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TEMPERATURE OF THE HUMAN BODY DURING RAPID ALTERNATE HEATING AND COOLING

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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

Eight nude resting male subjects were immersed in water. The temperature of the bath was varied cyclically from -5° to 42°C. Similar experiments were performed in air with temperatures varying from -5° to 120°C. Skin temperatures oscillated sinusoidally with amplitudes varying from 1° to 10°C and periods varying from 3.75 to 30 minutes. Variations in skin temperature below 30°C did not affect the oesophageal temperature. Sinusoidal variations in skin temperature above 34°C were reflected in nearly sinusoidal alterations in the oesophageal temperature. Sinusoidal variations in oesophageal temperature were accompanied by nearly sinusoidal alterations in rectal, sublingual and tympanic membrane temperatures, with damping characteristics and phase shifts typical for each site of measurement.

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SECTION I

INTRODUCTION

An observer of heat transfer and temperature regulation in the human body may conceive of it as a formation of partially self-maintaining organs of such structure and function as to preserve their optimal state of thermal equilibrium. These units are joined together by the circulation into the integrated functional whole of the organism in its physiological state of heat balance. Adjacent tissues, structure, the system of blood vessels, blood flow and metabolism are all factors affecting the heat-exchange in organs. These factors determine the individual nature of thermoregulation and the characteristic temperatures in the organs. The temperature of an individual organ is not homogeneous throughout its bulk but determined by the local relations of various thermal factors. We may thus speak of local tissue temperatures and of the range of variation in the tissue temperatures of an organ. In extreme environmental conditions and in the course of rapid alterations in the thermal surroundings, the differences between the temperature ranges of the organs may be multiplied many times. If local temperatures cannot be measured, the task remains of calculating them from the measured or assumed values of various thermal factors. The available information does not suffice as a foundation for the mathematical solution of tissue temperatures. The construction of a model for organ temperatures requires the execution of supplementary experimental studies.

By imposing alterations on the temperatures of skin, blood, or organs, and by simultaneously measuring at least two of these variables the relations between the temperatures in an organism may be demonstrated. In the work presented here variations have been imposed on the skin temperature by alterations in the environmental temperature. The oesophageal temperature has been used to express the temperature of blood in the central circulation. The rectal, sublingual, and tympanic membrane temperatures have been measured as organ temperatures.

SECTION II

METHODS

EXPERIMENTAL TUB

In order to achieve a tightly controlled, variable temperature homogeneously distributed on the skin surface, a water tub was constructed for the experimental exposure of supine subjects (fig.14). The temperature of the water in it could be varied according to a prepared plan by means of an automatic program controller. The controller was constructed in this laboratory and incorporated a Honeywell single-point potentiometric recorder to form the difference between the actual and set point temperatures. The thermocouple sensing elements were placed in water, one was located in the tub and the other in the inlet tube from the water circulating pump to the tub. The controller acted upon two magnetic valves which directed either hot or cold water into the tub. Sufficient mixing was achieved by admitting the water into the tub through perforations in pipings along both sides. The water level was kept constant by means of an overflow tube and the rate of water flow in the tub was adjusted with a pump and an associated valve.

EXPERIMENTAL ROOMS

The subjects were exposed to air at various temperatures in two interconnected rooms. The air temperature in one of them could be automatically adjusted to a constant level between +30°C and +140°C, and in the other between -5° and +30°C. The rate of air flow could also be controlled in the experimental rooms as well as the humidity in the hot room. The subject was moved from one room to the other lying supine on the net hammock which served as his support throughout the exposure period.

ASSESSMENT OF THE THERMAL ENVIRONMENT

Air and water temperatures were measured continuously by thermocouples at 4 points bilaterally from the subject's body. The temperatures were recorded continuously during the experiment with a multipoint Honeywell potentiometric recorder (in exposures to various air temperatures the accuracy of the measurement was ±0.5°C and in exposures to water it was ±0.2°C).

Air himidity was assessed by means of an Assmann psychrometer with an air flow rate of 2 m/s. Dry and wet bulb temperatures were measured by thermocouples and recorded by an electronic potentiometer (Honeywell).

MEASUREMENT OF ORGAN TEMPERATURES

Oesphageal temperatures were measured at distances of 37.5 and 44 cm from the nostril. The upper point of measurement was intended to coincide with the height of the pulmonary artery and the lower with the level immediately above the diaphragm, where it would lie in the vicinity of the wall of the left ventricle. The measuring thermocouples were soldered into the inner surfaces of 5-mm-long silver bulbs with an external diameter of 2.5-mm and the 0.1-mm lead ran inside a 2-mm-OD polythene tube.

The rectal temperature was measured at a depth of 12.5 cm from the external anal opening. The thermoelement lead ran in a 5-mm-OD flexible P.V.C. tubing to the tip of the probe, where the junction was soldered into a hole in the wall of a 25-mm-long and 5-mm-OD hollow silver bulb.

In exposures to varying temperatures of air, the skin temperatures were measured by a 0.1-mm diam. thermocouple, stretched taut between the arms of a thermally insulated flexible fork at cm on either side of the junction and attached to the other end of a 1-m light-weight wooden rod. This arrangement enabled the subject to perform the measurements himself, by applying the junction lightly on seven different regions of the skin. The temperature indication was steady in 10 seconds and could then be recorded by an electronic potentiometer (Honeywell). The skin temperature was calculated as the weighted mean from the seven different skin areas.

With subjects immersed in water the skin temperature was measured continuously from the skin surface of the thorax at the midaxillary line at left and from the skin surface of the lateral aspect of the left thigh. The sensing element was a 0.1-mm-diam. thermocouple, which was pressed to the skin by the lateral force component of a 50-g weight hanging freely from one lead at a level of some cm below the lower surface of the thigh, while the other lead was fixed on the midline of the upper surface of the thigh.

The temperature of the tympanic membrane was measured by a thermocouple of 0.1-mm-diameter wire, wound into a 7-to 8-mm long spiral of 3-mm OD. The copper to constantan joint, forming the sensing element proper, was situated at the tip of the spiral. The base of the spiral and leads leaving it were fixed to a 5-to 6-mm OD and 15-mm-long cylindrical hollow earplug, made of cork. The thermocouple leads were furthermore wound 6 to 7 times around the cylindrical surface of the earplug before joining the recording leads. By this means it was hoped to minimize possible stem errors.

The sublingual temperature was measured by means of a special rubber probe carrying a thermocouple at its 25-mm-long tip projecting obliquely towards the floor of the oral cavity, while the body of the probe was held rigidly between the clamped teeth.

EXPERIMENTAL SUBJECTS

Eight men, high-school students or laboratory personnel, between 24 and 39 years of age, and of varying physique (see table I) served as subjects. A preexposure medical examination revealed no history or present sign of recent disease, and the men were all found to be in a good physical condition; none of them was an actively competing athlete.

EXPERIMENTAL ROUTINE

The exposures were carried out in the course of the Autumn, Winter, and Spring months, always between 12 and 17 o'clock. After arriving at the laboratory the subject undressed himself, except for a set of light shorts. Standing in a room kept at 24° - 25°C the subject fixed the transducers for continuous measurement of temperatures at the skin surface, at the tympanic membrane, sublingually, in the oesophagus and in the rectum. In some experiments an assistant also fixed sensors for the measurement of intracutaneous, subcutaneous and intramuscular temperatures. Harnessing the subject with the transducers took from 1 to 1.5 hours.

The measurements in experiments with subjects exposed to air were begun in the ante-room, at 24° - 25°C, or in the cold room where the subject lay down on a net hammock. The experimental lay-out enabled the subject lying supine on the hammock to be transferred in 5 to 10 seconds from the cold into the hot room, or vice versa, without interrupting the measurements.

For experiments in water the subject was immersed, supine in the experimental tub, leaving only the part of the face around the lips and the nostrils, above the surface of the flowing water. The subject's trunk was weighted with two metal plates, each of 0.5 kg, placed across the thoracic and pelvic regions. The organ temperatures were stabilized by keeping the subject immersed for 30 - 45 minutes in water at 34° - 37°C before starting the actual experiment.

SECTION III
RESULTS AND DISCUSSION

The skin temperatures of the subjects were altered by exposing them to varying external temperatures either immersed in water or in air. As the reproducibility of the variation in skin temperature was better and more easily achieved in experiments with subjects immersed in water these exposures were given major emphasis. To facilitate the computational processing of the experimental data, the temperature changes were imposed on the skin varying the external temperature in a sinusoidal pattern. Temperatures were measured at points on the skin surface, intracutaneously, subcutaneously, in the vastus lateralis of the quadriceps femoris muscle, at the tympanic membrane, sublingually, and in the oesophagus both at the level of the pulmonary artery and in the proximity of the heart. The results have been processed and arranged to yield information mainly on the following two groups of possible interdependencies:

1. The relations between temperatures at the skin surface and in the oesophagus

2. The relations between the oesophageal temperatures and the other deep body temperatures

THE RELATIONS BETWEEN THE OESOPHAGEAL AND THE SKIN SURFACE TEMPERATURES

Experiments with Subjects Immersed in Water

Five reclining subjects were immersed naked in flowing water at temperatures varying sinusoidally in the range between 5° and 42°C. The amplitudes of the variations studied ranged from 1° to 10°C and the corresponding periods from 3.75 to 30 minutes. Besides exposures with regularly recurring cycles of temperature alternation, experiments were also performed with exposures in which the periods or amplitudes were made to grow or decrease steadily in successive cycles of variation. The studies were, furthermore, extended to exposures in which the average effective temperature was made to increase or decrease while the amplitude and period of the temperature cycle remained unaltered.

The results from the experiments with subjects immersed in water appear in figures 1 through 9 and in table II. For analyzing the relations between the skin surface temperature and the oesophageal temperatures, results from the exposures were arranged into three groups treated separately according to the temperature range covered by the variations in the skin surface temperature during the exposure. The first group included results from those exposures in which the skin surface temperature never exceed 34°C and the second from those in which this value never decreased below 34°C. The third group was made up of results from exposures in which the skin surface temperature oscillated on both sides of the 34°C limit at least momentarily during the experimental period.

Results from measurements in subjects immersed in water during exposure to alternating external temperatures not exceeding 34°C, ie, those forming the first group mentioned above are depicted in figures 7 through 9. In the second part of the recording in figure 9, the results may be seen from a sinusoidal alteration of skin temperature between 27° and 33°C in successive periods of 10, 20 and 30 minutes on the intracutaneous and deep organ temperatures of the body. The oscillations in the skin surface temperature elicited similar alterations in the intracutaneous and subcutaneous temperatures with their peak cycle amplitudes increasingly damped with the growth of the distance from the skin surface to the point of measurement. In the muscle, at a depth of 20 - 25 mm, the damping was so marked that only vague oscillations were measured. No reflection of the variations in skin temperature appeared in the oesophageal, sublingual or rectal temperatures in this temperature region of exposure. In figure 7 are depicted the deep organ temperatures during oscillations of the skin temperature, with a period of 15 minutes, around a steadily rising mean, initially decreased by rapid cooling. In figure 8 appear the results from a similar experiment, except that the skin temperature now oscillates, with a period of 20 minutes, around a steadily decreasing mean value. The results from the two latter types of exposure were similar to those obtained with variations below 34°C around a constant mean temperature as described above.

Results from experiments in which the skin temperature did not decrease below 34°C with subjects immersed in water are depicted in figures 1 through 4. During these exposures the skin surface temperature oscillated sinusoidally around a mean value of 37°C, with an amplitude of 3°C and with periods varying from 3.75 to 30 minutes. The cycles of temperature alteration during an exposure were arranged to increase in duration so as to bring the ratios of two successive periods to 1 : 1.5 or to 1 : 2. The sinusoidal alterations in skin temperature were found to be reflected in nearly sinusoidal variations taking place with equal angular velocities. The amplitudes of the cyclic variations increased with the lengthening of their periods while the phase shifts in respect to the superficial skin temperatures decreased. The amplitude dampings and phase shifts in the oesophageal temperature cycles were markedly smaller than the corresponding characteristics in the sublingual, rectal and tympanic membrane temperatures.

Results from experiments in which the skin temperature of water-immersed subjects varied on both sides of the 34°C level appear in figures 5 through 8. The oesophageal temperature was found to reflect the alterations in skin temperature occurring above 34°C. Whenever a sinking skin temperature reached below 34°C the association slackened or disappeared with the appearance of a retardation in the rate, or cessation of, the decrease in the oesophageal temperature at approximately 37° (figs. 5 through 8). The oesophageal temperature could be lowered to 36° or 35°C only by vigorous preliminary application of heat followed by exposure to an almost instantaneous fall in water temperature. A rapid increase in skin temperature could bring about a sudden decrease in the oesophageal temperature which had become stabilized at a level of 36°C. Such transient drops in the oesophageal temperature are indicated with arrows in figure 5.

DISCUSSION OF RESULTS PERTAINING TO THE RELATION BETWEEN TEMPERATURES AT THE SKIN SURFACE AND IN THE OESOPHAGUS IN EXPERIMENTS WITH SUBJECTS IMMERSED IN WATER

The peculiar relationship between the oesophageal temperature and the alterations in the skin surface temperature may conceiveably result from variations in cutaneous circulation brought about by shifts in the skin temperature beyond a definite range. Supposing that below a skin surface temperature of 34°C the cutaneous circulation serving mainly or exclusively thermoregulatory purposes suddenly ceases, the direct convective thermal connection between the skin below this level and the oesophagus would be represented by the nutritive cutaneous circulation solely. Taking account of the countercurrent heat exchange between the blood vessels and their surroundings, it appears possible that the resultant damping in a system with slow rates of blood flow, such as the one mentioned, might damp out any reflexions in the oesophageal temperature due to alterations in the skin temperature. This would render the oesophageal temperature relatively independent of cyclical alterations in the skin temperature. This seemed to hold for experimental conditions depicted in figures 7 through 9. Bursts of activity appearing in the thermoregulatory circulation in connection with rapidly rising skin temperatures might establish an association between the oesophageal and skin surface temperatures even in this temperature range, and might account for the drops in oesophageal temperature indicated by arrows in figure 5.

Sinusoidal alteration in skin temperature above 34°C was reflected in a corresponding nearly sinusoidal variation in oesophageal temperature, which might be interpreted to indicate continuous activity in the thermoregulatory cutaneous circulation.

The results from experiments in which the skin surface temperature oscillated on both sides of the 34°C limit indicated an alternating association and dissociation of the direct thermal coupling between the skin and the oesophagus, its presence or absence at any one time depending on whether the cycle of alternation in the skin temperature was going through a phase representing a temperature above or below 34°C. This observation, too, would seem to be explicable by alterations in a thermoregulatory cutaneous circulation dependent on the skin temperature, as discussed above.

THE QUANTITATIVE CHARACTERISTICS OF THE RELATIONSHIP BETWEEN THE TEMPERATURES AT THE SKIN SURFACE AND IN THE OESOPHAGUS

The experimental data for a more detailed analysis of the relation between the temperatures at the skin surface and in the oesophagus were selected from exposures in the temperature range from 34°C to 40°C, within which sinusoidal alterations in skin temperature were found to induce nearly sinusoidal variations with identical angular velocities in the eosophageal temperature. The interdependence of the variables could thus be characterized on the basis of amplitude dampings and phase shifts observed with various experimentally imposed frequencies of alteration in the skin surface temperature. In table II are listed amplitudes and phase shifts of peak alterations in skin and oesophageal temperatures of three experimental subjects measured during four different exposures. The periods of the temperature cycles employed were 3.75, 5, 7.5, 10, 15, 20 and 30 minutes. The exposures were designed with the objective of 3°C as the amplitude in the skin temperature variation in mind; the actual amplitudes measured during the experiments varied from 2.7° to 3.1°C. The amplitude of the oesophageal temperature cycle in one subject was found to increase from 0.15 to 1.0°C as the corresponding period was gradually lengthened from 3.75 to 30 minutes. The time lag concomitantly increased from 1.4 to 4.2 minutes and the phase shift was reduced from 135° to 50°.

The basis used for the calculation of amplitude damping and phase shift in the temperature curves from skin and oesophagus was an extremely simplified circulatory model. This system of heat transfer was formed of two constant flow circuits coupled in parallel: the circulatory circuits of the skin and of the internal organs. Each flow circuit is characterized by a dampening factor determined by the ratio of flow to mass ($1/a_1$ and $1/a_2$). Furthermore, the surface layer of the skin was thought to cause a linear damping, represented by the factor k. In such a circulatory circuit, the amplitude damping and phase shift may be solved as follows:

$$A_{oe} = \frac{k \cdot A_s}{\sqrt{1 + (\frac{w}{a_1})^2} \cdot \sqrt{1 + (\frac{w}{a_2})^2}} \qquad \text{Eq. 1.}$$

$$f = \text{arctg}\,\frac{w}{a_1} + \text{arctg}\,\frac{w}{a_2} \qquad \text{Eq. 2.}$$

A_s = amplitude of peak alteration in skin surface temp

A_{oe} = amplitude of peak alteration in oesophageal temp

f = phase shift in the temperature cycles

w = angular velocity of temperature alteration

k = constant accounting for the damping by superficial layers of the skin

a_1 = a number expressing the relative flow rate in the circulation of blood in the skin

a_2 = a number expressing the relative flow rate in the internal organs

The numerical values for the terms a_1 and a_2 for different frequencies of oscillation were obtained from Eq. 1 by solving with respect to these terms and inserting the following relation and numerical values:

$a_2 = 3 \cdot a_1$; the ratio of relative rate of blood flow in the skin to that in the internal organs was chosen as 1 : 3

A_s and A_{oe} = the peak amplitudes of respective temperature variations were determined experimentally

$k = 0.45$; this value was adopted on the basis of intracutaneous temperature measurements

The values for a_1 and a_2 derived by the foregoing calculation were inserted into Eq. 2 and the respective phase shifts at various frequencies of temperature oscillation were calculated. The values thus obtained for the phase shifts agreed with the corresponding experimentally obtained values within the limits of error in the measurements.

THE RELATION BETWEEN TEMPERATURES ON THE SKIN AND IN THE OESOPHAGUS

Experiments with Subjects Exposed to Variations in Air Temperature

Three naked supine subjects were exposed to almost instantaneously changing air temperatures within the range from -5° to +120°C (figures 10 through 12). In figure 13 results have been depicted from an exposure in which the temperature and humidity of ambient air were varied continuously in order to impose cyclical alterations on the skin temperature. In experiments with subjects exposed to variations in air temperature, the regional differences in skin temperature tended to become markedly large and varying with time, which renders difficult measurements relevant to studies concerned with physiological aspects of the body heat exchange. With appropriate programing of air temperature, humidity, and flow rate the regional differences in skin temperature may obviously be decreased. Such arrangements were, however, not undertaken in the present study, and the significance of the results from experiments with subjects exposed to varying air temperatures lies rather in the possible suggestions for future studies that any tentative conclusions might yield.

When the experimental subject was transferred rapidly from cold to hot surroundings, the skin temperature increased initially rapidly until this direction of change either became completely abandoned or was slowed down fairly abruptly to a level corresponding to the conditions in each specific exposure (fig. 11). Already before the cessation of the phase of increase, the temperature measured from the oesophagus at a depth corresponding to the level of the adjacent pulmonary artery has attained a fairly constant rate of increase, characteristic of the conditions of exposure, which indicates the role played by the circulation in this phase of alteration in the skin temperature. After cessation of the increase in skin temperature, the rate of increase in the oesophageal temperature may sometimes be seen to decrease (fig. 11). With the transfer from hot to cold conditions, there occurs an initially rapid fall which, however, may relatively abruptly reach a level characteristic for the conditions of exposure. Already, before cessation of the decrease in the skin temperature, the oesophageal temperature has changed its direction towards a rapid linear decrease, which indicates the importance of the circulation in this phase of alteration in the skin. When the period of decrease in the oesophageal temperature is over, the skin temperature may alter its course. It was furthermore found that as in experiments with subjects immersed in water, the temperature measured in the oesophagus reflects the alterations in the temperature in the skin with a smaller damping and phase shift than the other internal temperatures. When equations 1 and 2 were adopted for exposures in air, the mean values for "a," were 0.18, 0.23, and 0.25 and the calculated phase for periods of 13 and 15 minutes agreed fairly well with those measured in the experiments (table III).

THE RELATIONS BETWEEN OESOPHAGEAL TEMPERATURE AND OTHER BODY TEMPERATURES

The relations between oesophageal temperature and other body temperatures were studied in experiments with subjects immersed in water at temperatures varying between 34° and 40°C. In this temperature region, the oesophageal temperature oscillated sinusoidally. This was reflected in a nearly sinusoidal oscillation of equal angular velocity in the sublingual, rectal, and tympanic membrane temperatures. The concurrent phase lag and amplitude damping were smallest in the sublingual and biggest in the rectal temperatures.

In order to elucidate the relations between the amplitudes and the phases of the oesophageal temperature alterations and corresponding variables in the other body temperatures, a simple circulatory circuit was used. The oesophageal temperature represented the temperature of arterial blood. The ratio of flow to mass caused damping factors to appear, which were characteristics for each site of measurement. In such circuits of flow, the amplitude damping and phase shift may be solved as follows:

$$A = \frac{A_{oe}}{\sqrt{1 + (\frac{w}{a})^2}} \qquad \text{Eq. 3.}$$

$$f = \text{arctg}\ (\frac{w}{a})^2 \qquad \text{Eq. 4.}$$

A, A_{sl}, A_{ty}, A_r = the amplitude in the temperature of the peripheral organ .... °C

A_{oe} = the amplitude in the temperature of the oesophagus............ °C

f = phase shift.. °

w = angular velocity 1/m

a, a_{sl}, a_{ty}, a_r = a figure expressing the relative rate of flow of a peripheral organ

In table IV, the values for relative rate of flow (a_{ty}, a_{sl}, a_r) have been solved according to Eq. 3 for the sites of measurement at the tympanic membrane, sublingually and in the rectum with periods of 10, 20, and 30 minutes. The damping was slightest at the site of measurement of the sublingual temperature. The values of a_{sl} in three subjects varied within the range from 0.31 to 0.46. The mean values for each individual were, respectively, 0.34, 0.37, and 0.44. The frequency did not seem to affect the a_{sl} values in the range studied. At the site of measurement on the tympanic membrane, the values for a_{ty} varied within the range from 0.22 to 0.34; the individual mean values were, respectively, 0.26, 0.29, and 0.30. The frequency did not seem to affect the value of a_{ty}. The damping was most extensive at the site of measurement of the rectal temperature, the values for a_r varied within the range from 0.043 to 0.1. The individual mean values were, respectively, 0.079, 0.076, 0.097. The values of a_r did not seem to be affected by the frequency. Most of the phase lags in the temperature curves obtained sublingually and at the tympanic membrane were equal within limits of resolution of the measurements to the shifts derived by calculation from Eq. 4 with the values for a_{ty} and a_{sl} from Eq. 3 inserted. The phase lags measured from the rectal temperature curves were 0.8 minutes longer on the average, than those derived according to Eq. 4.

In results from experiments with subjects exposed to variations in air temperature, it may also be seen that the lag and damping in the sublingual temperature are slightest of the three in relation to the concomitant oesophageal temperature alteration, with tympanic membrane and rectal temperatures following in that order, the latter being the most sluggish. When the temperature curves for the oesophagus, the sublingual space, the rectum and the tympanic membrane depicted in figure 13 were treated as if they were actually sinusoidal and the values for a_{ty}, a_{sl} and a_r were solved from Eqs. 3 and 4, these were found to be of the same range of magnitude as those obtained with immersion in water (table V).

The simple circulatory model utilized here does not account for the heat exchange taking place in the arteries, nor the heat production by the organ subject to measurement, other than the conduction effects. Neither is any consideration given to the variation in flow during each period. The effect of these factors contributes to the error in the values of relative circulation calculated for each site of measurement. To what extent these values of relative flow are typical for the temperature range of the skin and the organism studied escapes conclusion.

SUMMARY

1. An experimental tub was constructed which enabled a temperature to be homogenously distributed on the skin surface in man. It was equipped with tight and accurate controls for maintaining either a narrowly defined steady level of temperature, or executing programed variations in temperature with amplitudes and/or periods of cyclic functions adjustable in a continuous manner. The desired temperature is imposed on the skin surface by a vigorous and turbulent flow of water in the tank around the subject.

2. In this tub the effects from skin temperatures, altered sinusoidally at various amplitudes and frequencies, on the concomitantly measured temperatures

in the oesophagus, at the tympanic membrane, in the sublingual space and in the rectum were studied. Variations in skin temperature below 34°C were without significant effect on the deeper temperatures, while sinusoidal oscillations in the temperature at the skin surface above 34°C were reflected in concomitant, nearly sinusoidal alterations in the deeper temperatures.

3. The relations between various body temperatures were expressed in terms of dampings and phase lags measured from recordings of experimentally produced cyclic alterations. Simple mathematical relations could be demonstrated between the skin and oesophageal temperatures, on one hand, and between the oesophageal and other body temperatures, on the other, in the experimental conditions employed.

TABLE I

DATA OF SUBJECTS

Subject	Age	Height cm	Weight kg	Body Area m^2
P.P.	39	186	92	2.13
V.M.	34	174	72.5	1.86
E.S.	27	173	68.5	1.81
R.R.	26	181	71	1.90
K.W.	25	169	62	1.71
T.L.	24	182	68.5	1.87
A.L.	23	173	64	1.76
K.H.	23	172	62	1.72

TABLE II

THE RELATION BETWEEN THE TEMPERATURES ON THE SKIN SURFACE AND IN THE OESOPHAGUS IN EXPERIMENTS WITH THREE SUBJECTS IMMERSED IN WATER. THE SYMBOLS ARE THOSE USED IN EQS. 1 AND 2.

Subj.	Period Min.	$2\ A_s$ °C	$2\ A_{oe}$ °C	a_1	a_2	f_m min.	f_c min.
A.L.	10	5.70	1.18	0.37	1.10	2.5	2.4
	20	5.85	1.80	0.32	0.95	3.5	3.3
	30	6.00	2.18	0.30	0.90	4.0	4.1
R.R.	10	6.20	0.95	0.30	0.90	2.8	2.7
	20	6.08	1.71	0.30	0.90	3.5	3.4
	30	5.90	2.26	0.33	1.00	3.9	4.0
V.M.	10	6.23	1.11	0.32	0.96	2.6	2.4
	20	5.90	1.75	0.30	0.90	3.6	3.4
	30	6.00	2.10	0.28	0.85	4.2	4.0
V.M.	3.75	5.90	0.33	0.40	1.20	1.4	1.4
	5	5.74	0.60	0.40	1.20	1.7	1.8
	7.5	5.73	0.92	0.38	1.15	2.1	2.3
	10	5.56	1.03	0.32	0.95	2.6	2.5
	15	5.43	1.28	0.30	0.91	3.3	3.2
	30	5.76	2.01	0.28	0.85	4.2	4.0

TABLE III

THE RELATION BETWEEN THE TEMPERATURES ON THE SKIN SURFACE AND IN THE OESOPHAGUS IN AN EXPERIMENT WITH A SUBJECT EXPOSED TO AIR. THE SYMBOLS ARE THOSE USED IN EQS. 1 AND 2.

Subj.	Period Min.	$2\ A_s$ °C	$2\ A_{oe}$ °C	a_1	a_2	f_m min.	f_c min.
K.H.	13	7.10	0.81	0.18	0.55	3.9	3.5
	15	8.10	1.60	0.23	0.70	3.8	3.7
	15	8.10	1.75	0.25	0.75	3.7	-

TABLE IV

THE RELATION BETWEEN OESOPHAGEAL AND SUBLINGUAL TEMPERATURES
IN EXPERIMENTS WITH THREE SUBJECTS IMMERSED IN WATER
THE SYMBOLS REFER TO EQS. 3 AND 4.

Subj	Period Min.	2 A_{ce} °C	2 A_{sl} °C	a_{sl}	a_{sl} Mean	f_m Min.	f_c Min.
A.L.	10	1.18	0.48	0.33		1.7	1.7
	20	1.80	1.28	0.32		2.0	2.4
	30	2.20	1.90	0.38	0.34	1.9	2.5
V.M.	10	1.10	0.49	0.31		1.0	1.8
	20	1.77	1.41	0.44		2.0	1.9
	30	2.12	-	-	0.37	-	-
R.R.	10	0.94	0.56	0.46		1.4	1.5
	20	1.70	1.37	0.42		2.4	2.1
	30	2.24	2.04	0.45	0.44	2.2	2.1

TABLE V

THE RELATION BETWEEN OESOPHAGEAL AND TYMPANIC MEMBRANE TEMPERATURES IN EXPERIMENTS WITH THREE SUBJECTS IMMERSED IN WATER THE SYMBOLS REFER TO EQS. 3 AND 4.

Subj.	Period Min.	$2\ A_{oe}$ °C	$2\ A_{ty}$ °C	a_{ty}	a_{ty} Mean	f_m Min.	f_c Min.
	10	1.18	0.46	0.26		2.0	1.9
A.L.	20	1.80	1.16	0.26		3.1	2.8
	30	2.20	1.70	0.26	0.26	2.9	3.0
	10	1.10	0.36	0.22		1.6	2.0
V.M.	20	1.77	1.25	0.31		2.8	2.5
	30	2.12	1.78	0.34	0.29	3.1	2.6
	10	0.94	0.42	0.32		2.9	1.7
R.R.	20	1.70	1.11	0.27		3.3	2.7
	30	2.24	1.88	0.31	0.30	3.0	2.8

TABLE VI

THE RELATION BETWEEN THE OESOPHAGEAL AND RECTAL TEMPERATURES IN EXPERIMENTS WITH THREE SUBJECTS IMMERSED IN WATER SYMBOLS AS IN EQS. 3 AND 4

Subj.	Period Min.	$2\,A_{oe}$ °C	$2\,A_r$ °C	a_r	a_r Mean	f_m Min.	f_c Min.
A.L.	10	1.18	0.12	0.063		3.3	2.4
	20	1.80	0.42	0.075		5.7	4.2
	30	2.20	0.73	0.074	0.079	7.0	5.8
V.M	10	1.10	0.18	0.100		3.4	2.4
	20	1.77	0.37	0.067		4.4	4.3
	30	2.12	0.59	0.062	0.076	6.9	6.1
R.R.	10	0.94	0.16	0.101		3.1	2.4
	20	1.70	0.47	0.095		4.7	4.1
	30	2.24	0.94	0.095	0.097	6.0	5.5

TABLE VII

THE RELATIONS BETWEEN THE OESOPHAGEAL TEMPERATURE AND THE SUBLINGUAL, RECTAL AND TYMPANIC MEMBRANE TEMPERATURES IN AN EXPERIMENT WITH A SUBJECT EXPOSED TO AIR

Subj.	Period Min.	$2\ A_{oe}$ °C	$2\ A_{sl}$ °C	a_{sl}	f_m Min.	f_c Min.
K.H.	13	0.81	0.52	0.41	0.8	1.7
	15	1.60	1.30	0.50	-	1.6
	15	1.75	-	-	-	-

Subj.	Period Min	$2\ A_{oe}$ °C	$2\ A_{ty}$ °C	a_{ty}	f_m Min.	f_c Min.
K.H.	13	0.81	0.43	0.30	1.5	2.0
	15	1.60	0.94	0.30	2.1	2.2
	15	1.75	1.07	0.30	-	2.2

Subj.	Period Min.	$2\ A_{oe}$ °C	$2\ A_r$ °C	a_r	f_m Min.	f_c Min.
K.H.	13	0.81	0.07	0.075	2.6	3.0
	15	1.60	0.26	0.070	3.5	3.4
	15	1.75	0.35	0.081	-	3.3

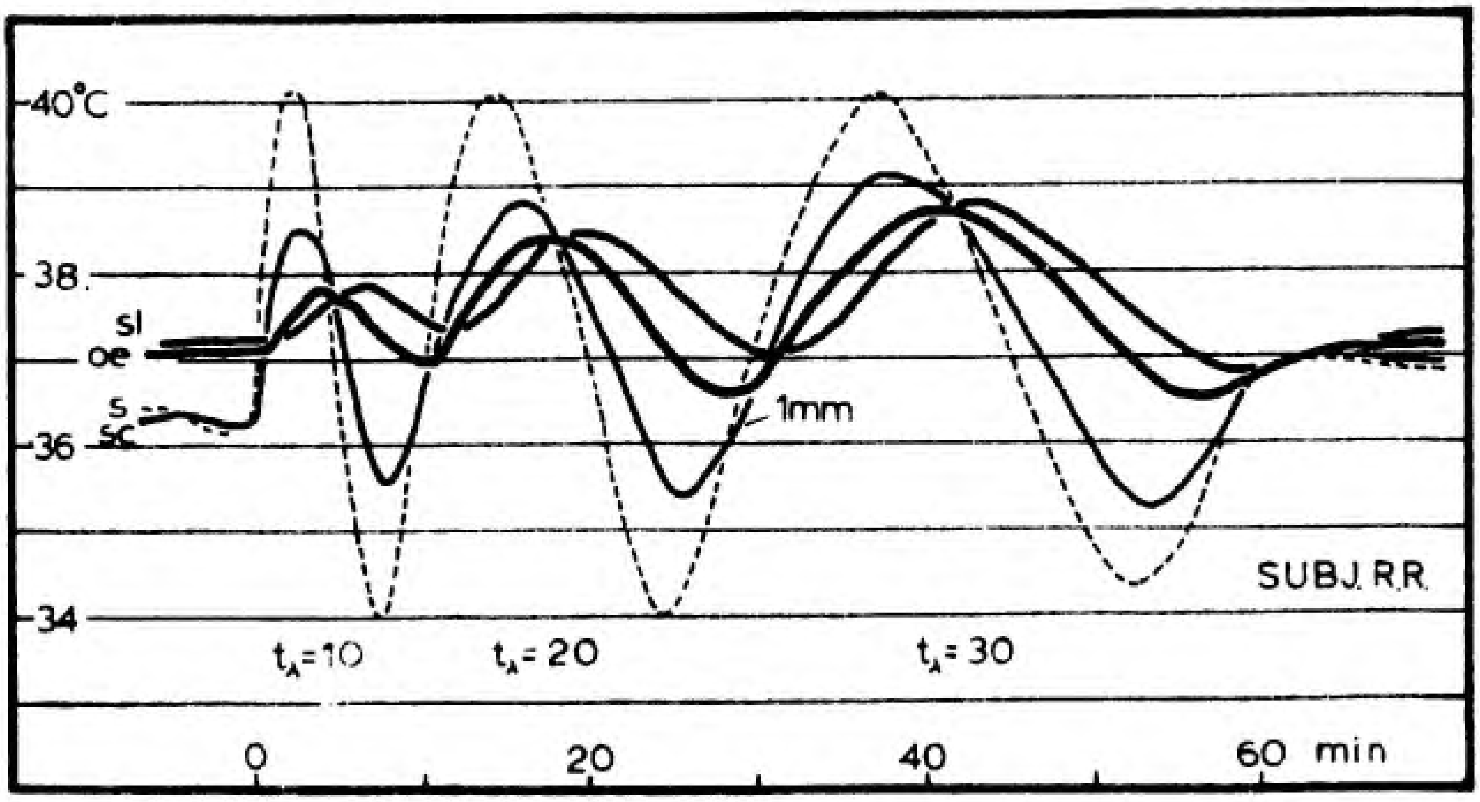

Figure 1. Temperatures in Subject Immersed into Flowing Water of Alternating Temperature Programed to Produce Approximately Sinusoidal Oscillations in Skin Temperature of 3° C Amplitude and Successive Periods of 10, 20 and 30 Minutes; Mid-Level Skin Temperature 37° C, See Text for Details. Curves:

Skin Surface Temperature on Lateral Aspect of Thigh......... (s)
Intracutaneous Temperature.................................. (sc)
Sublingual Temperature...................................... (sl)
Oesophageal Temperature (at 37.5 cm from nostril)........... (oe)

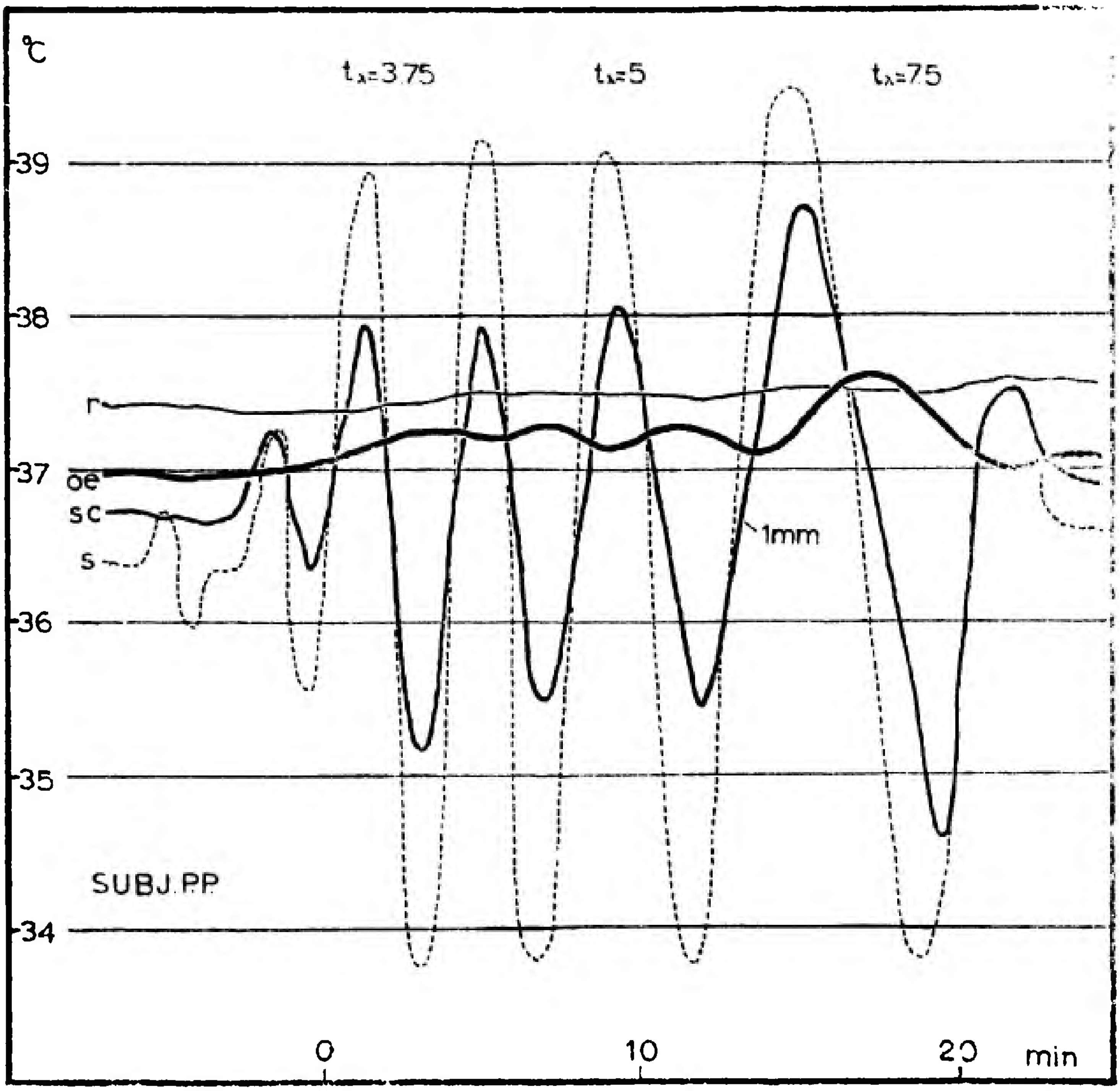

Figure 2. Temperatures in Subject During Approximately Sinusoidal Oscillations in Skin Temperature with a 37° C Mid-Level, 3° C Amplitudes and Successive Periods of 3.75, 5 and 30 minutes. Experimental Arrangement as in Fig. 1. Curves Designated as in Fig. 1, with the Addition of

Rectal temperature.. (r)

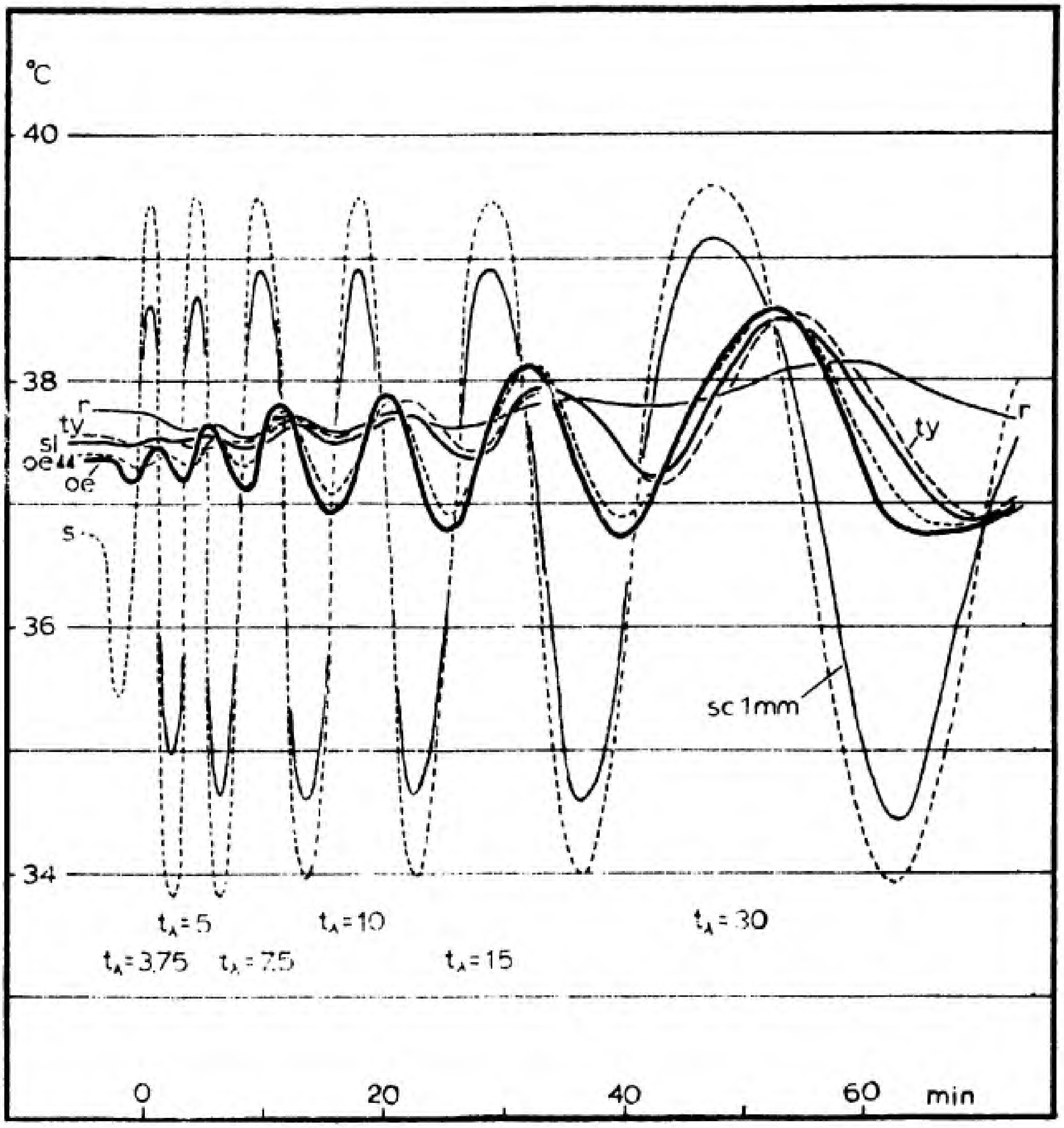

Figure 3. Temperatures in Subject During Approximately Sinusoidal Cyclical Alterations in Skin Temperatures with a 37° C Mid-Level, 3° C Amplitudes and Periods Increasing from 3.75 to 30 Minutes. Experimental Arrangement as in Fig. 1. Curves Designated as in Previous Figures with the Addition of

Tympanic Membrane Temperature................................ (ty)
Oesophageal Temperature (at 44 cm from nostril)............. (oe 44)

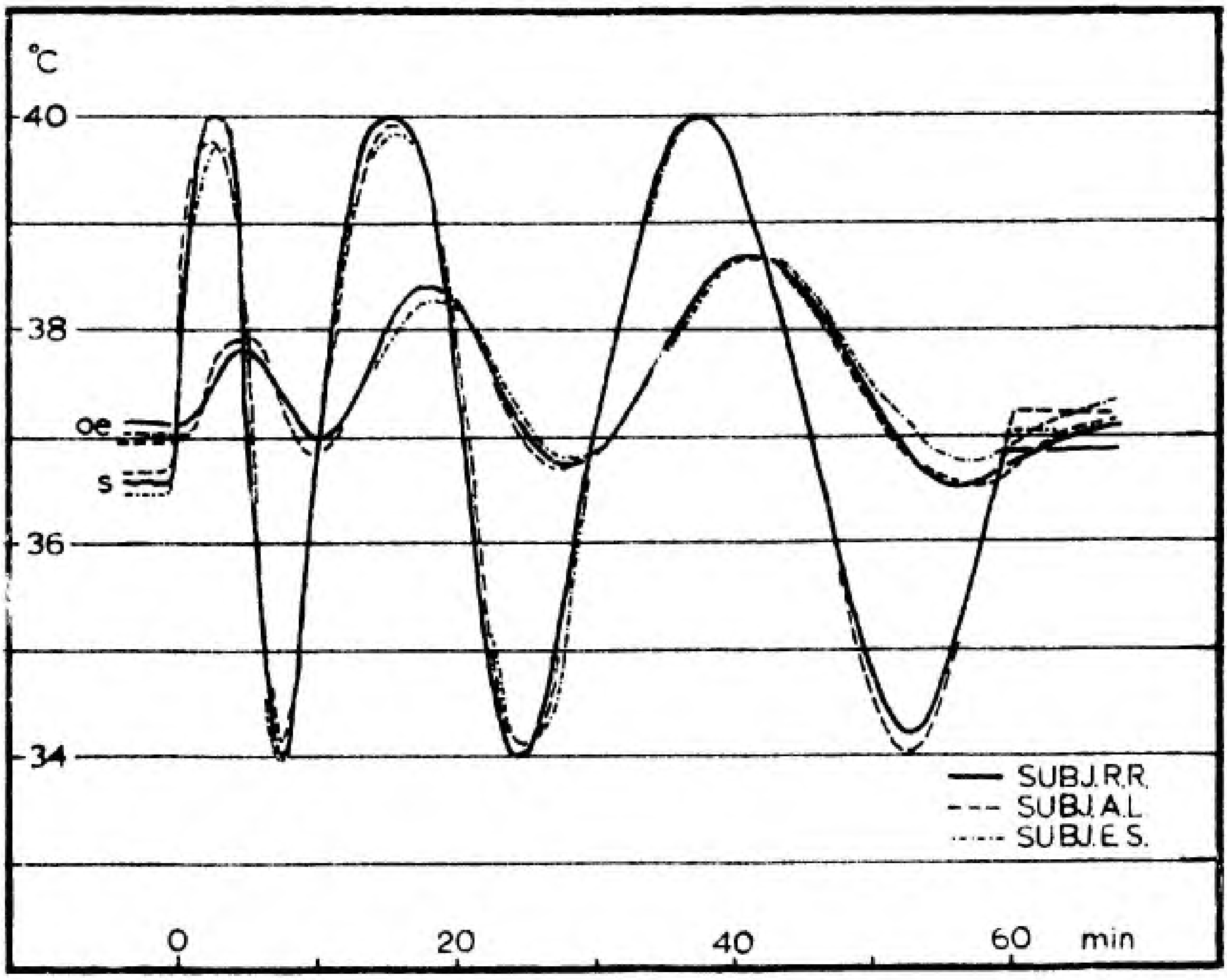

Figure 4. Oesophageal Temperatures in 3 Subjects During Approximately Sinusoidal Oscillations in their Skin Temperatures at a Mid-Level of 37° C, with 3°C Amplitudes and Successive Periods of 10, 20, and 30 Minutes. Experimental Arrangement as in Fig. 1. Curves Designated as in Figures 1 and 2.

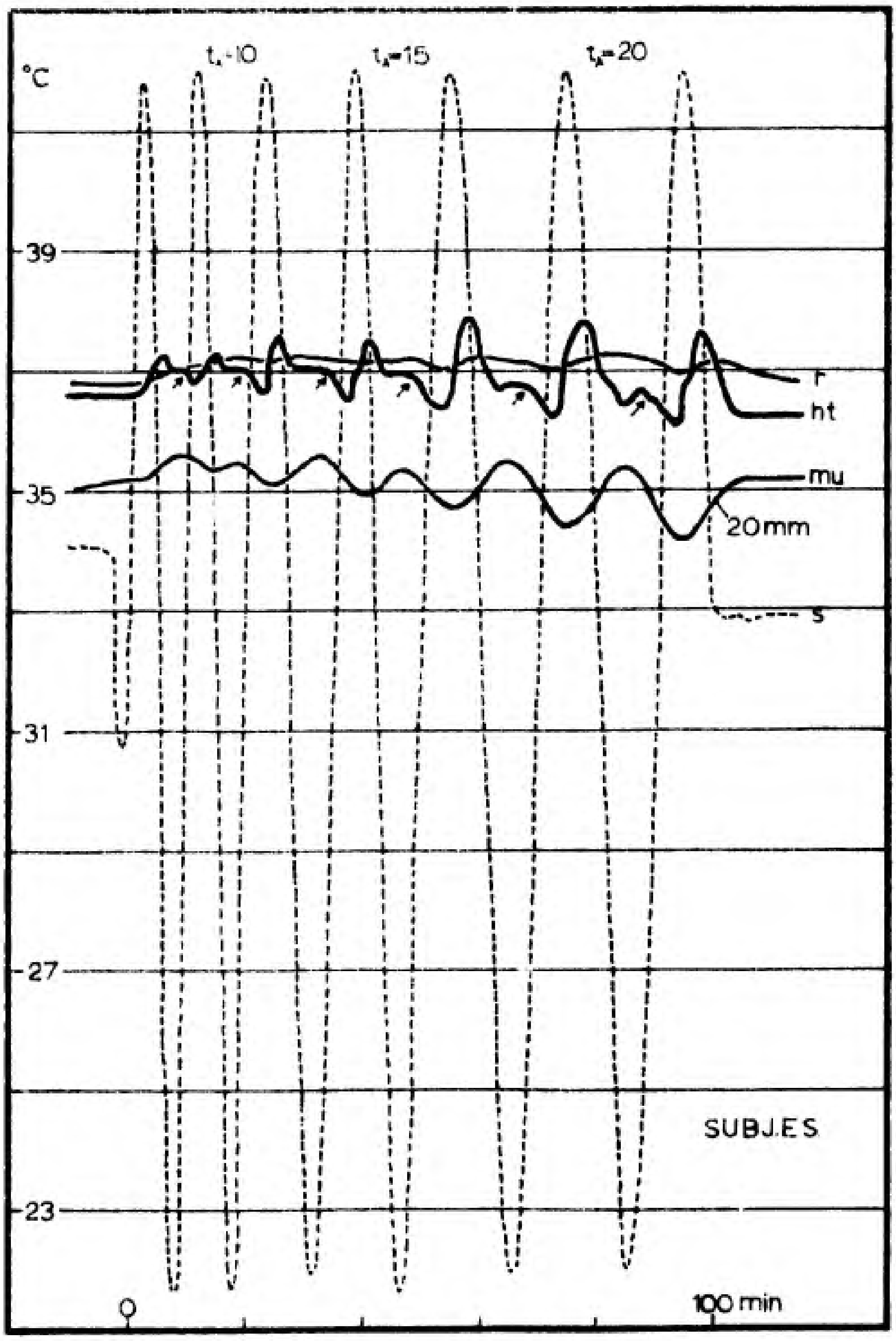

Figure 5. Deep Body Temperatures During Large Approximately Sinusoidal Oscillations in Skin Temperature Around a Mid-Level of 32° C with a 10° C Amplitude and Periods Increasing from 10 to 20 Minutes. Experimental Arrangement as in Fig. 1. Note Exceptional Asymmetry in the Curves Recorded from the Oesophagus; the Notches Marked with Arrows in the Descending Phase of the Cycle are Discussed in Detail in the Text. Designation of Curves as in Previous Figures with the addition of

Intramuscular Temperature (at a Depth of 20 mm from Skin Surface in the vastus Lateralis Muscle of the Thigh.............(mu 20 mm)
Oesophageal Temperature (at 44 cm from Nostril).........(ht)

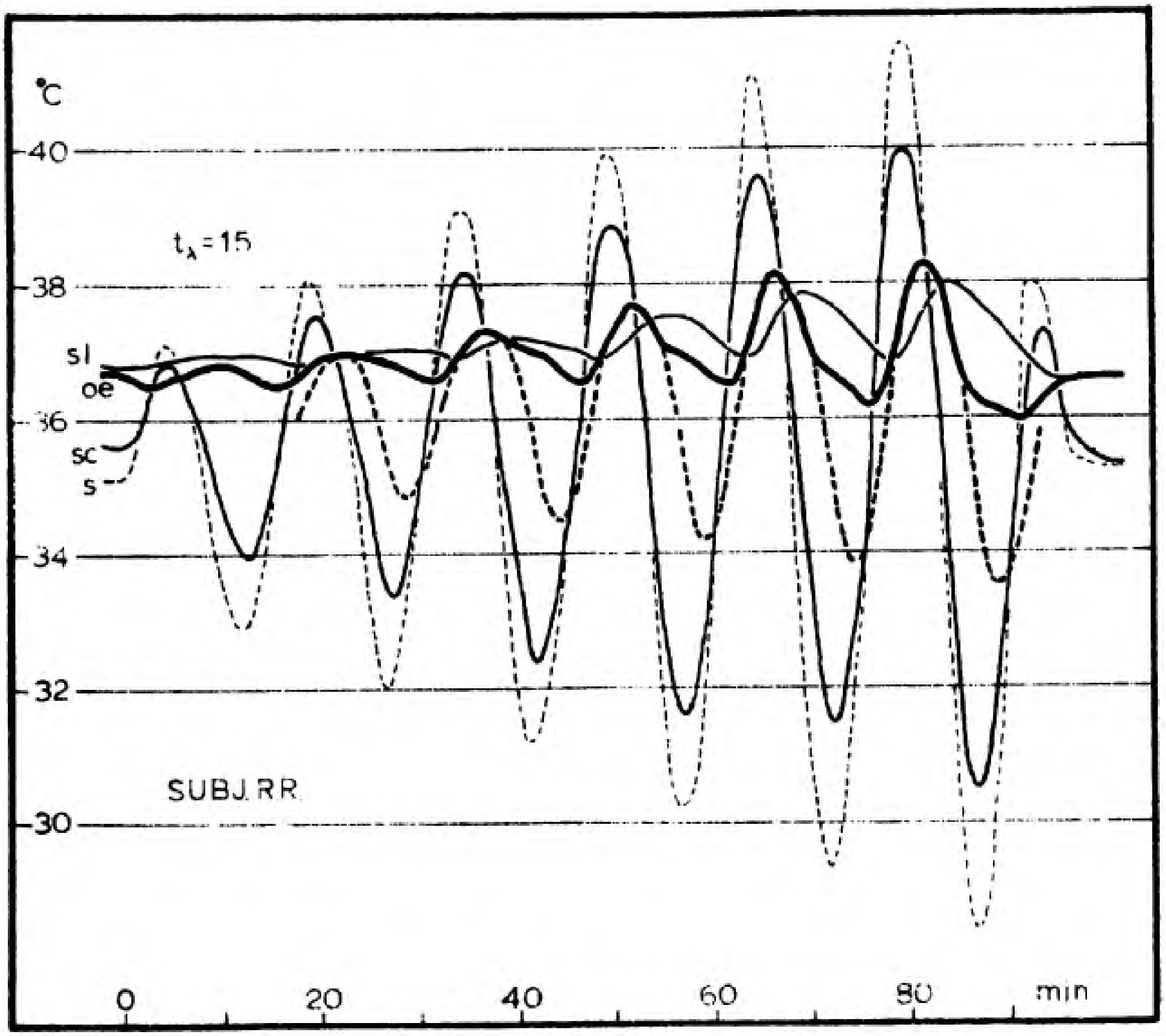

Figure 6. Internal Temperatures in Experimental Subject During Forced Approximately Sinusoidal Oscillations of Steadily Increasing Amplitude Around a Mid-Level of 35° C and with a Period of 15 Minutes. Experimental Arrangement as in Fig. 1. Curves Designated as in Previous Figures.

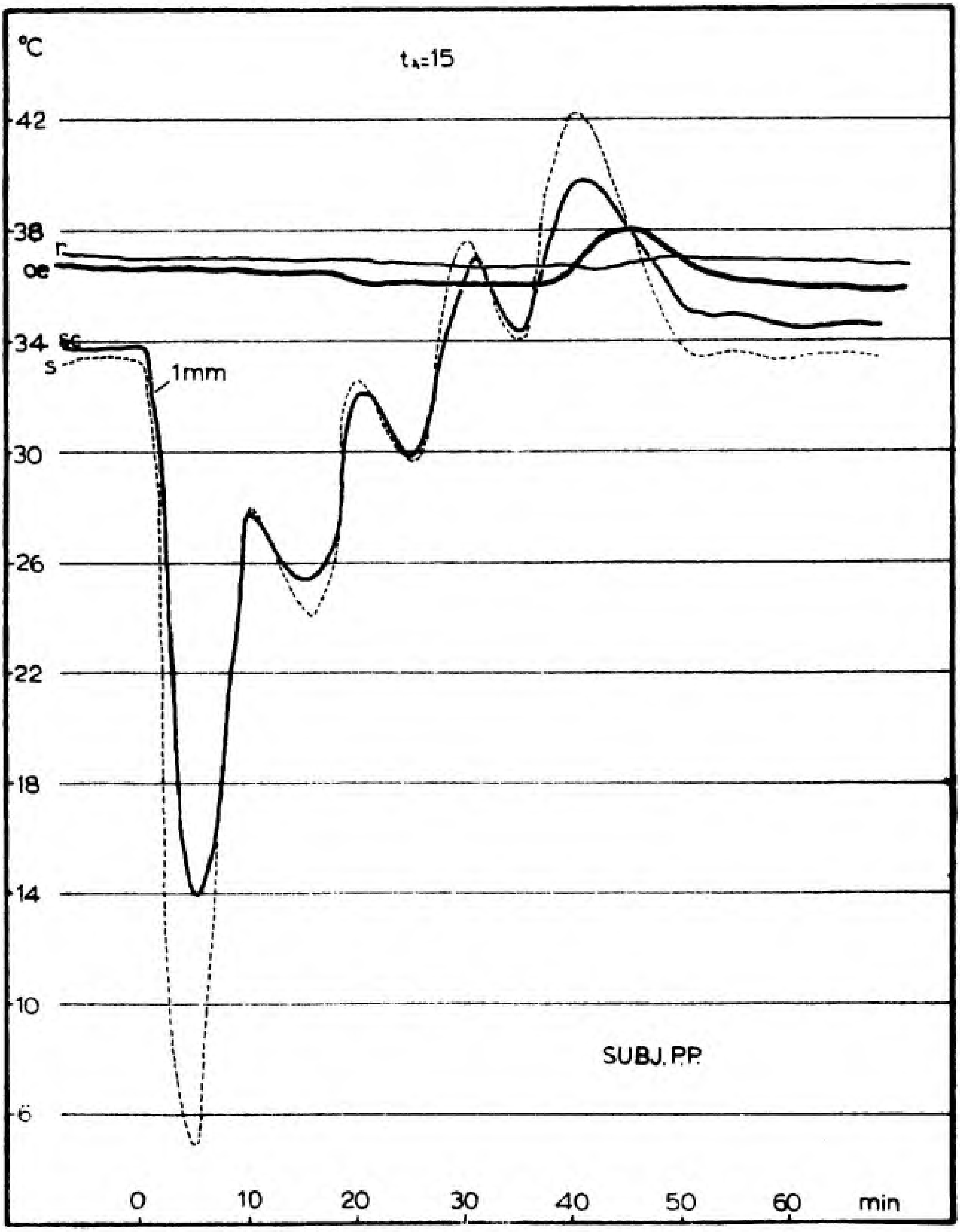

Figure 7. Internal Temperatures in Experimental Subject During a Steep Decrease in Skin Temperature, Followed by Cyclical Variations of About 4° C Amplitude and a Period of 15 Minutes Around a Steadily Increasing Mean Value. Experimental Arrangement in Principle as in Fig. 1. Curves Designated as in Figures 1 and 2.

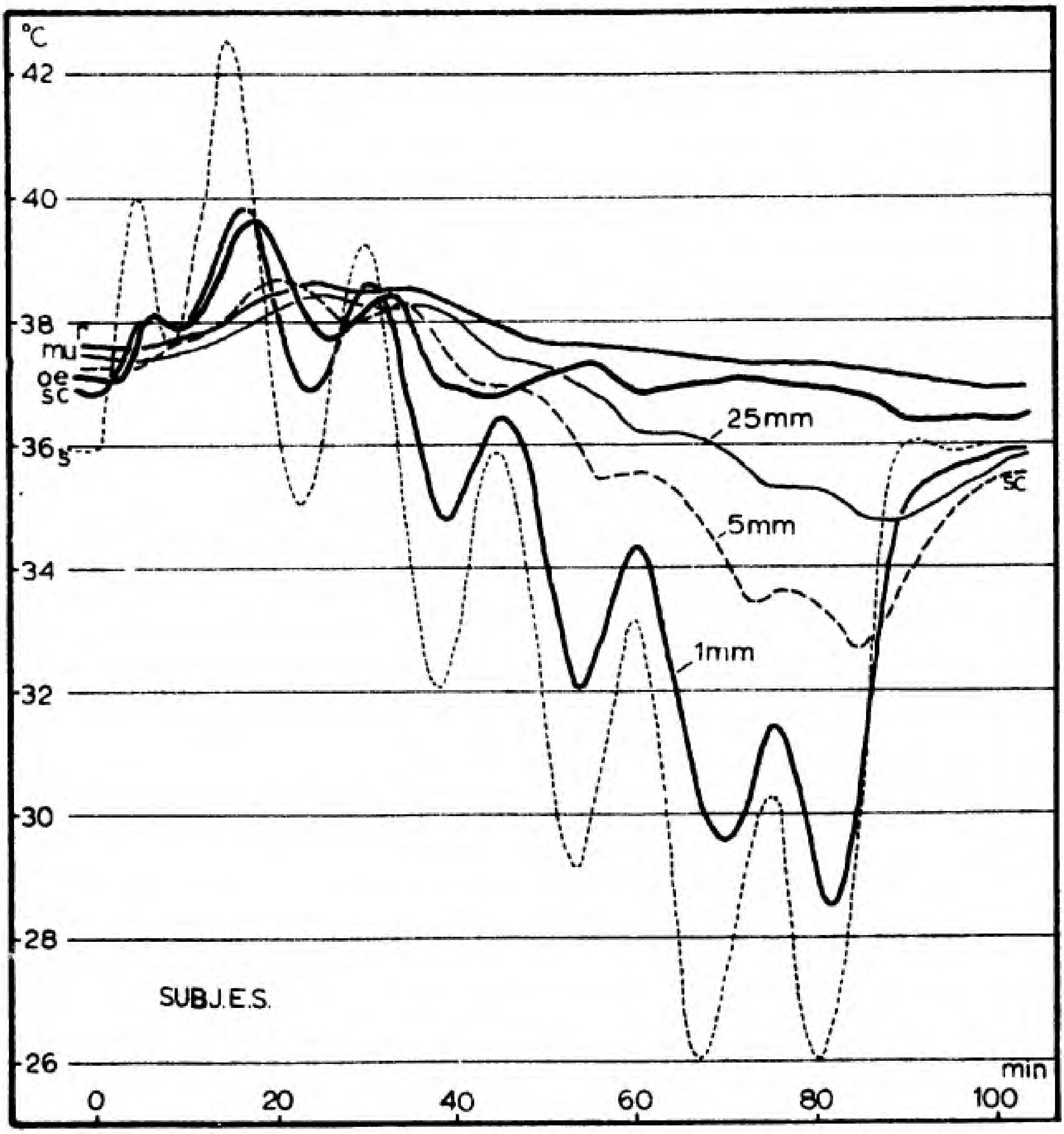

Figure 8. Internal Temperatures in Experimental Subject During Approximately Sinusoidal Variations of About 3.5° C Amplitude and a Period of 20 Minutes in Skin Temperature Around a Decreasing Mean Value. Experimental Arrangement in Principle Similar to that in Fig. 1. Curves Designated as in Figures 1 and 2, Except for

Intracutaneous Temperature (1 mm depth from Skin Surface on the Lateral Aspect of the Thigh) (sc 1 mm)
Subcutaneous Temperature (5 mm depth) (sc 5 mm)
Intramuscular Temperature (25 mm depth) (mu 25 mm)

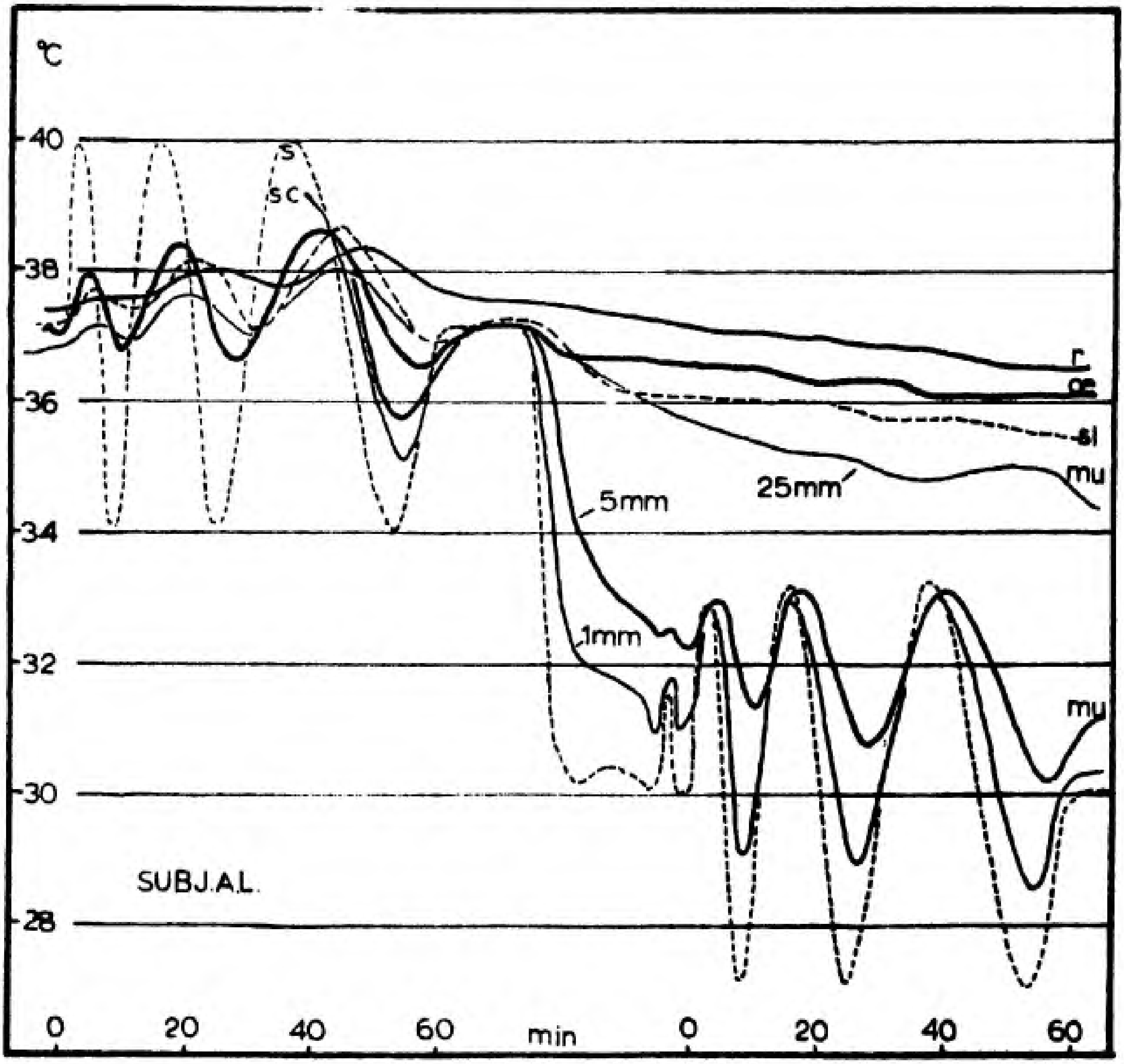

Figure 9. Internal Temperatures in Experimental Subject During Approximately Sinusoidal Variations in Skin Temperature of 3° C Amplitude in Two Successive Series with Cycles of 10, 20 and 30 Minutes, each Around Mid-Level Values of 37° C and 30° C, in that Order. Experimental Arrangement in Principle Similar to that Described in Fig. 1. Curve Designation as in Fig. 8.

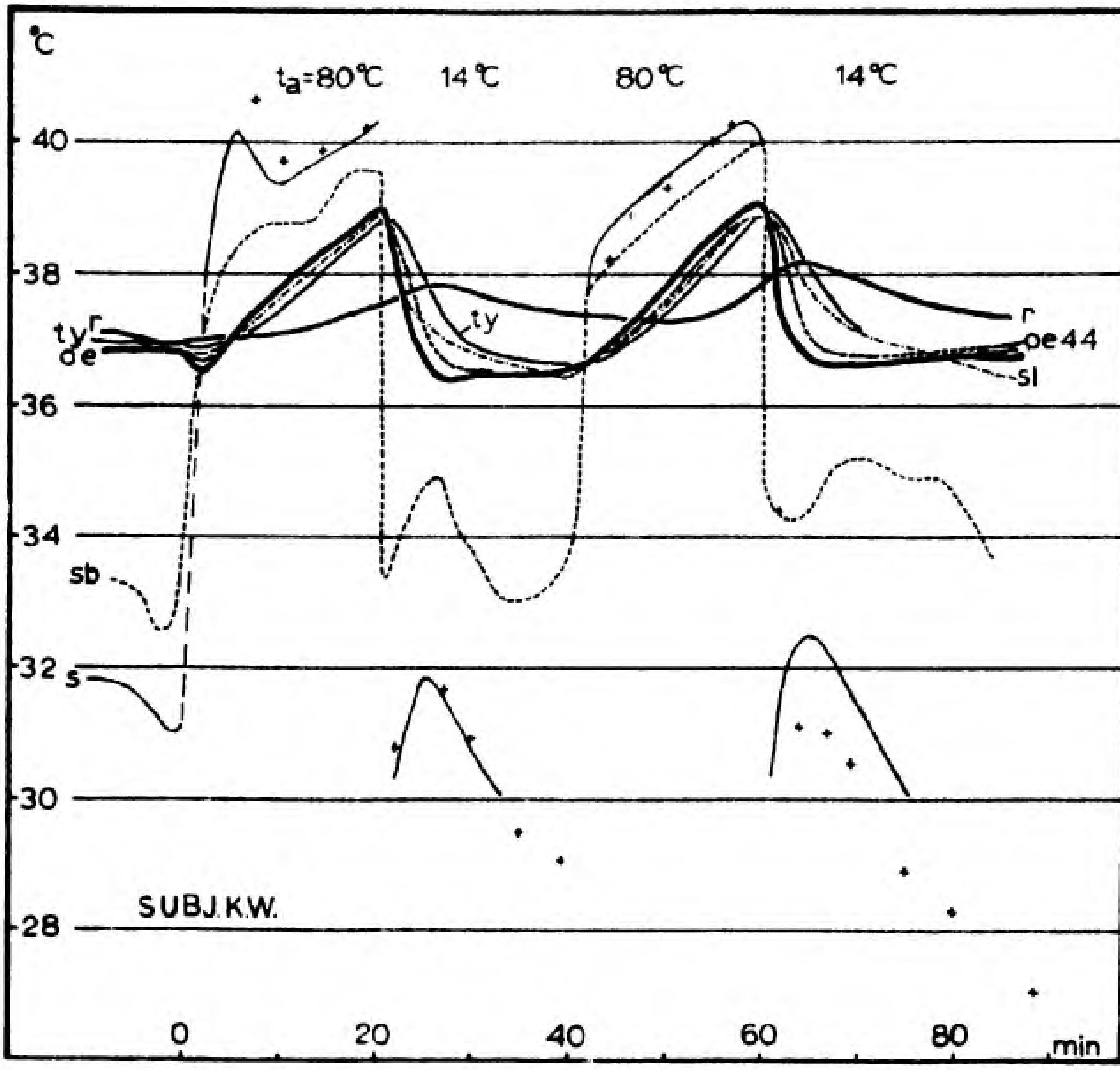

Figure 10. Skin and Internal Temperatures in Nude Experimental Subject During Successively Repeated 20 Minutes Exposures to, Alternately, Relatively Calm Air at 80° C and Rapidly Flowing Air at 14° C, in that Order. Curve Designations as in Previous Figures with the Addition of

Mean Skin Surface Temperature.................................. (+)
Skin Surface Temperature of Chest.............................. (sb)

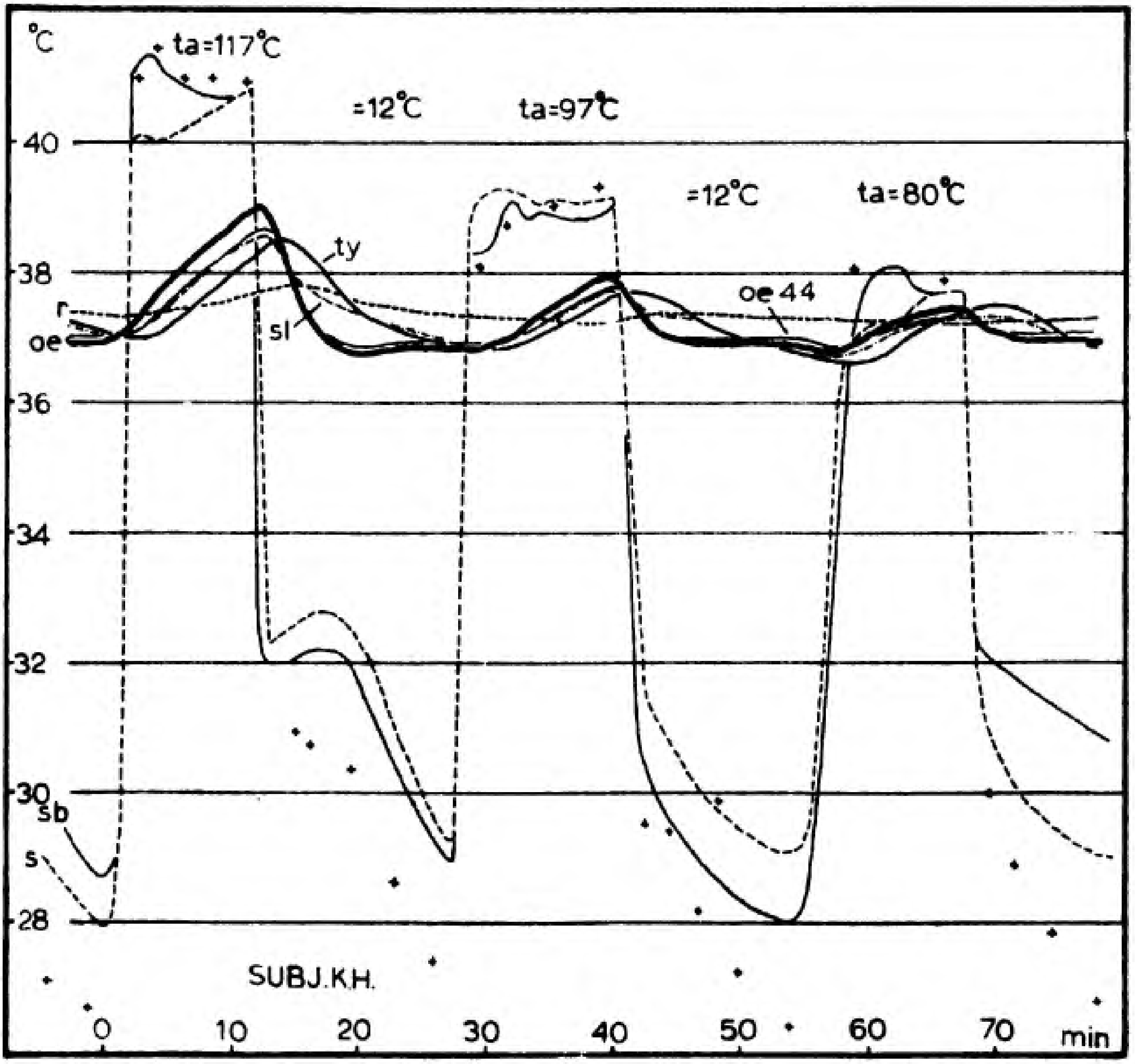

Figure 11. Skin and Internal Temperatures in Naked Experimental Subject During Three Successive Periods of Exposure to Relatively Calm Air at 117° C, 97° C and 80° C, respectively, alternating with Rapidly Flowing Air at 12° C. Curve Designation as in Previous Figures.

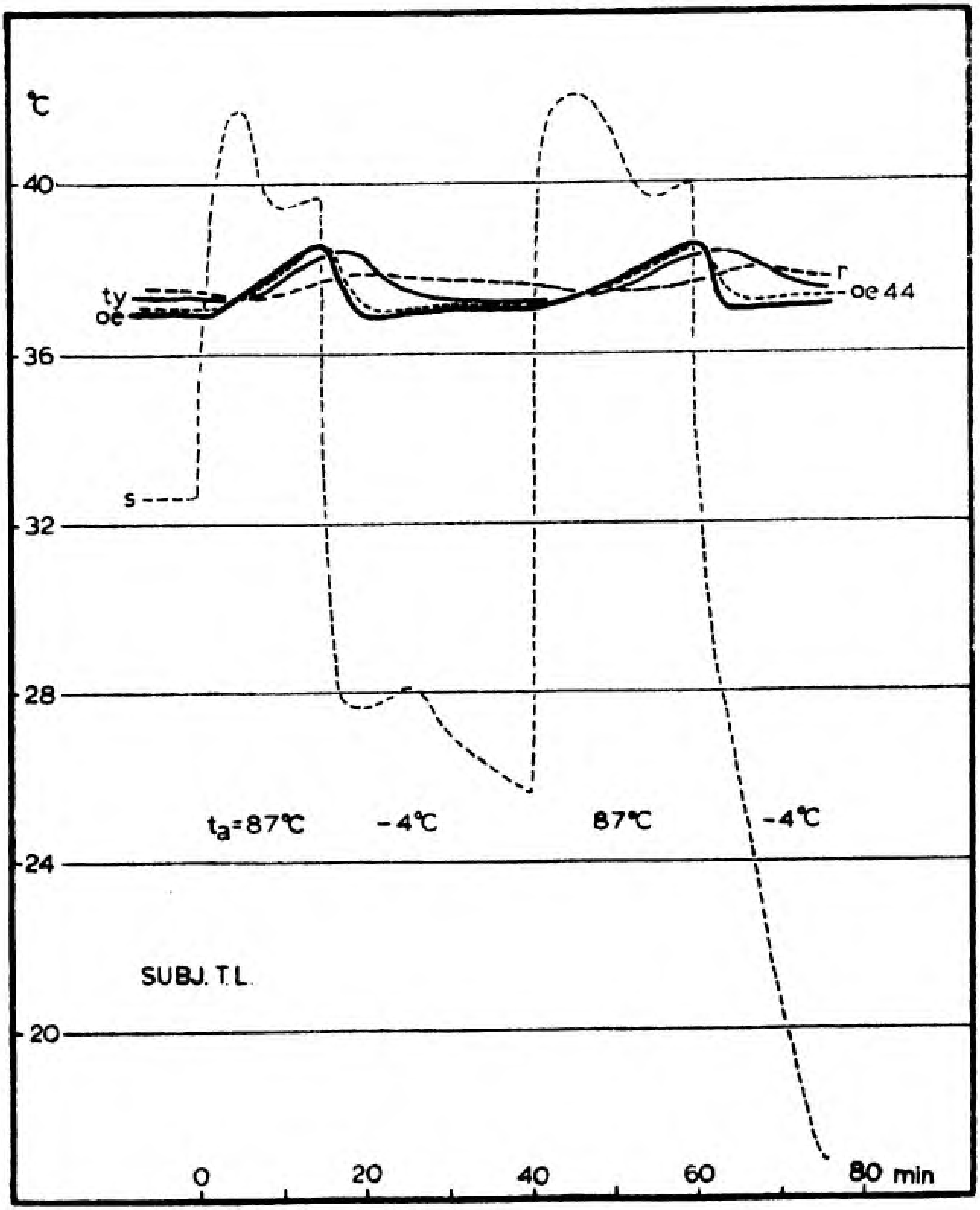

Figure 12. Skin and Internal Temperatures in Naked Experimental Subject During Successive Periods of Exposures to Relatively Calm Air at 80° C, air at -4° C with twice the Flow Rate in the Preceding Exposure to Cold, in that Order. Curve Designation as in Previous Figures.

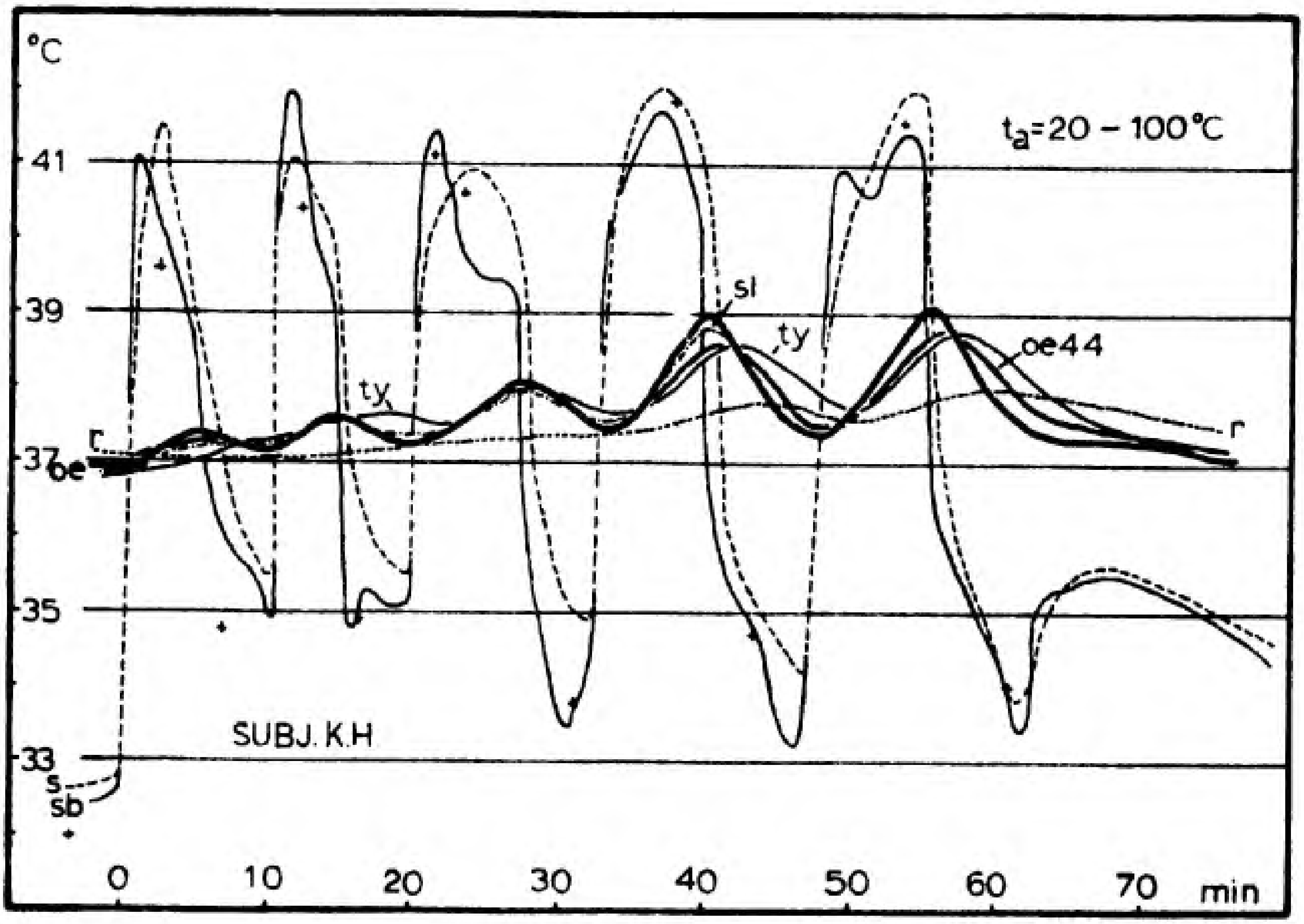

Figure 13. Skin and Internal Temperatures in Naked Experimental Subject During Exposure to Air of Continually Altered Temperature and Humidity to Produce Cyclic Variation in the Skin Temperature, for Details See Text. Curve Designation as in Previous Figures.

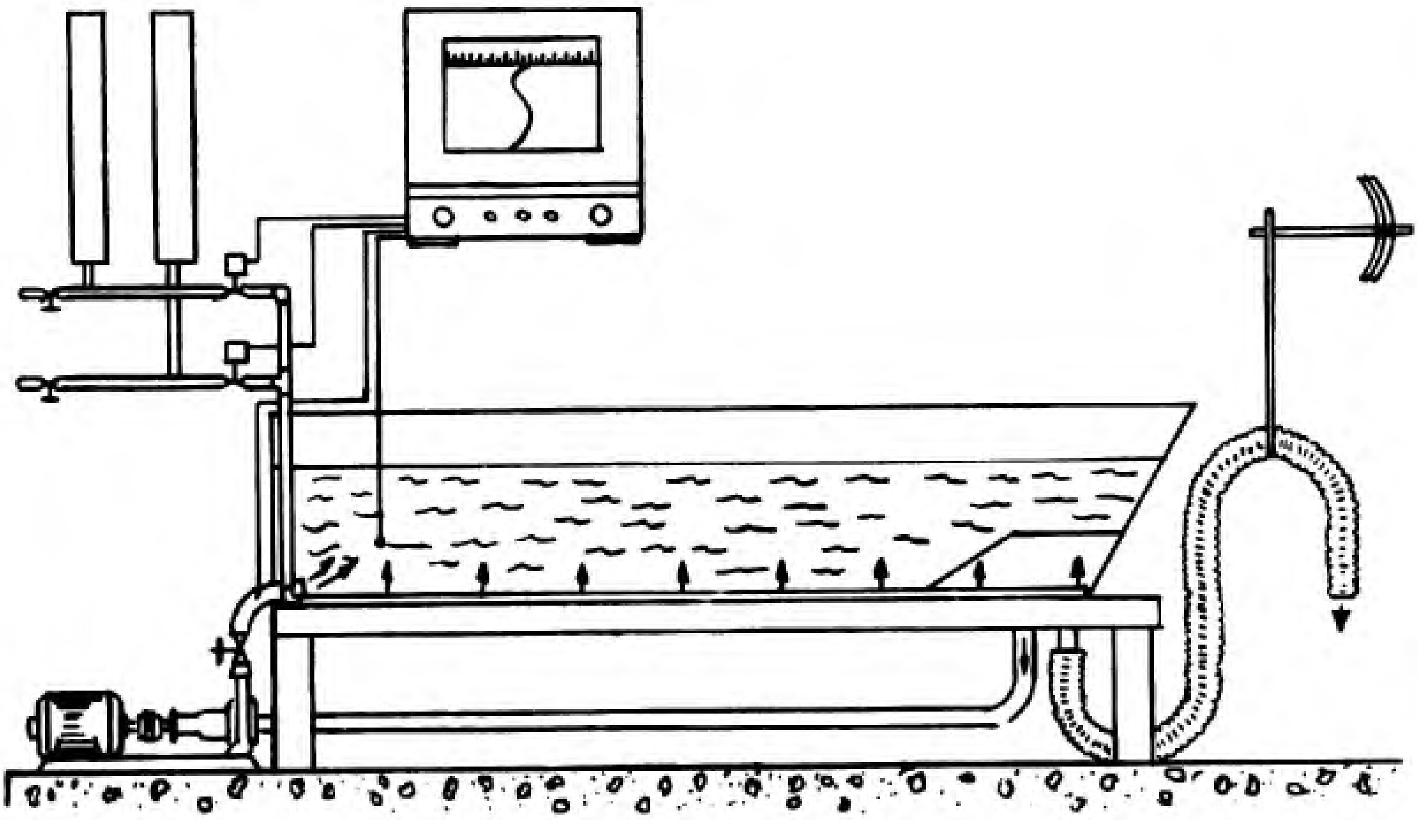

Figure 14. Experimental Tub, See Text for Details.

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Eight nude resting male subjects were immersed in water. The temperature of the bath was varied cyclically from -5° to 42°C. Similar experiments were performed in air with temperatures varying from -5° to 120°C. Skin temperatures oscillated sinusoidally with amplitudes varying from 1° to 10°C and periods varying from 3.75 to 30 minutes. Variations in skin temperature below 30°C did not affect the oesophageal temperature. Sinusoidal variations in skin temperature above 34°C were reflected in nearly sinusoidal alterations in the oesophageal temperature. Sinusoidal variations in oesophageal temperature were accompanied by nearly sinusoidal alterations in rectal, sublingual and tympanic membrane temperatures, with damping characteristics and phase shifts typical for each site of measurement.

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