AM-66-16

THE AEROMEDICAL ASSESSMENT OF HUMAN SYSTOLIC AND DIASTOLIC BLOOD-PRESSURE TRANSIENTS WITHOUT DIRECT ARTERIAL PUNCTURE

Michael T. Lategola, Ph.D
Hiley Harrison
Charles Barnard

Approved by

J. Robert Dille

J. Robert Dille, M.D.
Chief, Civil Aeromedical Institute

Released by

P V Siegel MD

P. V. Siegel, M.D.
Federal Air Surgeon

May 1966

FEDERAL AVIATION AGENCY
Office of Aviation Medicine

THE AEROMEDICAL ASSESSMENT OF HUMAN SYSTOLIC AND DIASTOLIC BLOOD-PRESSURE TRANSIENTS WITHOUT DIRECT ARTERIAL PUNCTURE

I. Introduction.

In civil aeromedical research, there are several experimental areas in which the continuous measurement of systolic and diastolic blood-pressure transients would be of immense value. Some of these potential areas of study are: (1) rapid decompression of aircrew and passengers for the delineation of critical minimum-oxygen-pressure levels and for oxygen-mask testing, (2) dynamic assessment of changing work levels related to optimal aircrew and air traffic controller performance, and (3) assessment of cardiopulmonary transients in pilots during stressful and fatiguing flight maneuvers.

One possible method of obtaining beat-to-beat blood pressure measurements is shown in Figure A1. (All Figures, A1 through A11, are in the Appendix.) This figure reveals an assessment as obtained by direct systemic arterial puncture in an anesthetized dog. The high and low points of each pressure wave represent the momentary systolic and diastolic blood pressures, respectively. Although this procedure is routinely used in animals, and occasionally in humans,[1–4] the contraindications for general human use are many and severe. Despite local anesthesia, arterial puncture is painful and will hence militate against the attainment of "normal" baseline pressures. The danger of sepsis, blood-clotting and damage to the aterial intima are always present. It is for these main reasons that human experimental protocols have relied heavily on the indirect measurement of blood pressures. In "steady-state" experiments, the auscultative, blood-pressure-cuff method has been used successfully[5, 6]. Utilizing this method, the assessment of systolic blood pressure can be obtained with an average accuracy of ±2 mm Hg. Since the the diastolic blood-pressure measurement depends on subjective audial judgment of the proper "fall-off" of arterial Korotkov sounds, the measureure accuracy of this parameter is in the order of ±5 mm Hg. In recent years, this situation has been improved by the appearance of automatically recording, auscultative, blood-pressure devices which have substituted on objective microphone for the ear of the investigator. This type of device has improved the accuracy of both systolic and diastolic blood pressure assessments in the steady-state. When automatically cycled, however, this apparatus, at best, can yield only two reasonably accurate determinations of both systolic and diastolic pressures per minute. An example of this type of recorded measurement is shown in Figure 2.* The vertical oscillations superimposed on the pressure tracing emanate from the microphone in the brachial blood-pressure cuff. The oscillation amplitude is proportional to the volume of the Korotkov sounds. During the pressure deflation cycle, the first audio oscillation marks the value of the systolic blood pressure. The diastolic blood pressure is marked by the first audio oscillation which is less than one-third of the preceeding maximum audio oscillation occurring during the entire deflation period. Each pressure determination has an accuracy of ± one-half the average pressure drop between each sequential pair of audio oscillations. Therefore, it should be obvious that in order to obtain more than two of these complete cycles per minute, the deflation "pressure-bleed" rate would have to be increased, thereby increasing the inter audio-oscillation pressure drop and hence decreasing the accuracy of each pressure determination. Because of this accuracy limitation and the requirement to increase the frequency of the pressure determinations to assay short-duration transient phenomena, a search was instituted for a compromise system that would fulfill this need without resort to direct arterial puncture.

---

* "Physiograph" recorder—E&M Instrument Co., Houston, Texas.

II. Procedure.

A suitable compromise system was devised. It consists of two commercially available apparatuses used in a novel manner. For the intended purpose, one device was extensively modified, while the other was used essentially as originally designed.

A. *Diastolic Blood Pressure.*—This pressure was measured utilizing a modification of an existing automatic blood-pressure apparatus.* Its normal operation was the automatic sensing and recording of auscultative diastolic and systolic pressures (in that order) from a brachial cuff. The qualitative operational pattern of this system is shown in Figure A3. This particular apparatus was designed (with preset switches) to measure both pressures at three optional rates: once per minute, once per 3 minutes and once per 6 minutes. The cycle, as shown in Figure A3, could also be manually invoked to repeat as many as four times per minute. However, this was still far below the measurement rate needed for our purposes. Furthermore, if cycled at four per minute for several minutes, the relatively high cuff pressure which would exist for the major portion of the measuring time would be detrimental to the circulation of that portion of the arm distal to the pressure cuff. Edema and severe ischemic discomfort would rapidly ensue.

Since another apparatus that could measure the systolic pressure rapidly and virtually continuously (to be described consequently) already existed, the Systems Research Labs. apparatus was modified to cycle the measurement of diastolic pressure only. With reference to the cycle pattern shown in Figure A3, this was achieved mainly by "chopping off" the systolic portion of the cycle at point C, at which point, the coincidence of a sensed pressure pulse with the first appearance of Korotkov sounds (diastolic blood pressure) activates a relay for rapid deflation of the cuff. The cycle is reactivated by a preset pressure-sensitive relay when the cuff pressure during rapid deflation falls to a value of 10 mm Hg. This cycle-reactivation pressure is low enough to allow the maintenance of noncongestive, venous blood-flow levels in the arm distal is encuff. The cuff-pressure-sensing transducer is energized continuously so that the whole pressure cycle is sensed and then recorded by a readout device.** Visualization of the whole pressure cycle allows the investigator to make favorable momentary readjustments of cuff inflation and deflation rates to attain the maximum number of determinations per minute. In such a pattern, as shown in Figure A4, the highest pressure attained before the onset of rapid cuff deflation is the system's measurement of diastolic pressure. Utilizing this modified system, the diastolic pressure has been measured from 10 to 34 times per minute for protracted time periods without ischemic discomfort to the subject. The average confidence level of this type of diastolic pressure measurement, as judged by the cuff-pressure rise between consecutive pulse beats, is ±3 mm Hg. This confidence level varies directly with the rate of the slow-inflation portion of the cycle.

B. *Systolic Blood Pressure.*—This pressure was measured utilizing an SM–2 continuous systolic blood-pressure monitor.† This system operates as follows: as shown in Figure A5, a miniature pressure cuff is positioned on the finger near its base (A) and an SM–2 crystal pressure sensor (B) immediately distal to the cuff to sense pulse pressure. Arterial pulsations sensed by the crystal pickup activate stepwise inflation of the cuff to a pressure exceeding the momentary systolic pressure. A slower, continuous, cuff-pressure "bleed" then allows deflation of the cuff until the sensed appearance of the first pulse to escape the pressure restriction of the cuff. This sensed pulse reactivates the stepwise cuff inflation. The point at which the deflation is reversed is a measure of systolic pressure. An example of the resulting pattern of measurement is shown in Figure A4. The magnitude of each step-inflation of cuff pressure can be controlled by presetting the inflation solenoid aperture. The cuff-pressure "bleed" rate has a similar control. In this fashion, upwards of 20 determinations per minute are routinely possible. Because of the ischemic risk of such high sustained cuff pressures, continuous measurement for more than 5 minutes is inadvisable. For the recording of long-duration, steady-state procedures, a zero-pressure rest of 10 seconds per minute is sufficient to deter any appreciable digital ischemia. Several 5 minute periods of continuous measurement, with ade-

---

* Systems Research Labs., Inc., Dayton, Ohio.

** A Heiland, 6-channel, 914 B "Visicorder".

† Spinco Division, Beckman Instruments, Inc., Palo Alto, California.

quate zero-pressure rest intervening have been employed with ischemic impunity and minimal discomfort to the subject. When simultaneous measurement of both systolic and diastolic pressures is required, the systolic finger cuff is placed on one limb and the diastolic cuff on the other. Both cuffs cannot be used on the same limb for obvious reasons of measurement artifact and potential ischemia. In actual use, the "systolic arm" is sling-supported so that the finger used is positioned at the same level as the brachial diastolic cuff. This is done so that both pressures are referenced to the apex level of the heart. If the "systolic finger" is placed above or below this level, an appropriate hydrostatic-pressure correction must be invoked. Positions below the apex cardiac level are not recommended since the additional hydrostatic pressure may increase ischemic susceptibility. A matched pair of ±5 psid Statham transducers were used to sense both pressures so that both transducers could be calibrated simultaneously. The previously mercury-calibrated aneroid "Tycos" gage in the SM-2 apparatus was used to calibrate both transducers.

III. Results.

In order to obtain a more comprehensive reflection of cardiopulmonary-function transients, concomitant measurements of the electrocardiogram (ECG), instantaneous heart rate (HR), respiratory rate (f), and tidal volume (V_T) have been recorded along with the systolic and diastolic pressures utilizing the 6-channel "Visicorder". The ECG electrodes are positionel suprasternally in order to minimize skeletal muscle "noise." The instantaneous HR is obtained by electronic integration of the time interval between sequential "QRS spikes." The f and V_T are obtained by recording the impedance change from a pair of lateral electrodes located in the horizontal cardiac plane of the thorax. When body position remains essentially unchanged, the V_T calibration is linear throughout the entire chest-volume range and proportional to the height of the impedance displacement. Several examples of transient physiological phenomena have been recorded using this total system in order to demonstrate its capabilities. In each example, each trace is identified by letter and described in the accompanying legend.

A. *Valsalva Maneuver.*—During this procedure, a large, single inspiration is followed by closure of the glottis and positive intrapulmonic pressure application by the subject. This is shown in Figure A6, the valsalva being effected between points X and Y. The momentary mobilization of stored pulmonary blood volume causes a phasic increase and then decrease in the HR and systolic and diastolic pressures with appropriate rebound phenomena upon release of the positive intrapulmonic pressure.

B. *Mueller Maneuver.*—During this procedure, a substantial expiration towards residual volume is followed by glottis closure and negative intrapulmonic pressure application by the subject. This is shown in Figure A7, the mueller being effected between points X and Y. The phasic HR and pressure changes again follow as a consequence of the concomitant flux in pulmonary blood volumue. The rebound raise in HR immediately following the cessation of negative intrapulmonic pressure application is somewhat spectacular.

C. *Hyperventilation.*—During this procedure, nine rather large V_T's were invoked in rapid sequence by the subject. This is shown in Figure A8, the hyperventilation occurring between X and Y. During the hyperventilation, a sharp rise and increase in phase swings is manifested by the HR concomitant with a continuous drop in diastolic pressure. The systolic pressure was relatively unaffected by this maneuver. Upon cessation of the hyperventilation, there occurs a compensatory rebound rise in diastolic pressure and an even further rise in HR.

D. *Orthostatic Stress.—For this procedure* (Figure A9), the resting subject lies supine on a tilt table and at point X, the table is tilted to a 45° feet-downward position. The table is returned to horizontal at point Y. The classical slow rises in both HR and diastolic pressure are readily manifested during the tilt period. The shift in the end expiratory baseline at tilt reflects an overall change in baseline impedance due to downward visceral displacement.

E. *Bicycle Ergometry.*—This procedure was primarily used to test the artifactual susceptibility of the blood-pressure devices to body movement. The subject sat at rest in an upright position on a bicycle ergometer until signalled to commence pedalling at a rate of 60 cycles per minute and against a constant friction of 50 watts. The "systolic arm" was sling-supported at the apex heart level. This record is shown in

Figure A10. The onset of exercise is marked on the record as point X. The two large remarkable phasic swings in HR just preceding point X coincided with the subject's comfort adjustment in preparation to commence pedalling. The widening of pulse pressure (increasing systolic and decreasing diastolic pressures), increasing HR, f, and V_T as the exercise progressed are all classical physiological responses. This record demonstrates that body movements during ergometry of this type are tolerated quite well by the blood-pressure systems as well as the others concomitantly measured.

Treadmill ergometry was attempted after the bicycle test, and the resultant "body bounce" of walking caused artifactual pulse sensing by the systolic-pressure system, thereby negating its value as a true measure of systolic pressure under this particular condition. A double-signal pulse sensor is presently being explored as a possible solution to this type of body-bounce artifact. The diastolic-pressure system was not adversely affected by treadmill walking, and hence its measurements were deemed valid.

F. *Rapid Decompression.*—The combined cardiopulmonary assay system was tested for its capability of measuring physiological dynamics during a rapid decompression of a subject from 8,000 to 40,000 feet. The subject remained in an upright, seated position throughout this procedure. The subject was not denitrogenated before the decompression. At decompression, the subject was without a mask, and, at an appropriate altitude-synchronized signal, he proceeded to don the mask, which consequently remained on with a positive-pressure source of 100% oxygen for the remainder of the test procedure. The left arm, on which the "systolic-finger" device was mounted, remained resting on the "arm" of the seat. The "systolic finger" was kept at the apex cardiac level during the whole procedure. The right forearm, the hand of which donned the mask, was at all other times resting in a quiet position in the lap of the subject. The record obtained is shown in Figure A11. The letter X denotes the onset of rapid decompression. The mask was donned at point Y, and the chamber altitude of 40,000 feet was attained at point Z. The altitude for the remainder of the record remained at 40,000 feet. With the exception of the momentary disruption of the diastolic-pressure measurement at point Y (during mask donning), all systems funtioned satisfactorily. The sharp rise in systolic and diastolic pressures just at the onset of decompression, followed by a gradual fall in both pressures until attainment of 40,000 feet is unique. The dramatic rise in HR just prior to mask donning and its consequent sustained level is remarkable as is the concomitant increase in both f and V_T. This total system has already been used to measure two experimental series of rapid decompression experiments. The results of these decompression studies will appear in a consequent publication.

REFERENCES

1. Kroeker, E. J., and Wood, E. H.: Comparison of simutaneously recorded central and peripheral arterial pressure pulses during rest, exercise and tilted position in man. *Circ. Res.* 3:623, 1955.
2. O'Donnell, T. V., and McIlroy, M. B.: The circulatory effects of squatting. *Am. Heart Jour.* 64:347, 1962.
3. Henschel, A. F., DeLaVega, F., and Taylor, H. L.: Simultaneous direct and indirect blood pressure measurements in man at rest and work. *J. Appl. Physiol.* 6:506, 1954.
4. Tabakin, B. S., Harrison, J. S., Meriam, T. W. Jr., and Caldwell, E. J.: Hemodynamic response of normal men to graded treadmill exercise. *J. Appl. Physiol.* 19:457, 1964.
5. Korotkov, N. S.: On methods of studying blood pressure. *Izv. Voennomed. Akad.* 11:365, 1905.
6. Bordley, J., Connor, C. A. R., Hamilton, W. F., Kerr, W. J., and Wigger, C. J.: Recommendations for blood pressure determinations by sphygmomanameters. *Circ.* 4:503, 1951.

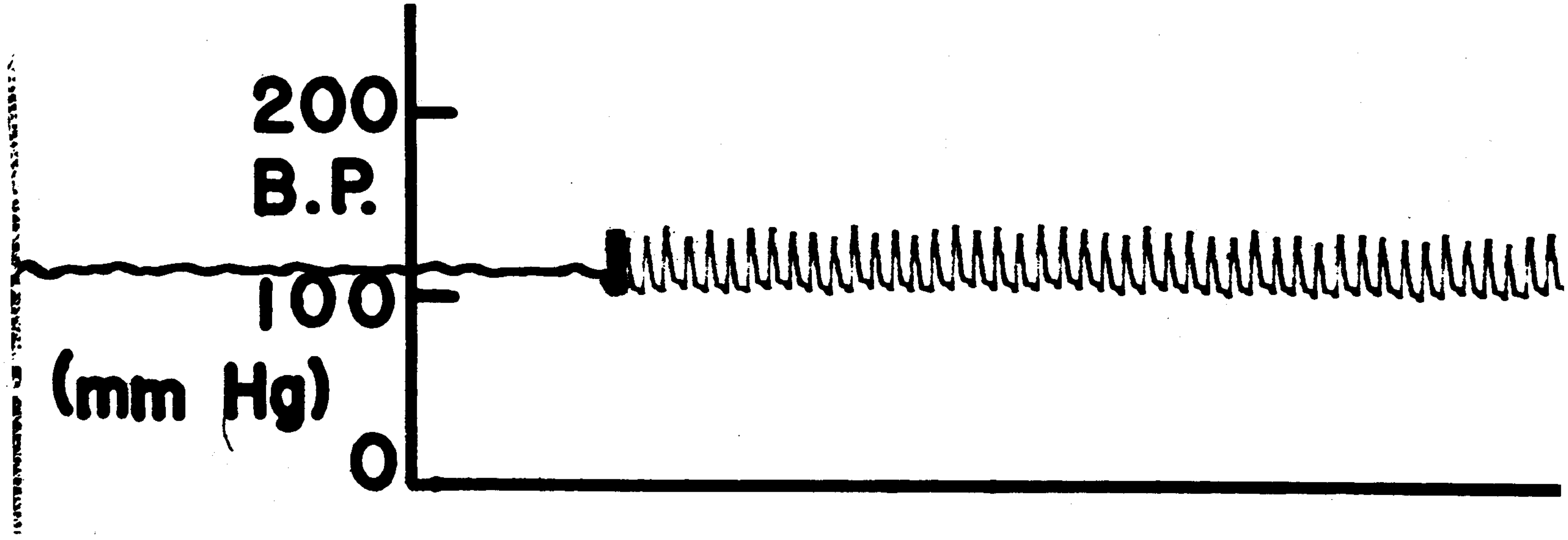

Figure A1. Intraarterial blood pressure tracing obtained via hypodermic-needle puncture in an anethetized dog.

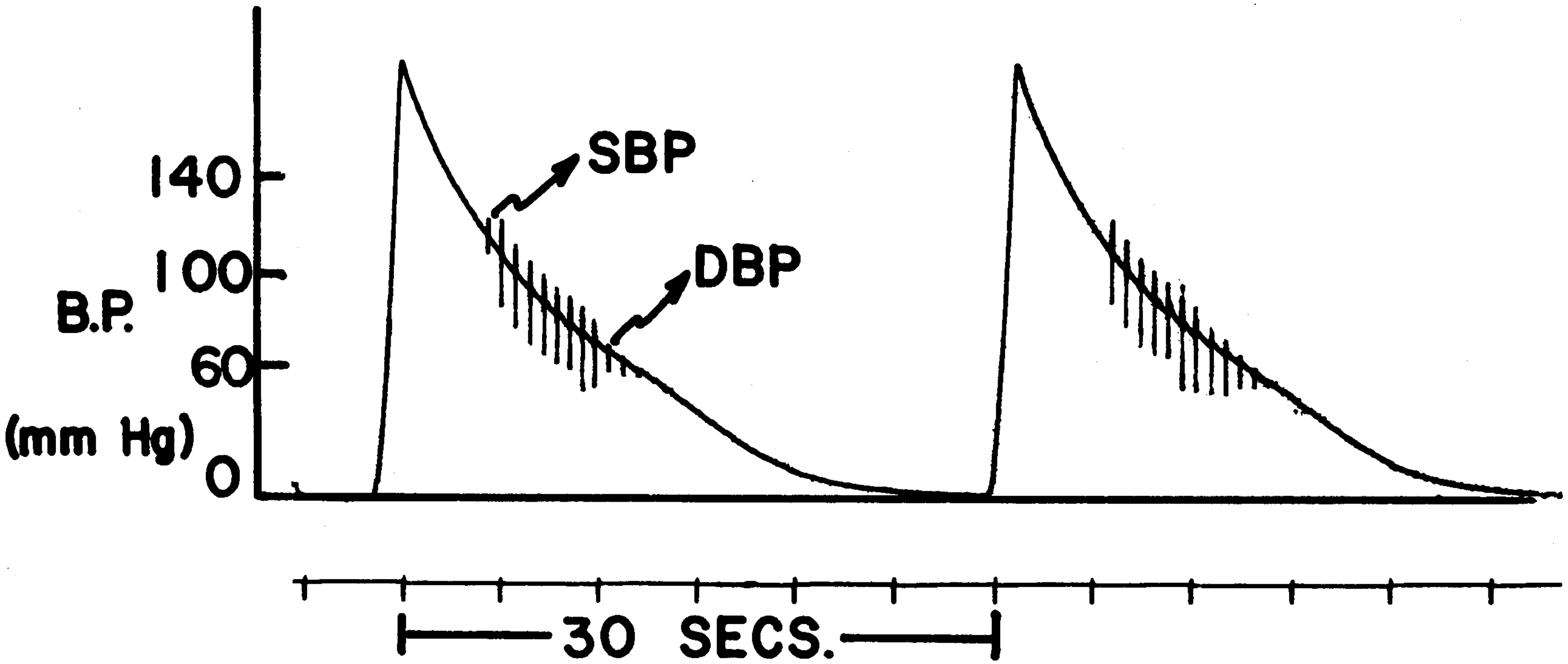

FIGURE A2. Automatic systolic and diastoic blood-pressure measurement obtained from a brachial arm cuff on a human subject.

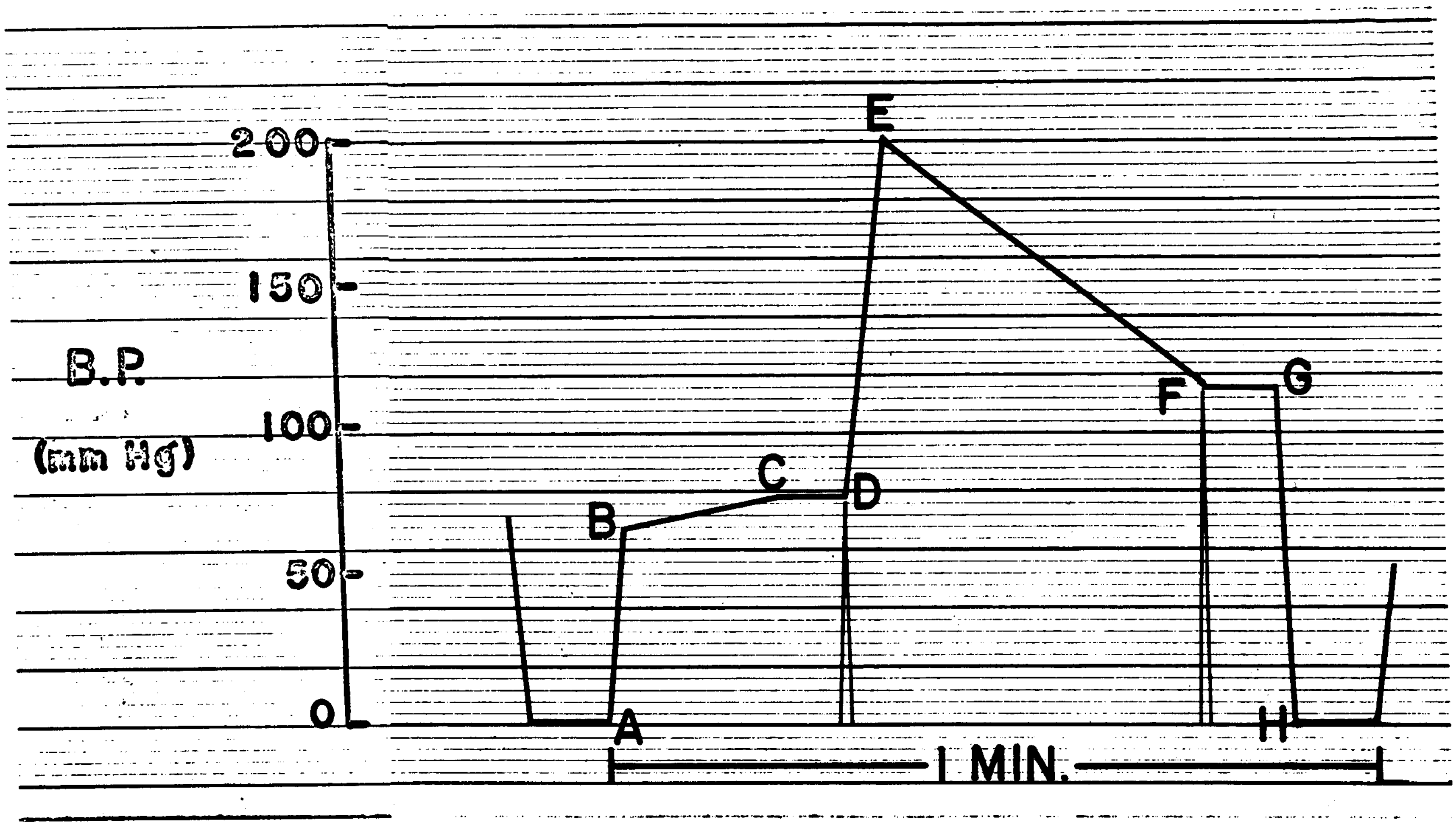

FIGURE A3. Diagrammatic representation of automatically obtained blood-pressure cycle. Device used was the Systems Research Labs automatic blood-pressure apparatus. A-B: rapid cuff inflation. B-C: slow cuff inflation. C: first sensed appearance of both pulse beat and Korotkov sounds. D: second consecutive appearance of both pulse beat and Korotkov sounds and "spike" readout of diastolic blood pressure. D-E: rapid inflation to 200 mm Hg. E-F: slow deflation of cuff pressure. F: first appearance of pulse beat and Korotkov sounds. G: second consecutive appearance of both pulse beat and Korotkov sound and "spike" readout of systolic blood pressure. G-H: rapid cuff deflation. Cycle is reactivated by automatic timing device.

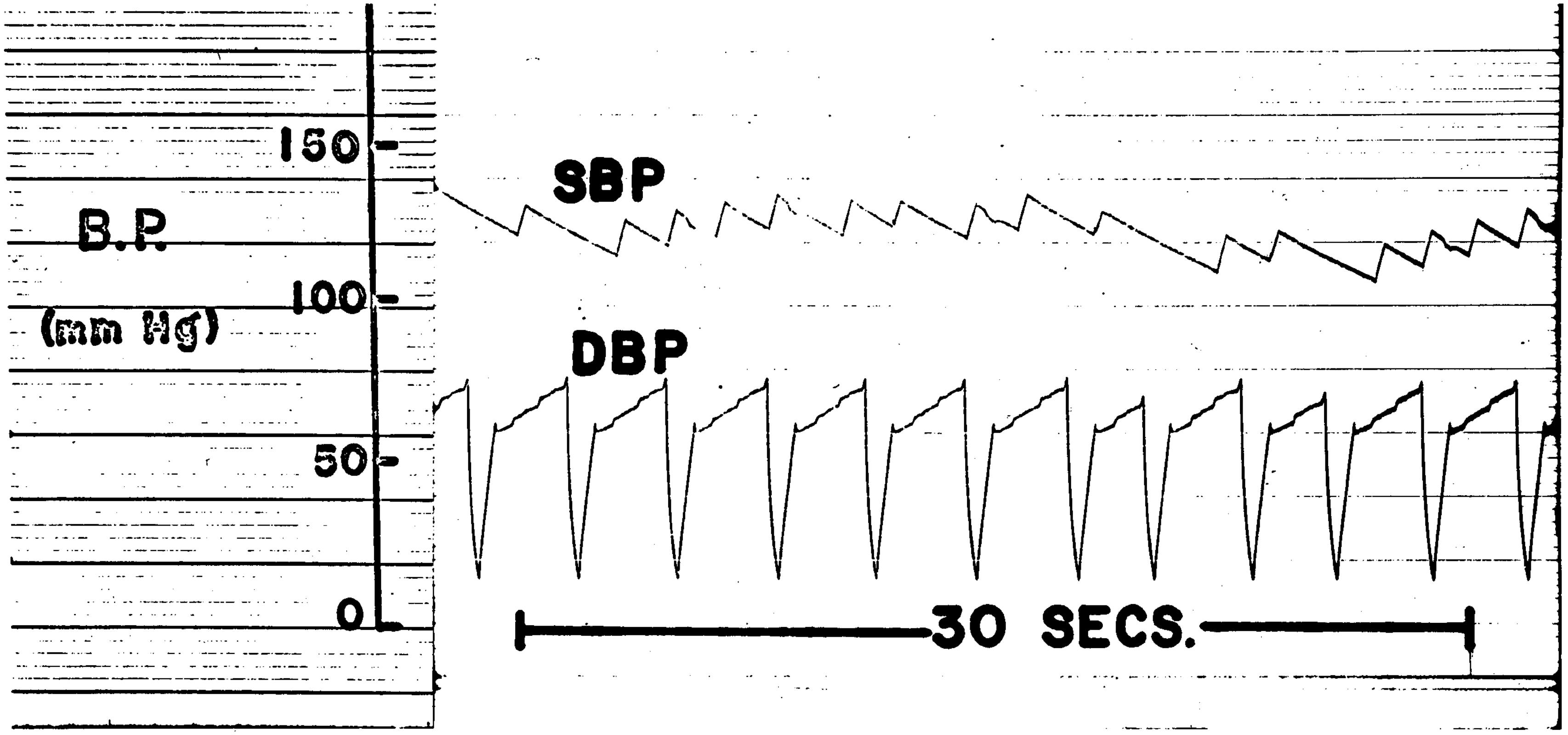

Figure A4. Systolic blood-pressure (SBP) and diastolic blood pressure (DBP) records as obtained from a digital cuff on one limb and a brachial cuff on the other.

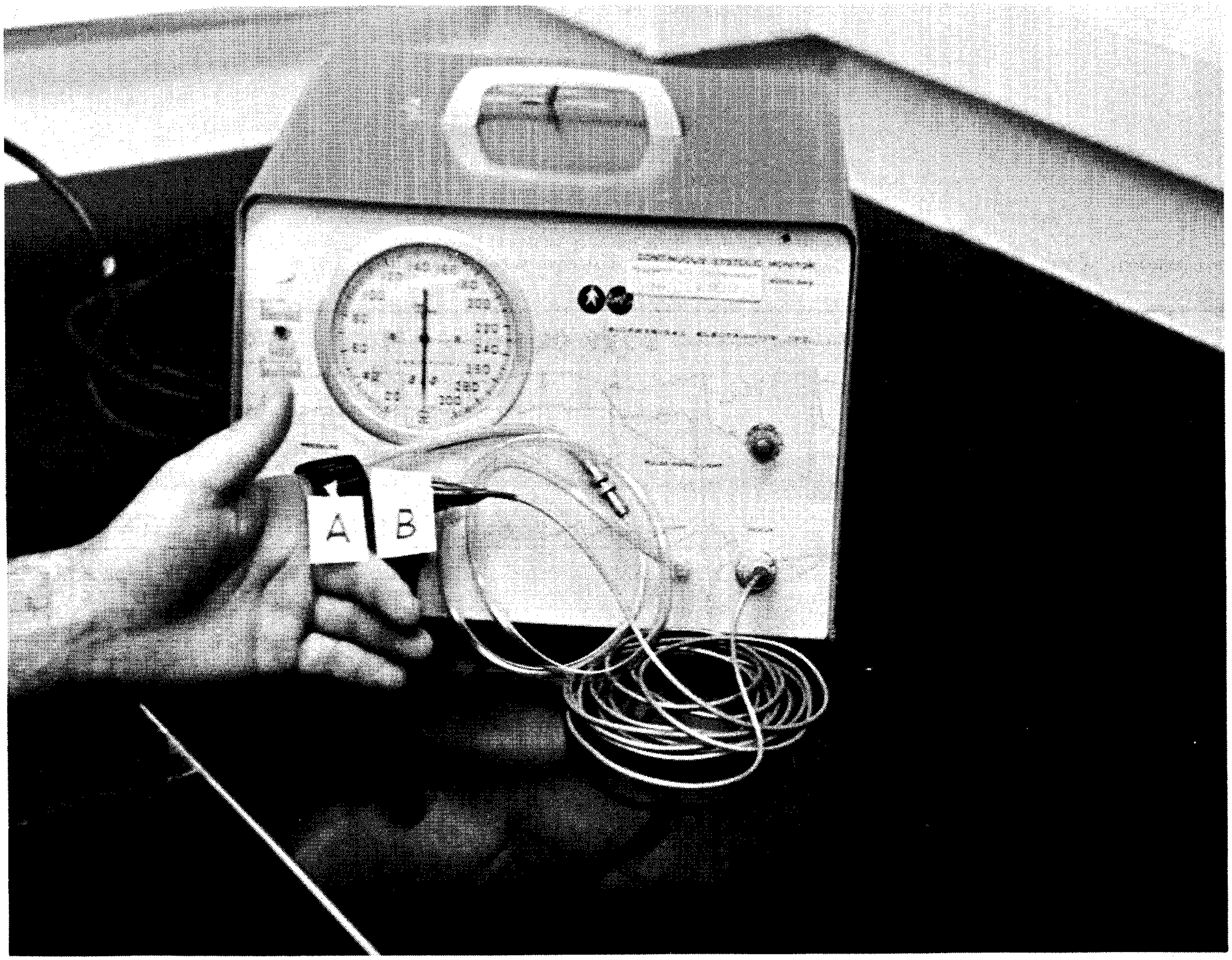

FIGURE A5. Closeup view of digital cuff (A) and SM-2 crystal pulse sensor (B) as used for virtually continous systolic blood-pressure measurement.

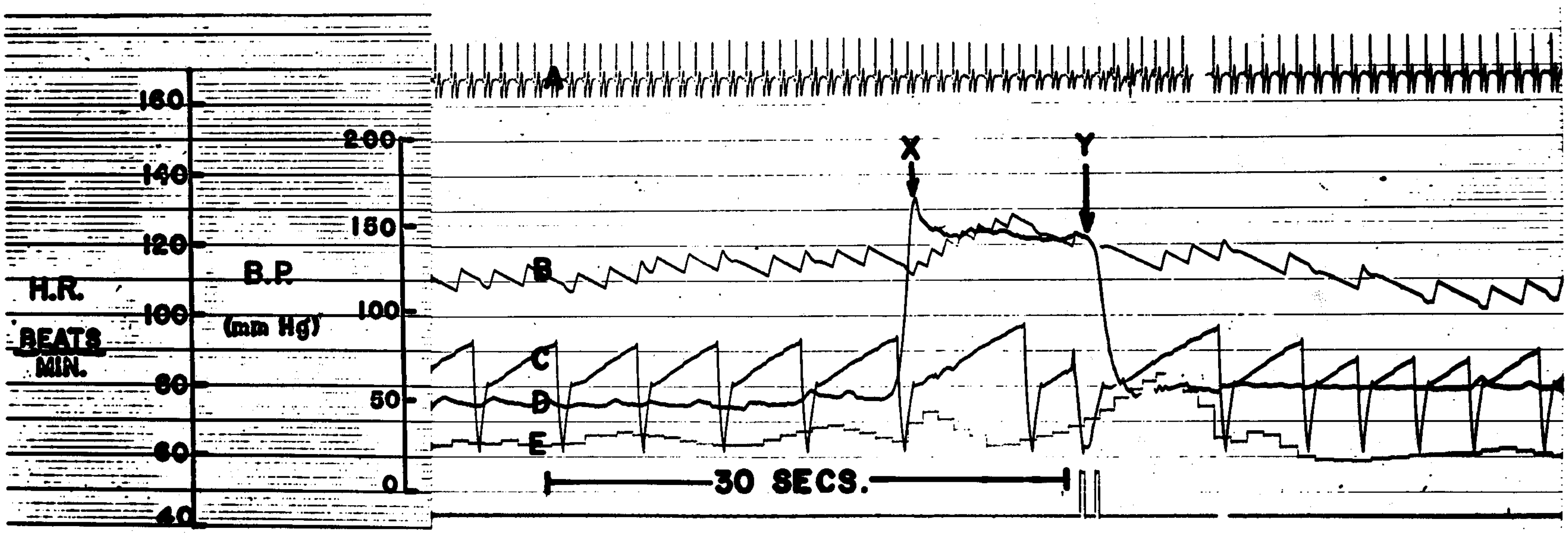

FIGURE A6. Record of physiological response to a respiratory valsalva maneuver. The maneuver is effected between points X and Y. Labelled traces are as follows: A-ECG, B-systolic blood pressure, C-diastolic blood pressure, D-respiration, and E-instantaneous heart rate.

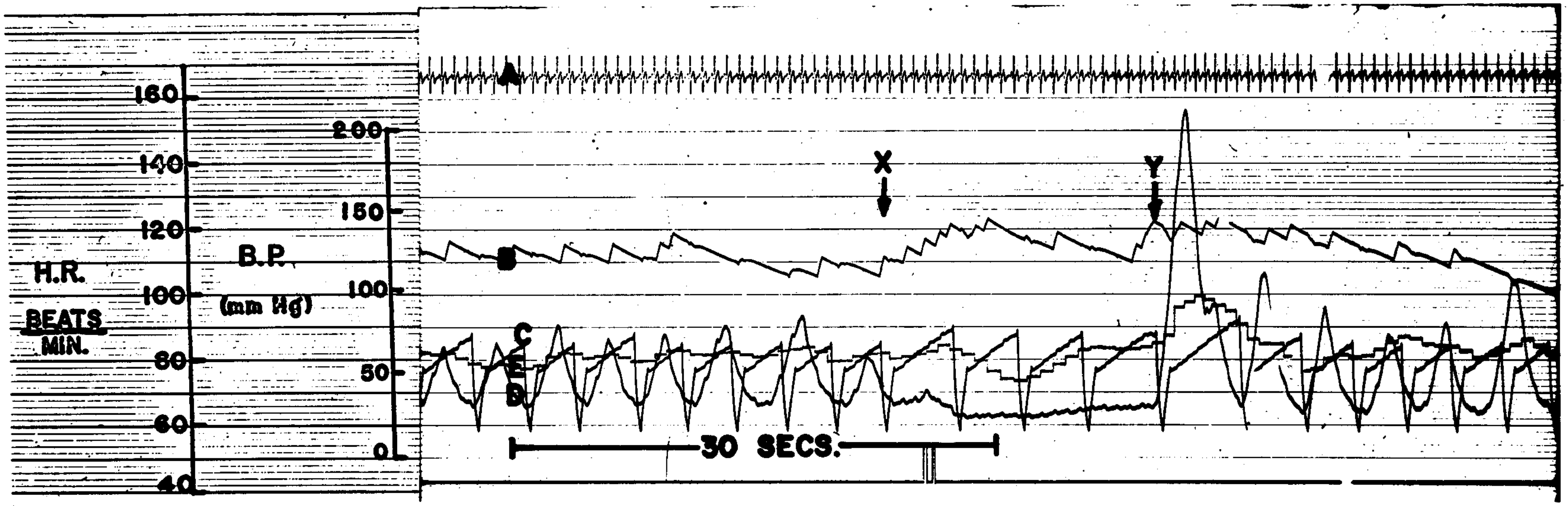

FIGURE A7. Record of physiological responses to a respiratory mueller maneuver. The maneuver is effected between points X and Y. Labelled traces are as follows: A :ECG, B-systolic blood pressure, C-diastolic blood pressure, D-respiration, and E-instantaneous heart rate.

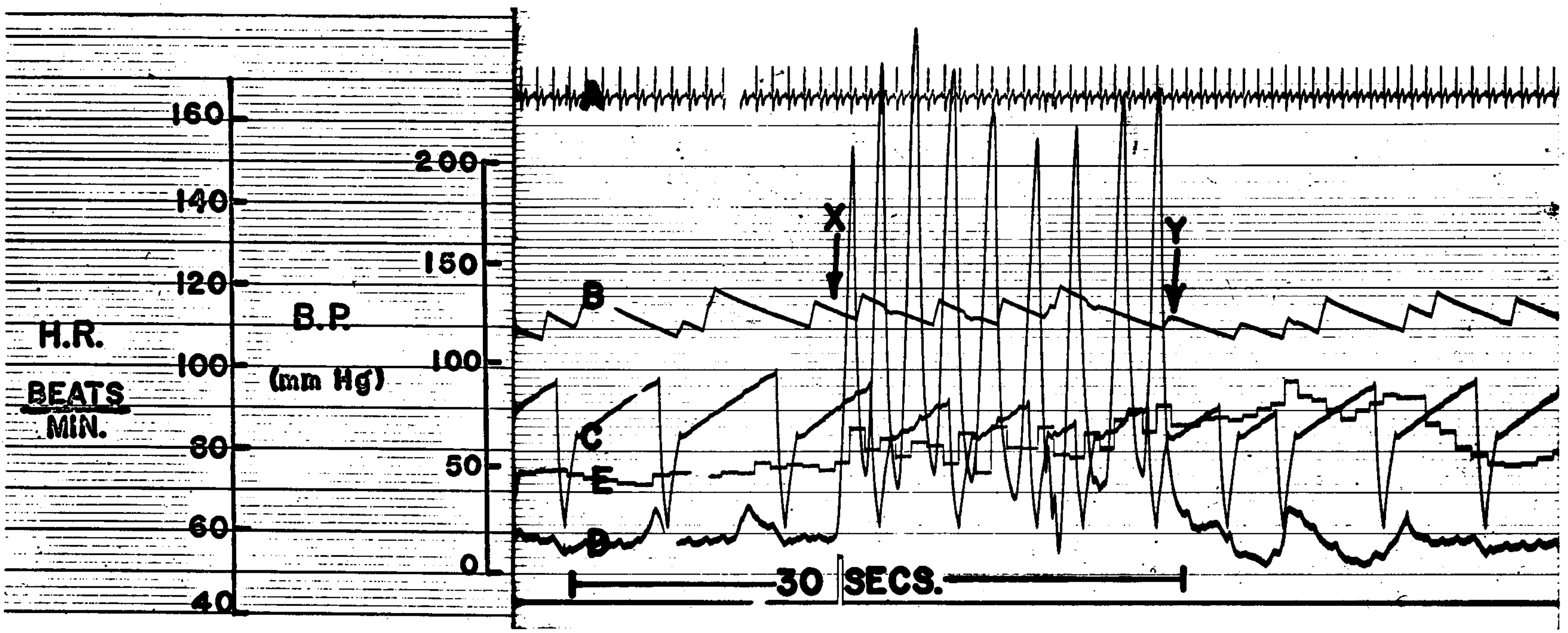

FIGURE A8. Record of physiological responses to respiratory hyperventilation. Hyperventilation was effected between points X and Y. Labelled traces are as follows: A-ECG, B-systolic blood pressure, C-diastolic blood pressure, D-respiration, and E-instantaneous heart rate.

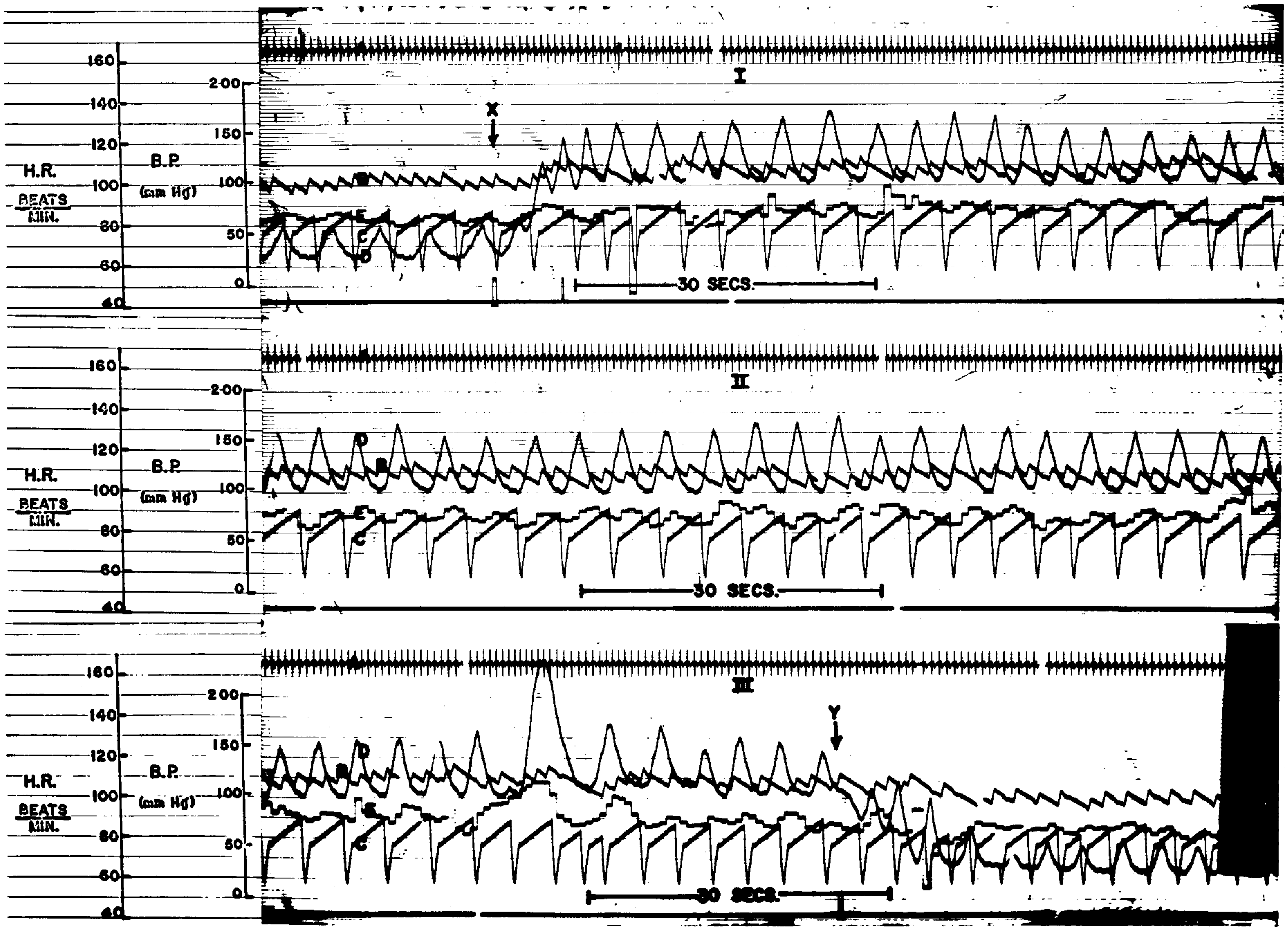

FIGURE A9. Record of physiological responses to orthostatic stress by tilting subject from supine, horizontal position to 45° feet-downward (X) and return to horizontal (Y). Labelled traces are: A-ECG, B-systolic blood pressure, C-diastolic blood pressure, D-respiration, and E-instantaneous heart rate.

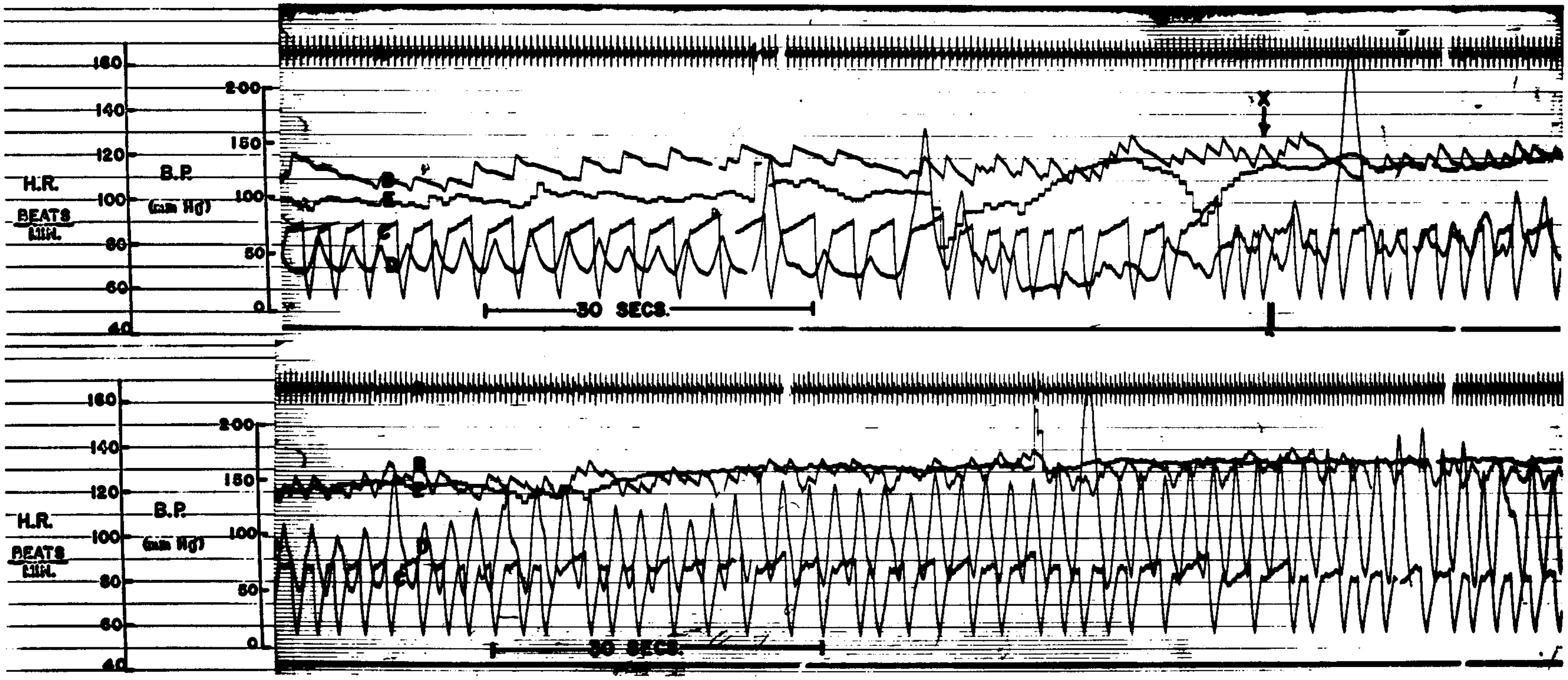

FIGURE A10. Record of physiological responses to bicycle ergometry. Onset of bicycle exercise occurs at point X. Labelled traces are as follows: A-ECG, B-systolic blood pressure, C-diastolic blood pressure, D-respiration, and E-instantaneous heart rate.

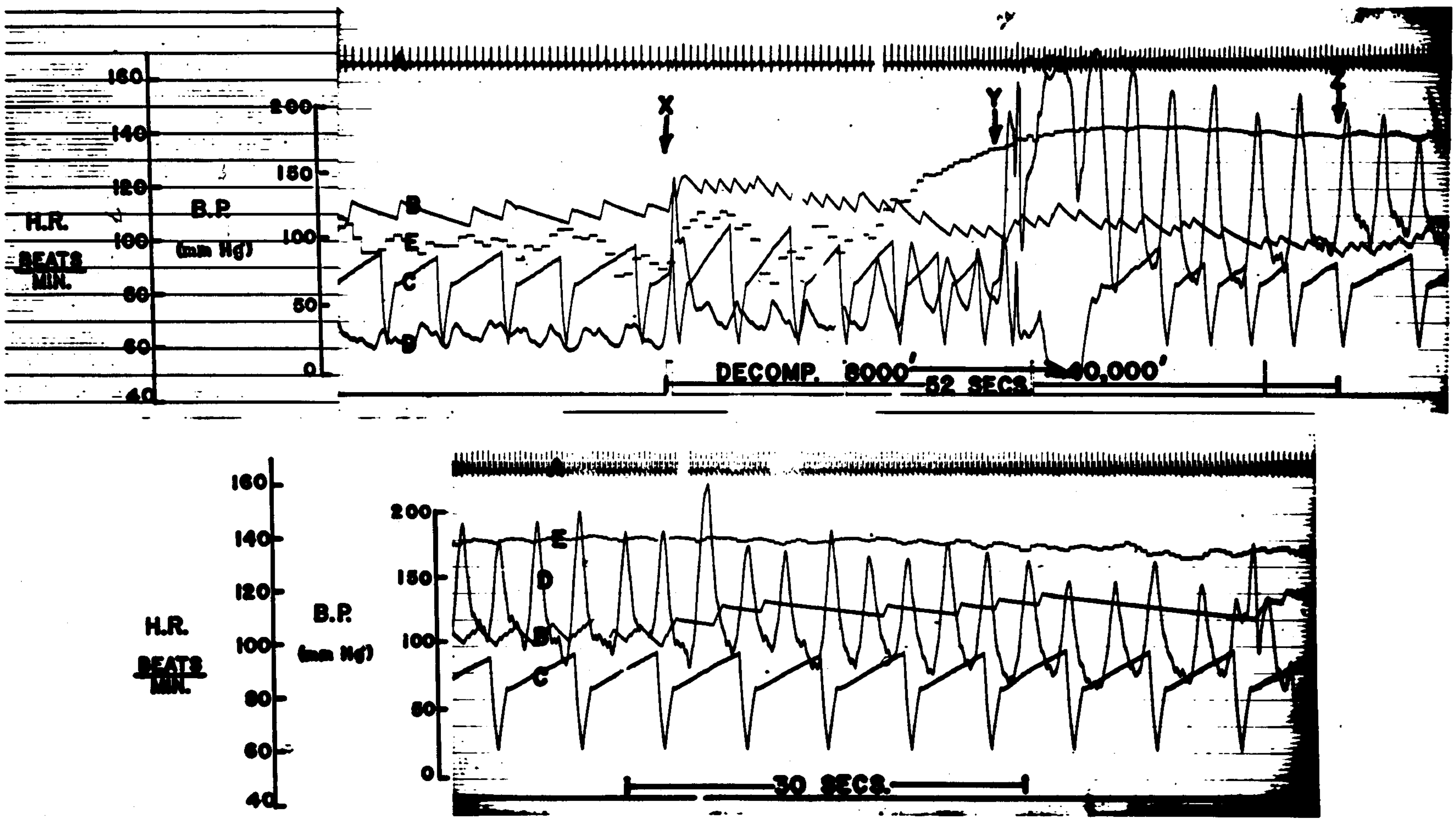

Figure A11. Record of physiological responses of a subject exposed to rapid decompression from 8,000 to 40,000 feet in an altitude chamber without prior denitrogenation and including oxygen-mask donning. Rapid decompression onset occurred at point X, mask donning at point Y, and attainment of 40,000 feet at point Z. Labelled traces are as follows: A-ECG, B-systolic blood pressure, C-diastolic blood pressure, D-respiration, and E-instantaneous heart rate.