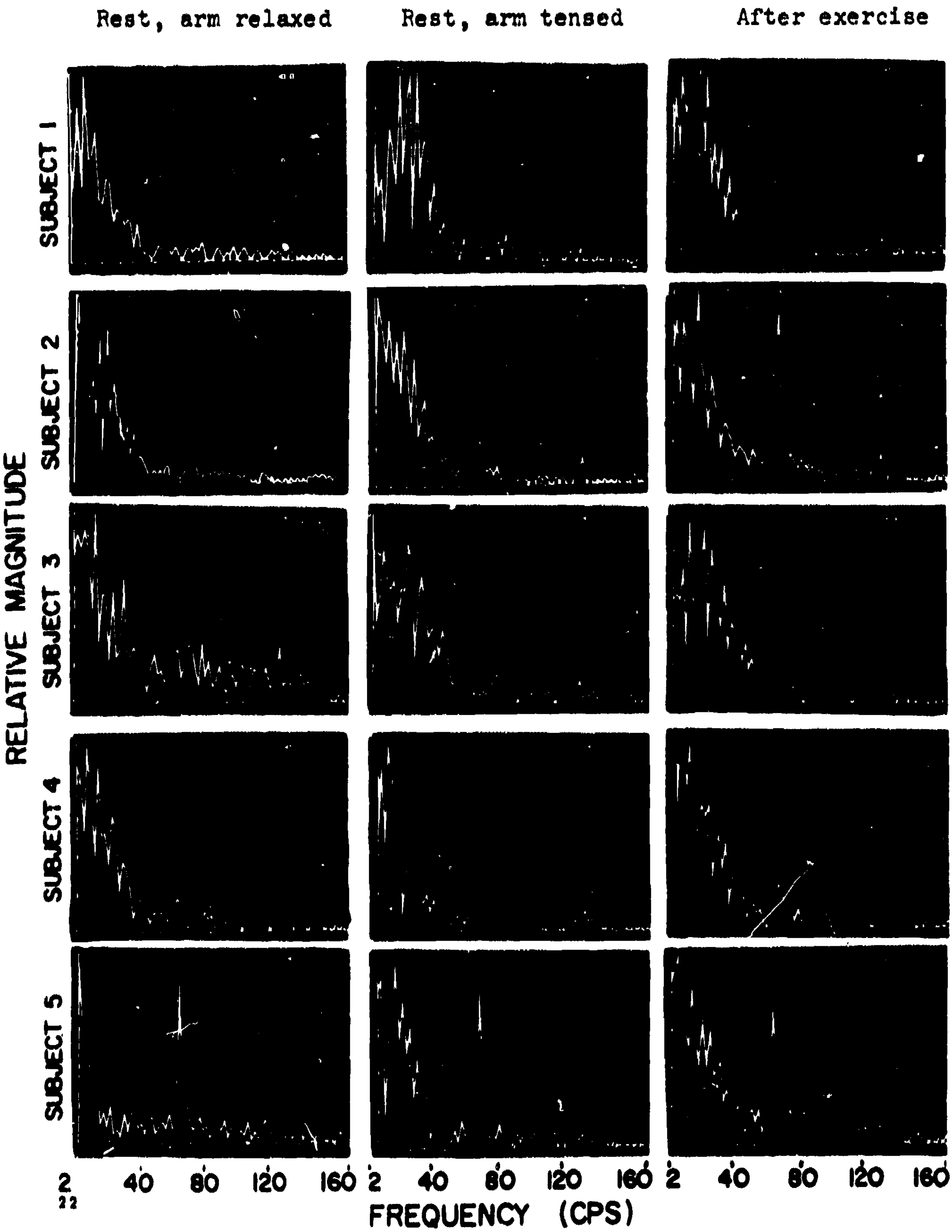

FIGURE 26

Normalized average Fourier transforms of phase 2 Korotkov sounds of five subjects obtained during three rest/exercise maneuvers.

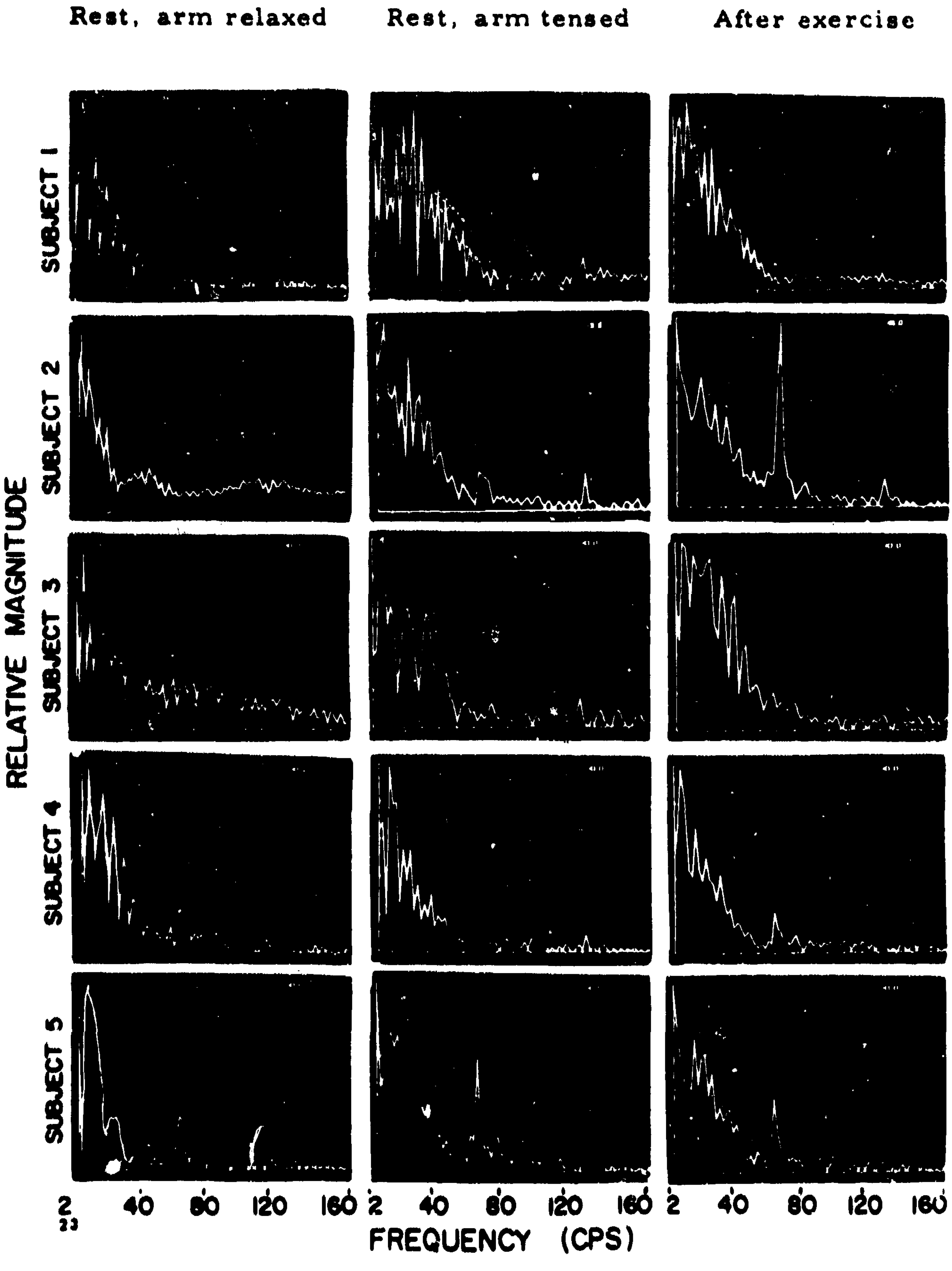

FIGURE 27

Normalized average Fourier transforms of phase 3 Korotkov sounds of five subjects obtained during three rest/exercise maneuvers.

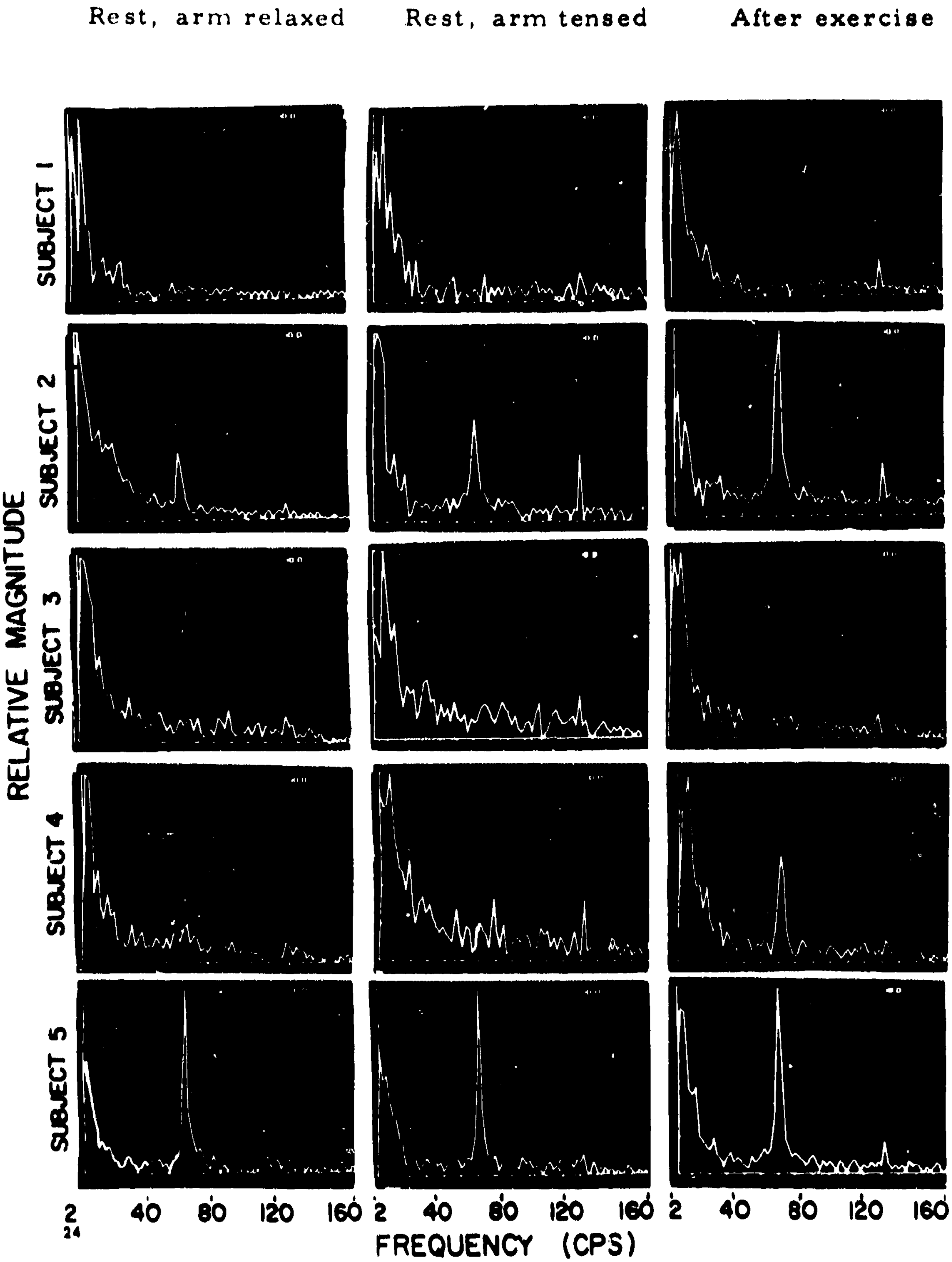

FIGURE 28

Normalized average Fourier transforms of phase 4 Korotkov sounds of five subjects obtained during three rest/exercise maneuvers.

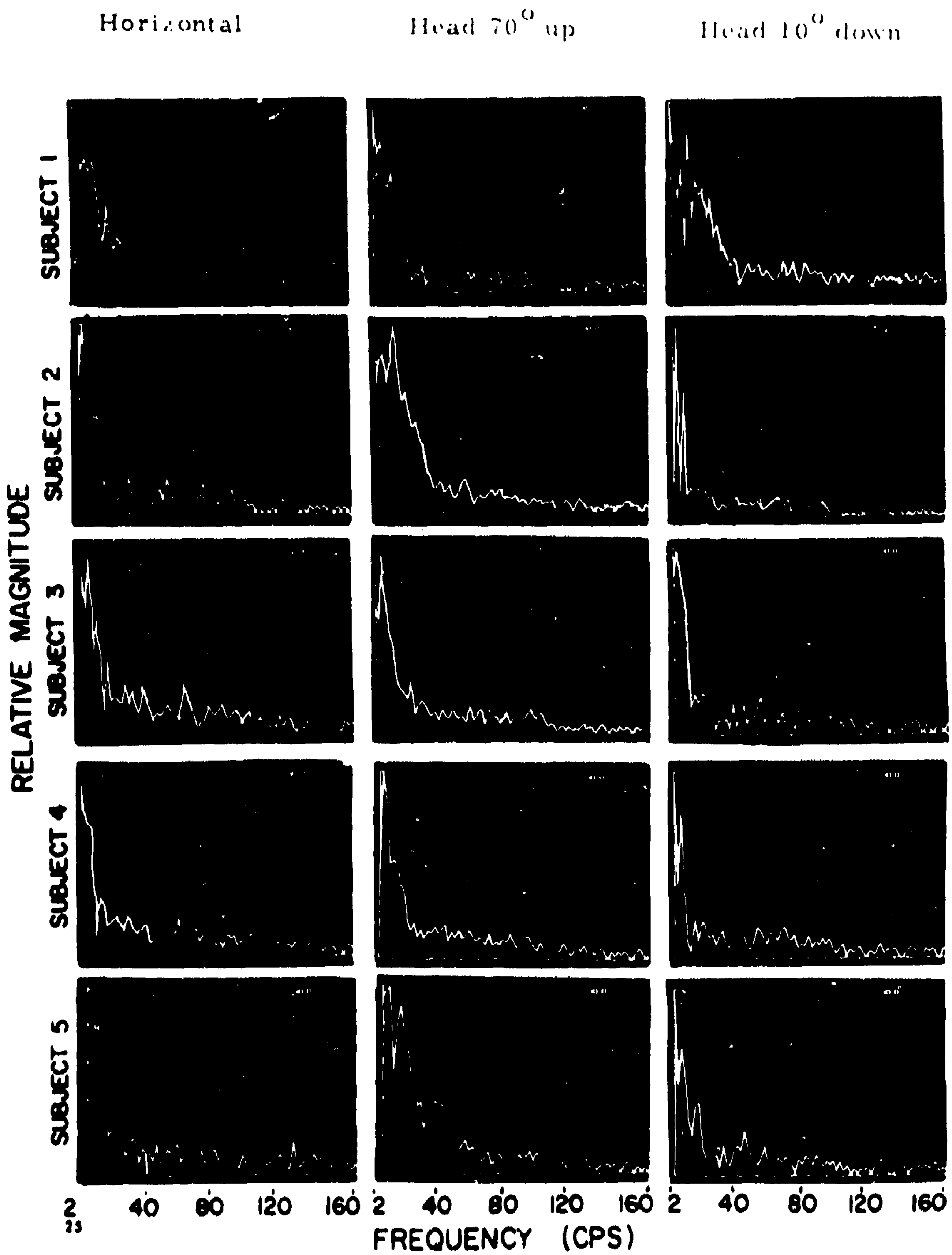

FIGURE 29

Normalized average Fourier transforms of phase I Korotkov sounds of five subjects obtained during three tilt-table maneuvers.

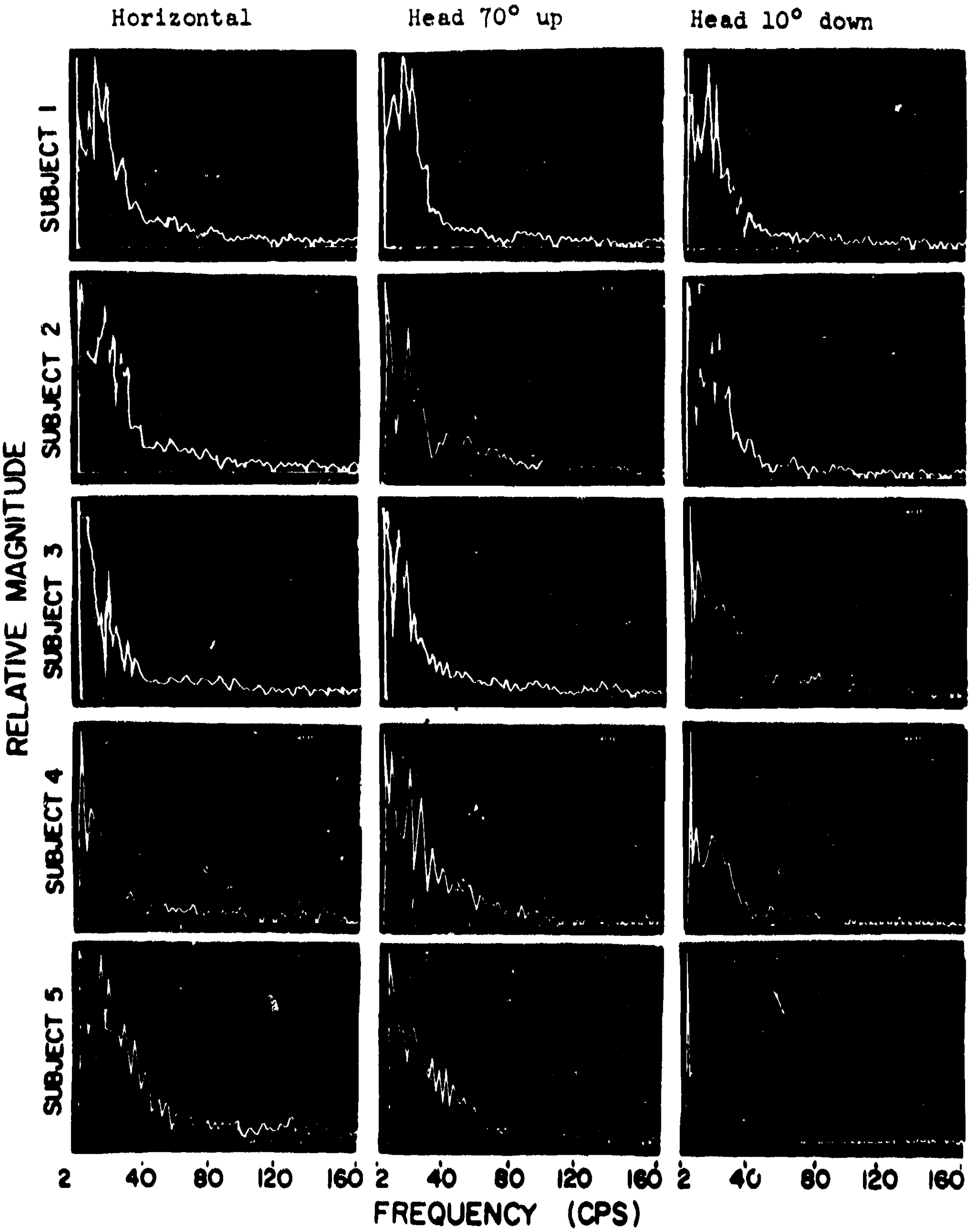

FIGURE 30

Normalized average Fourier transforms of phase 2 Korotkov sounds of five subjects obtained during three tilt-table maneuvers.

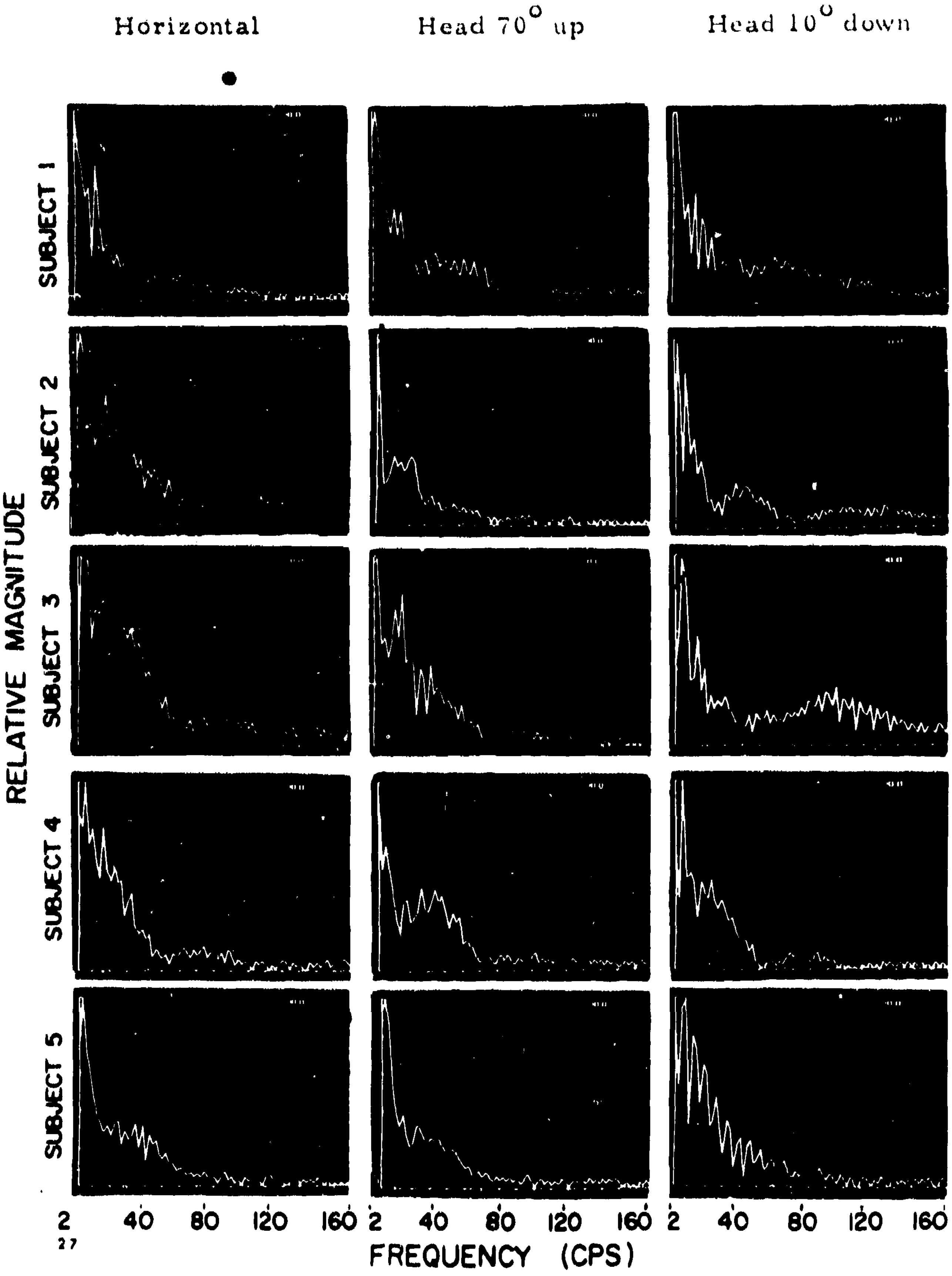

FIGURE 31

Normalized average Fourier transforms of phase 3 Korotkov sounds of five subjects obtained during three tilt-table maneuvers.

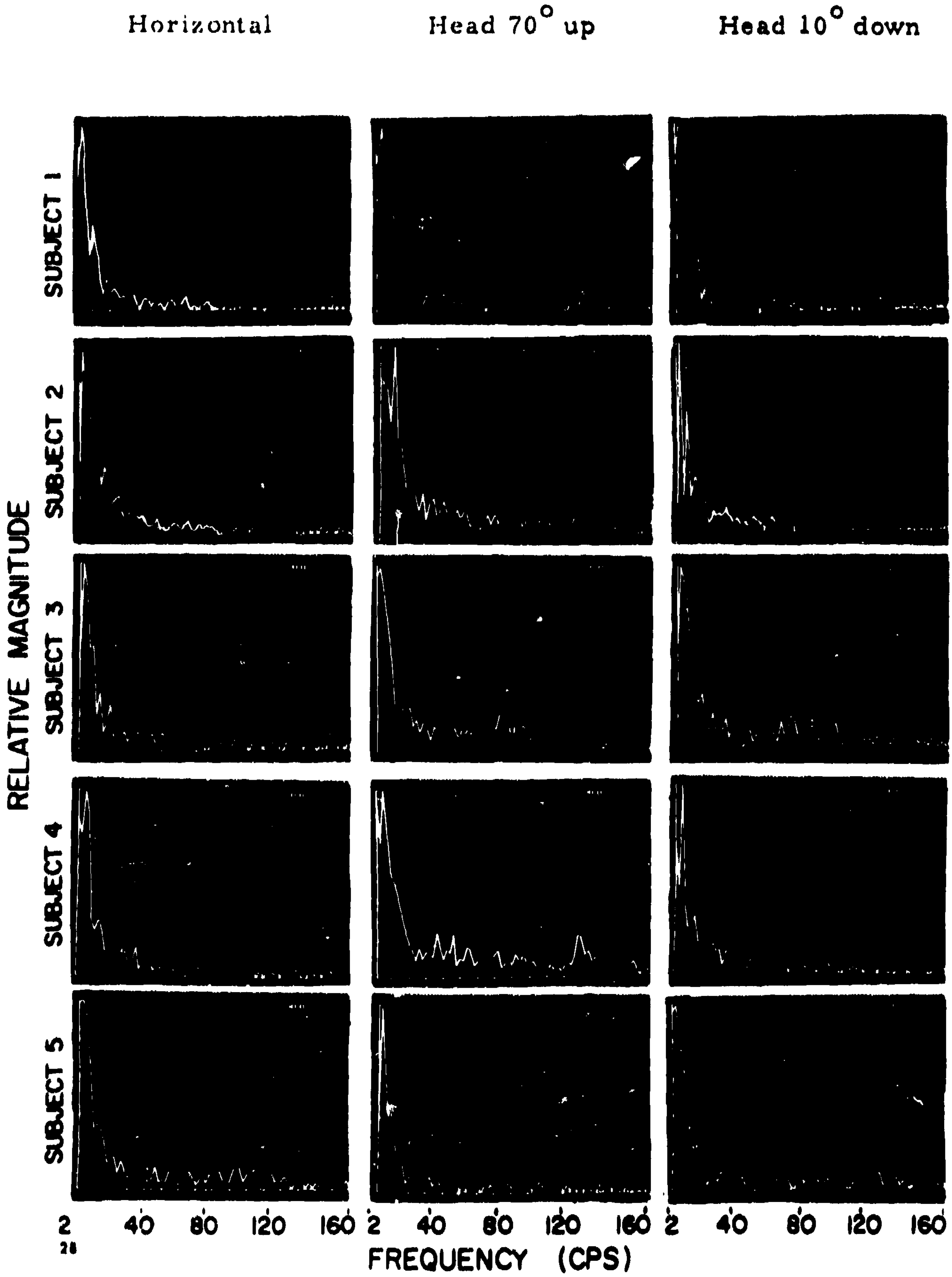

FIGURE 32

Normalized average Fourier transforms of phase 4 Korotkov sounds of five subjects obtained during three tilt-table maneuvers.

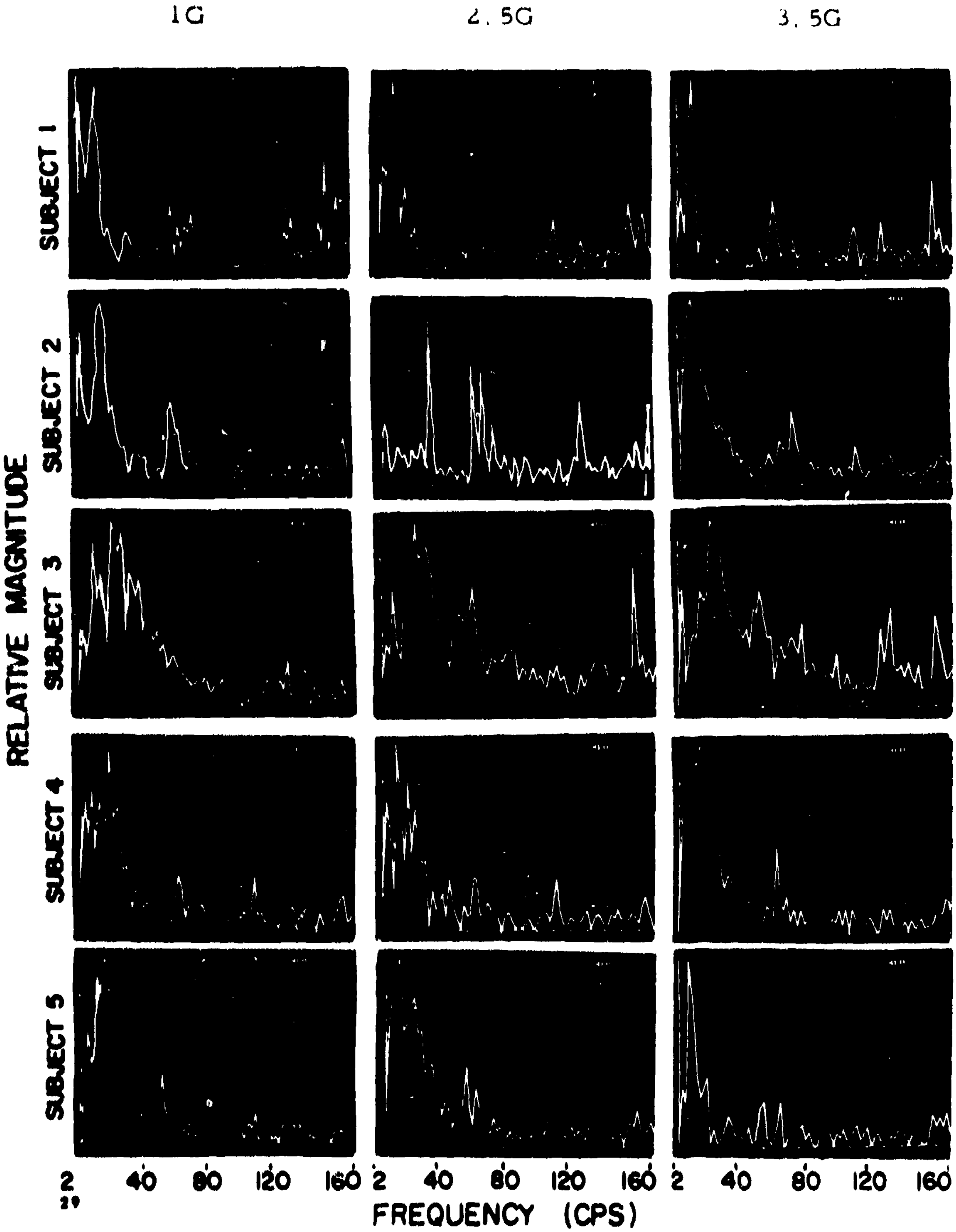

FIGURE 33

Normalized average Fourier transforms of phase 1 Korotkov sounds of five subjects obtained during three centrifuge maneuvers.

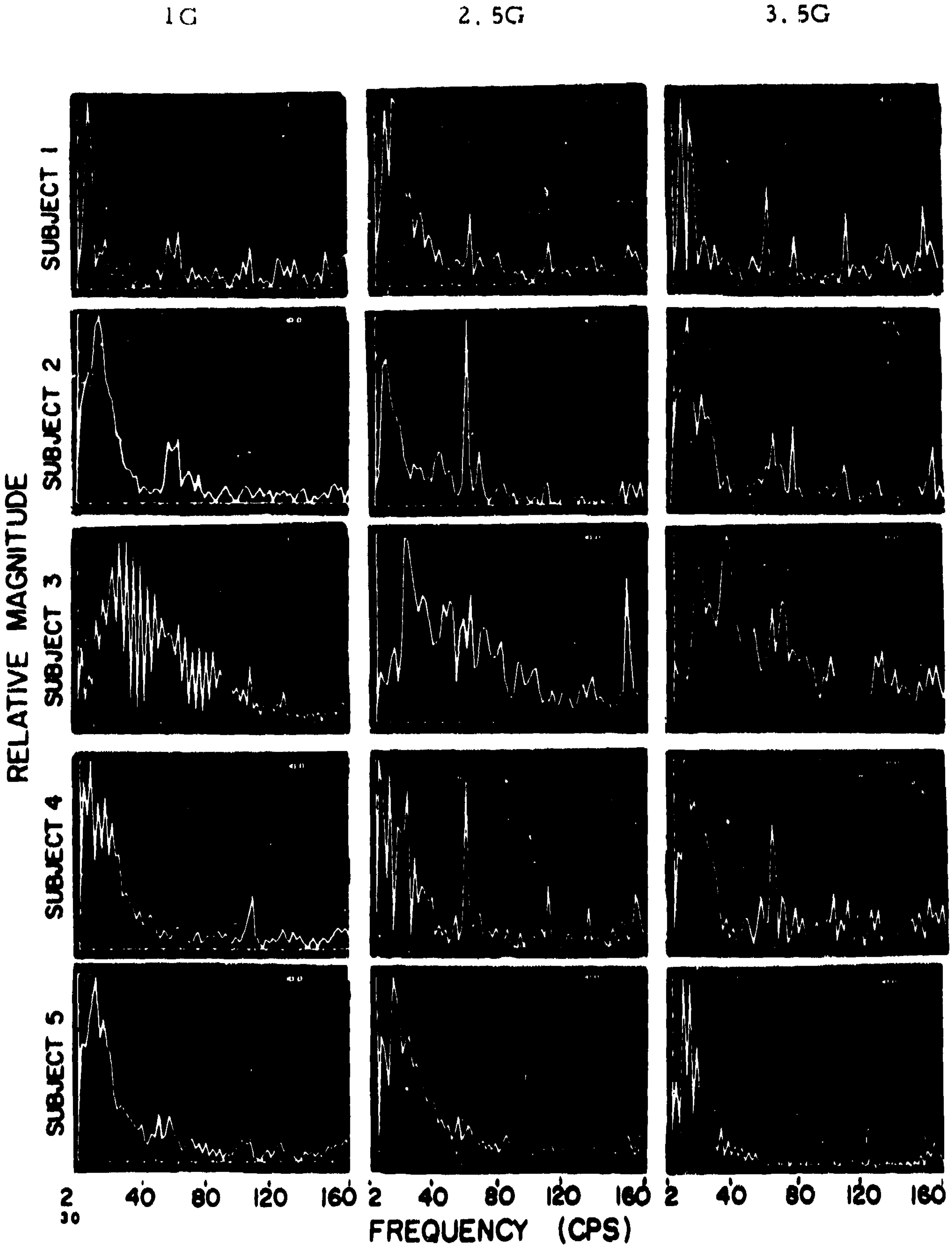

FIGURE 34

Normalized average Fourier transforms of phase 2 Korotkov sounds of five subjects obtained during three centrifuge maneuvers.

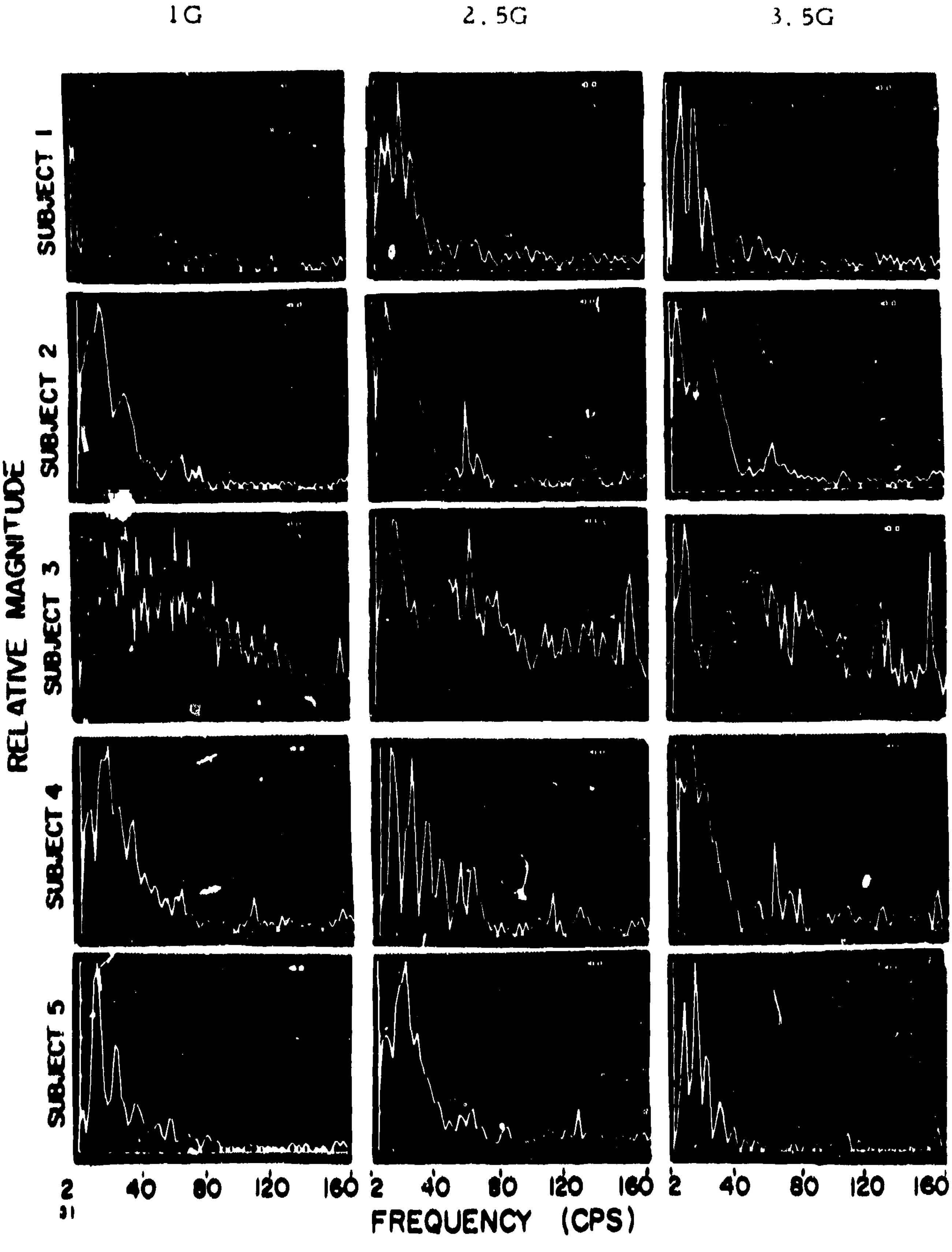

FIGURE 55

Normalized average Fourier transforms of phase 3 Korotkov sounds of five subjects obtained during three centrifuge maneuvers.

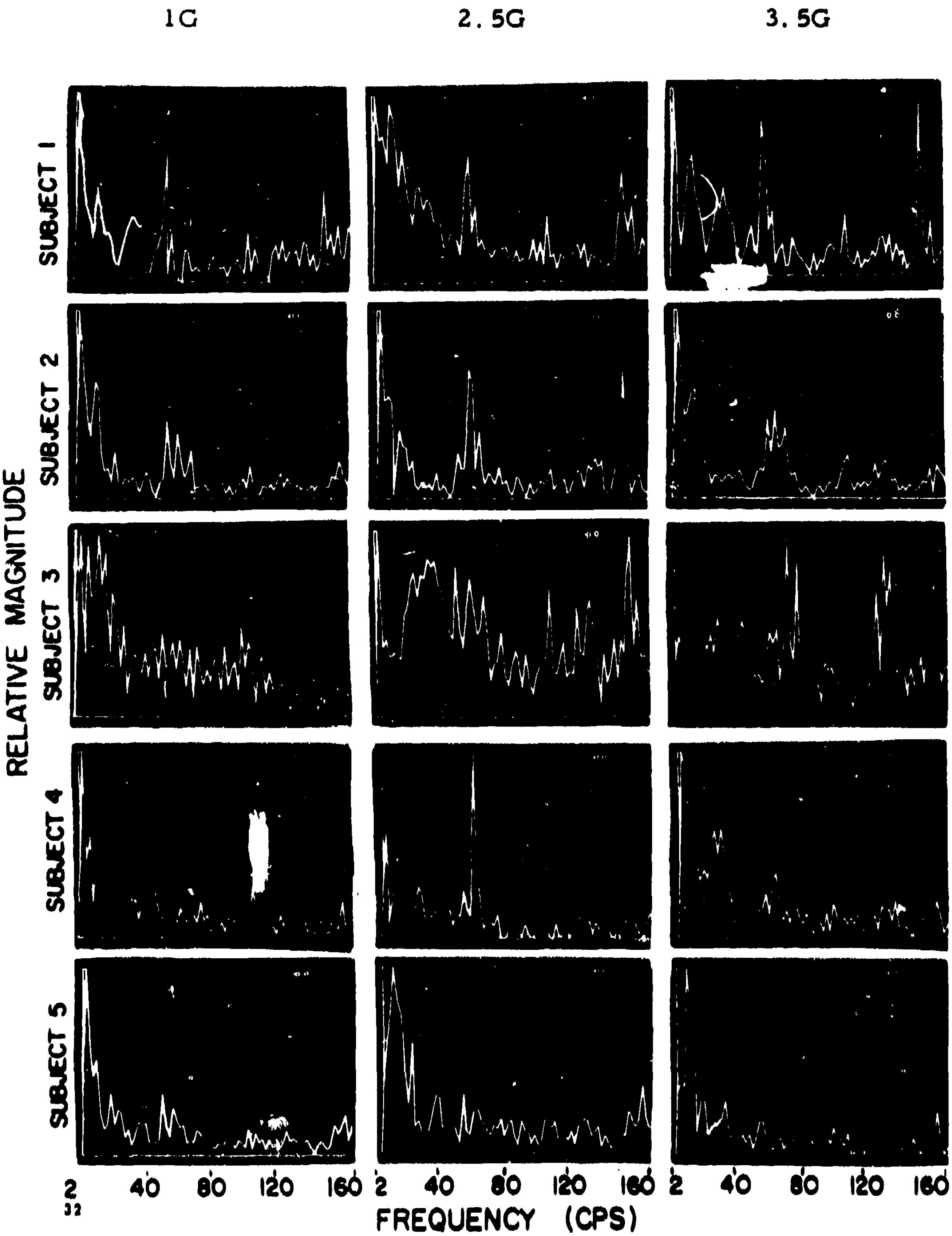

FIGURE 30

Normalized average Fourier transforms of phase 4 Korotkov sounds of five subjects obtained during three centrifuge maneuvers.

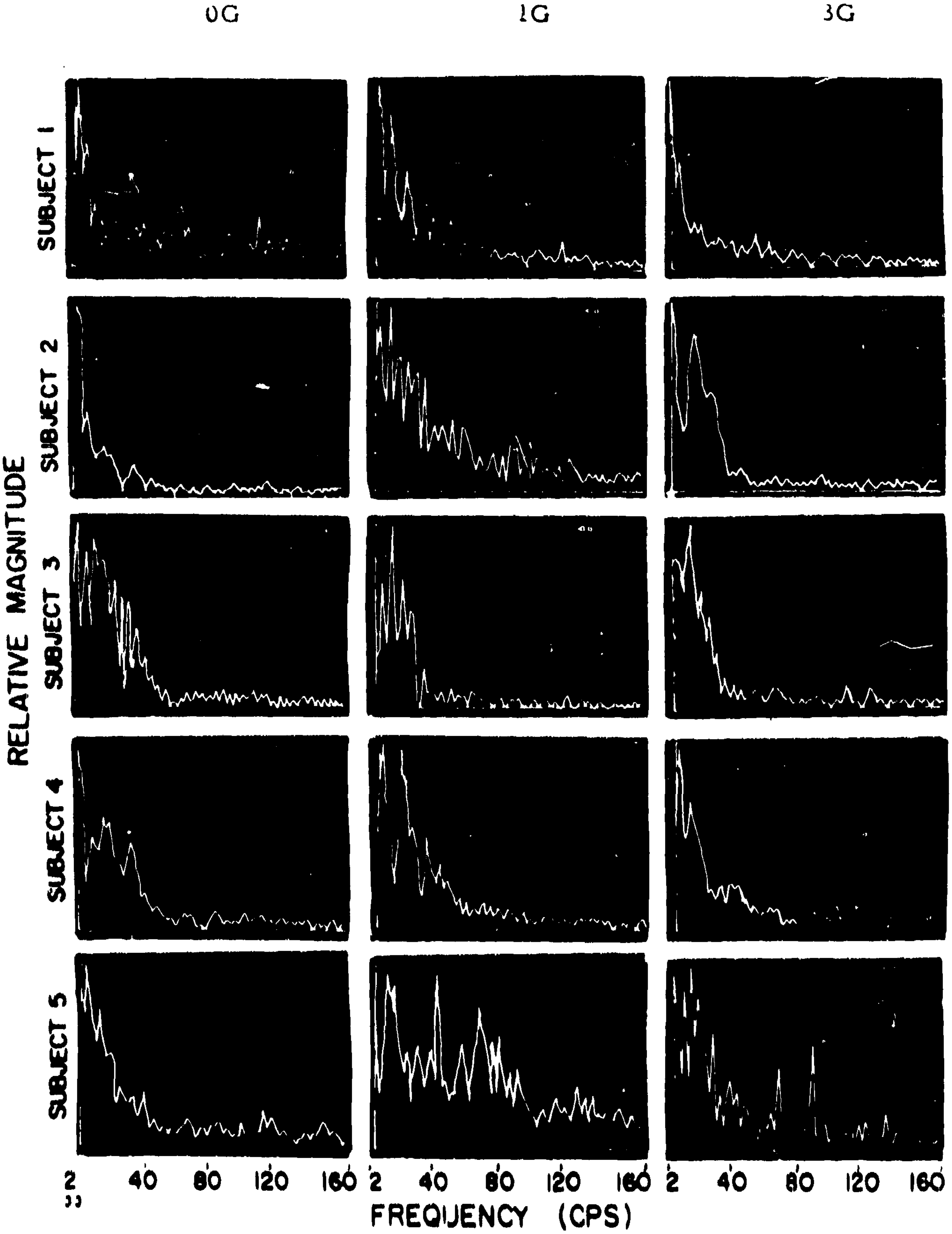

FIGURE 37

Normalized average Fourier transforms of phase I Korotkov sounds of five subjects obtained during three flight maneuvers in NF-100 aircraft.

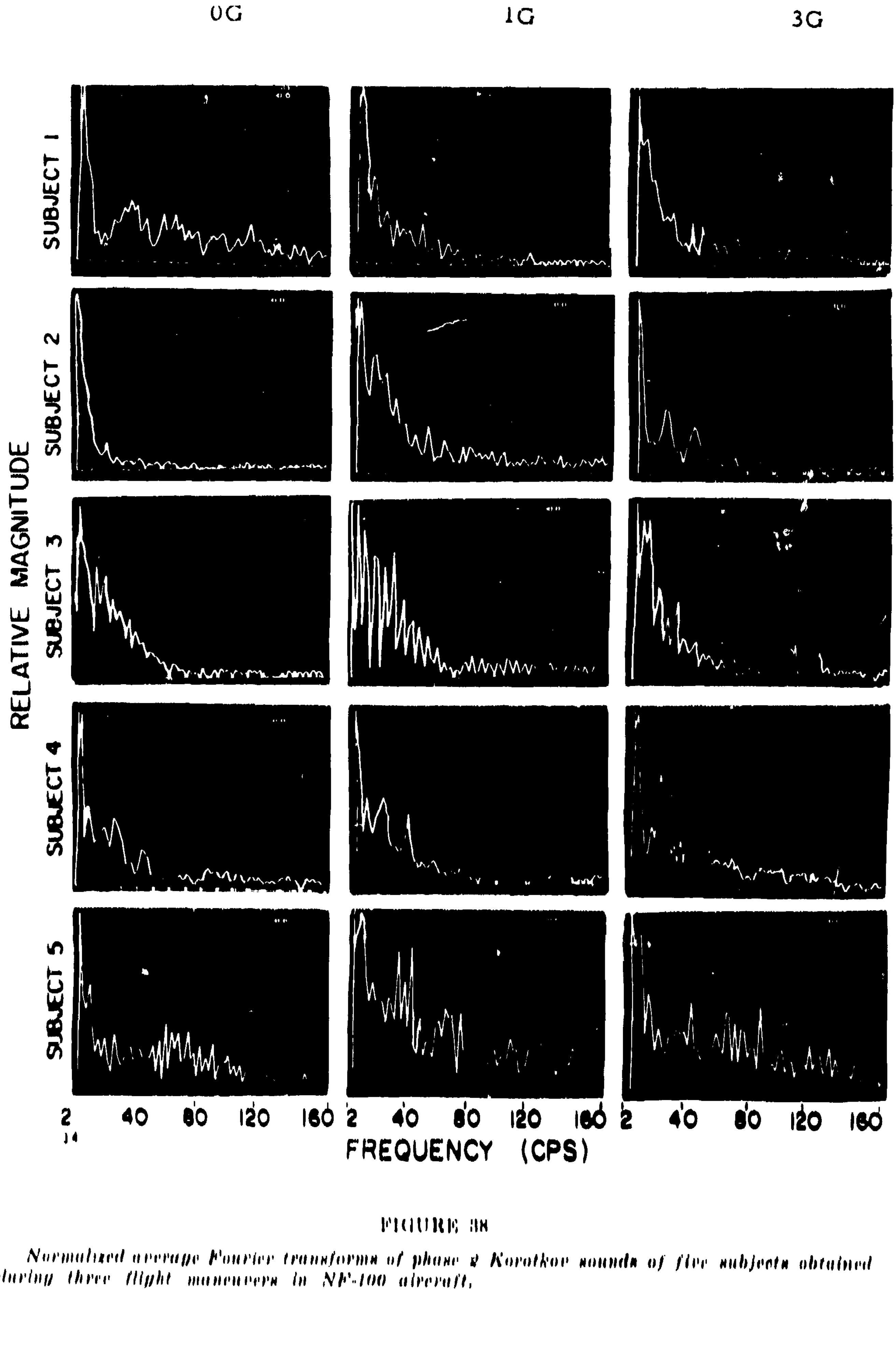

FIGURE 38

Normalized average Fourier transforms of phase 2 Korotkov sounds of five subjects obtained during three flight maneuvers in NF-100 aircraft.

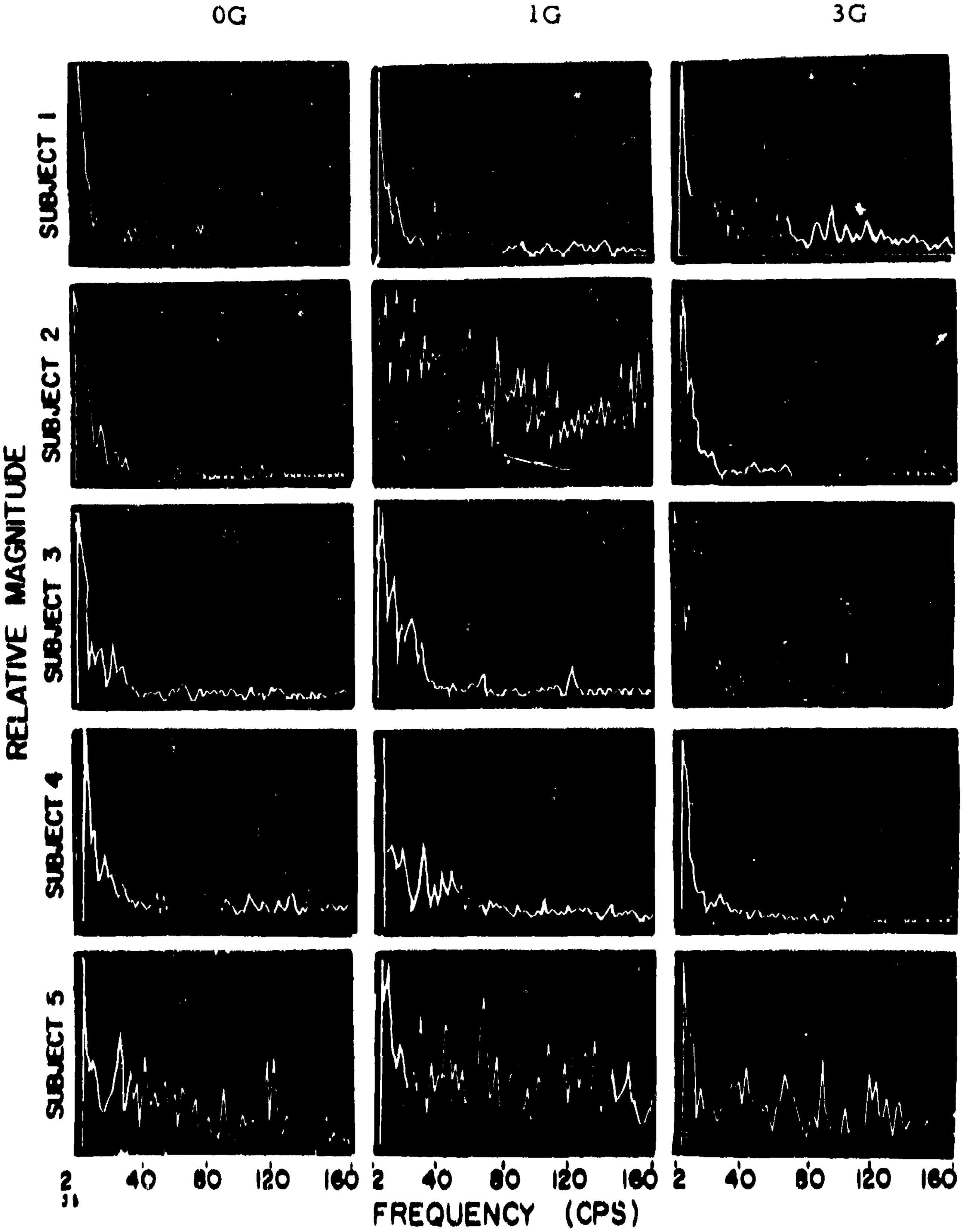

FIGURE 30

Normalized average Fourier transforms of phase 3 Korotkov sounds of five subjects obtained during three flight maneuvers in NF-100 aircraft.

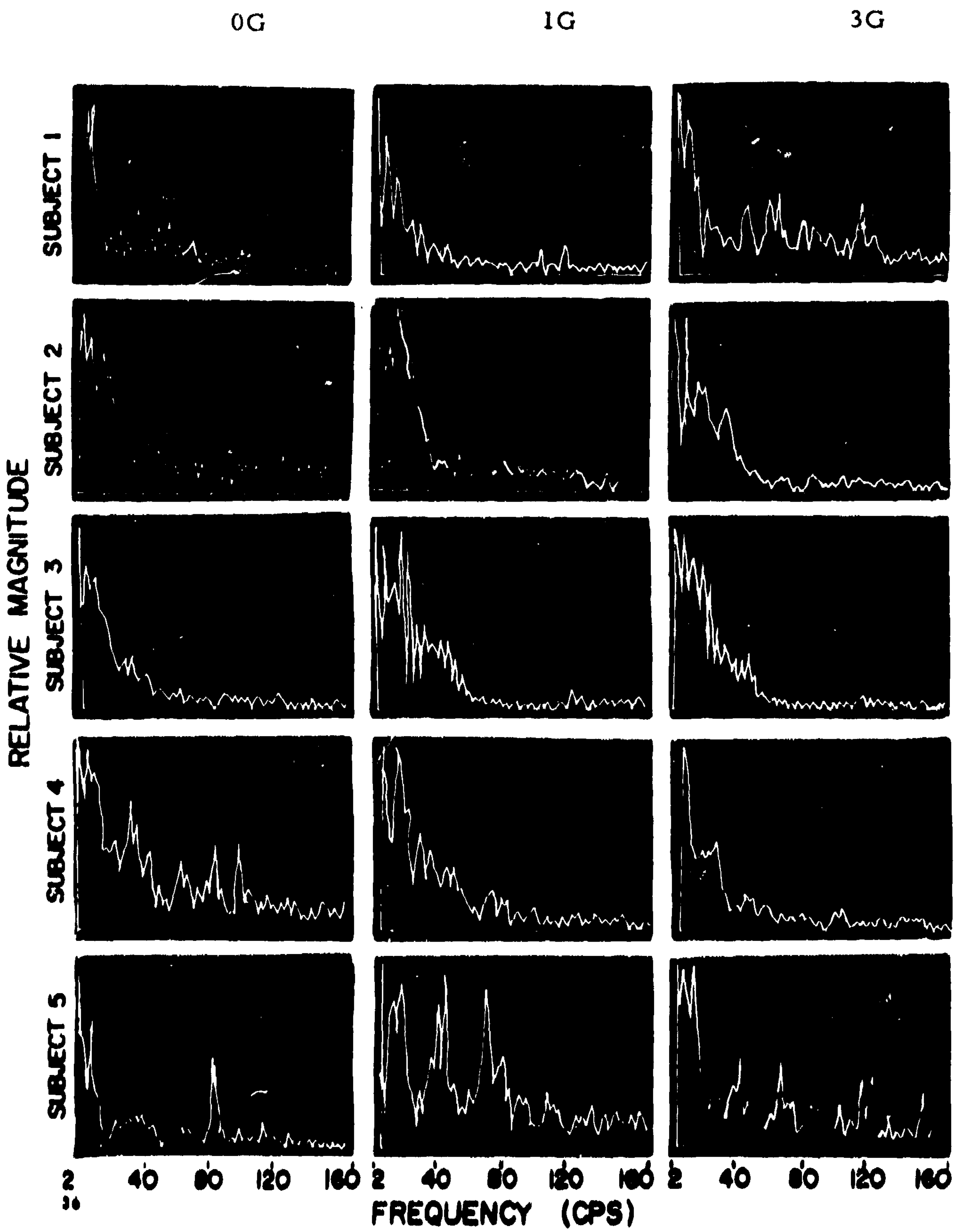

FIGURE 40

Normalized average Fourier transforms of phase 4 Korotkov sounds of five subjects obtained during three flight maneuvers in NF-100 aircraft.

of sounds. Therefore, it might be concluded from the data in this study that recognition of Korotkov sounds could be achieved more reliably by locating a single-filter center frequency at a very low frequency, say 10 cps, where energy always occurs. Use of a high-detection threshold for this single, low-frequency filter might well prove more reliable than a coincidence technic with several low-threshold filters placed in the higher frequency range where components occur *on the average*.

VI. RECOMMENDATIONS

The results determined in this study do not represent an end but a strong beginning toward a complete description of Korotkov sound characteristics. The frequency analysis technic employed reveals a "fingerprint" which is useful for devising filtering methods of recognizing Korotkov sounds. This study has also shown, however, that a more exacting "fingerprint" can be determined by extending efforts to analyze all three of the parameters of a transient—frequency, amplitude, and time (fig. 2). Although this study has shown the frequency spectrums of the 4 Korotkov sound phases to be grossly similar, figure 2 shows marked differences in the waveforms of the recorded Korotkov sounds. Evidently, then, the time sequence of occurrence of the various frequency components is noticeably different for each of the 4 Korotkov sound phases.

It is recommended, therefore, that future analysis efforts use computer technics which can also provide time-domain information. Such analysis technics, although necessarily quite sophisticated, will produce a more precise fingerprint of Korotkov sounds. With this added information, it is reasonable to presume that a simple and more reliable device can be devised for recognizing Korotkov sounds.

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13. ABSTRACT

The purpose of this investigation was to determine the frequency content of the sound signals (Korotkov sounds) obtained from the microphone located in the arm cuff of an automatic blood pressure measuring instrument. Korotkov sound recordings were made for five subjects in five experimental situations: rest, postexercise, passive tilting, centrifuge rides, and flights in NF-100 aircraft. The frequency analysis was performed by using a digital computer to obtain the Fourier transforms of the sound signals. The Fourier transforms were displayed on the computer oscilloscope and photographed. The photographs were then arranged in a number of rectangular arrays for convenient comparison of the frequency content of the Korotkov sounds as related to the several types of Korotkov sounds, experimental situations, and subjects.

Initial study of the 240 average Fourier transforms contained in these arrays indicates no readily observable common characteristics except that most of the sound energy is almost always located below 50 cps.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Biodynamics						
Korotkov blood pressure sounds						
Frequency analysis (blood pressure sounds)						
Fourier transform (blood pressure analysis)						
In-flight monitoring (blood pressure sounds)						
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