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Evaluation of thermal strain by physiological measurements

Évaluation de l'astreinte thermique par mesures physiologiques

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 9886 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Sub-Committee SC 5, *Ergonomics of the physical environments*.

Annexes A, B, C and D of this International Standard are for information only.

International Organization for Standardization
Case Postale 56 • CH-1211 Genève 20 • Switzerland

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Introduction

This International Standard is part of a series of standards concerned with the assessment of thermal stress and strain.

This series of International Standards aims in particular at:

a) establishing specifications for the methods of measuring physical parameters characterizing thermal environments;

b) establishing methods for assessing thermal stress in cold, moderate and hot environments.

The analysis methods described by these latter standards allow the prediction of the average physiological response of subjects exposed to a thermal environment. Some of these methods are not applicable under exceptional climatic circumstances, when the characteristics of the exposed subjects differ greatly from the average or when special means of protection are used.

In these cases, or for the sake of research, it may be useful or even necessary to measure directly the physiological strain experienced by the subject.

This International Standard gives a series of specifications concerning the methods of measurement and interpretation of the physiological parameters considered as reflecting the response of the human organism placed in a hot or cold environment.

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Evaluation of thermal strain by physiological measurements

1 Scope

This International Standard describes methods for measuring and interpreting the following physiological parameters:

a) body core temperature;

b) skin temperatures;

c) heart rate;

d) body mass loss.

The choice of variables to be measured and techniques to be used is at the discretion of those responsible for the health of the employees. These persons will have to take into account not only the nature of the thermal conditions, but also the degree of acceptance of these techniques by the employees concerned.

It should be emphasized that direct measurements on the individual may only be carried out on two conditions:

a) if the person has been fully informed about the discomfort and the potential risks associated with the measurement technique and gives free consent to such measurements;

b) if the measurements present no risk for the person which is unacceptable in view of general or specific codes of ethics.

In order to simplify this choice, annex A presents a comparison of the different methods concerning their field of application, their technical complexity, the discomfort and the risks that they might involve.

This International Standard defines the conditions which are to be met in order to ensure the accuracy of the data gathered from the different methods. The measurement methods are described in annex B. Limit values are proposed in annex C.

This International Standard is not concerned with experimental conditions for which investigators may develop alternative methods intended to improve knowledge in this area. It is recommended, however, when conducting such studies in the laboratory, to use the methods described below as references, so that results can be compared.

2 Measurement of body core temperature, t_{cr}

2.1 General

The term "core" refers to all the tissues located at a sufficient depth not to be affected by a temperature gradient through surface tissue. Temperature differences are however possible within the core depending on local metabolisms, on the concentration of vascular networks and on local variations in blood flow. The core temperature is thus not a unique concept and measurable as such. This temperature may be approximated by the measurement of temperature at different points of the body:

a) oesophagus: oesophageal temperature, t_{es};

b) rectum: rectal temperature, t_{re};

c) gastro-intestinal tract: intra-abdominal temperature, t_{ab};

d) mouth: oral temperature, t_{or};

e) tympanum: tympanic temperature, t_{ty};

f) auditory canal: auditory canal temperature, t_{ac};

g) urine temperature, t_{ur}.

The order of presentation of these different techniques has been adopted only for the clarity of the presentation.

Depending on the technique used, the temperature measured can reflect

— the mean temperature of the body mass; or

— the temperature of the blood irrigating the brain and therefore influencing the thermoregulation centres in the hypothalamus. This temperature is usually considered for assessing the thermal strain sustained by a subject.

2.2 Measurement techniques for indicators of body core temperature

2.2.1 Oesophageal temperature, t_{es}

2.2.1.1 Principle of the method

The temperature transducer is introduced in the lower part of the oesophagus, which is in contact over a length of 50 mm to 70 mm with the front of the left auricle and with the rear surface of the descending aorta. In this position, the temperature transducer registers variations in arterial blood temperature with a very short reaction time.

The upper part of the oesophagus presses against the trachea and the measurement of temperature at that level is affected by breathing. On the contrary, if the transducer is placed too low, it records gastric temperature.

The transducer is also influenced by the temperature of the saliva swallowed by the subject. The oesophageal temperature is therefore not given by the mean value of the recorded temperatures but by the peak values. This is particularly true in cold environments, where the saliva can be chilled.

2.2.1.2 Interpretation

Of all the indirect measurements of t_{cr} mentioned above, t_{es} is the one which most accurately reflects temperature variations in the blood leaving the heart, and in all probability, the temperature of the blood irrigating the thermoregulation centres in the hypothalamus.

2.2.2 Rectal temperature, t_{re}

2.2.2.1 Principle of the method

A temperature transducer is inserted in the rectum; this being surrounded by a large mass of abdominal tissues with low thermal conductivity, the rectal temperature is independent of ambient conditions.

2.2.2.2 Interpretation

When the subject is resting, the rectal temperature is the highest of the body temperatures. When the subject is working, on the contrary, t_{re} is directly affected by the production of heat from the local muscles: with an equal expenditure of energy per unit of time, t_{re} is higher when work is performed with the legs than when it is carried out exclusively with the arms.

t_{re} essentially gives an indication of the mean temperature of body core mass. It may only be considered as an indicator of blood temperature and therefore of the temperature of the thermoregulation centres when heat storage is slow and when work is performed using the whole body.

When heat storage is low and work is essentially performed with the legs, the measurement of t_{re} leads to a slight overestimation of the temperature of the thermoregulation centres. On the contrary, in case of rapid storage, during intense thermal stress of short duration, t_{re} rises at a slower rate than the temperature of the thermoregulation centres, continues to rise after the exposure has stopped and finally decreases progressively. Rising speed and lag time are depending on the exposure and recovery conditions. In theses cases t_{re} is an inappropriate way in which to estimate the strain sustained by a subject.

2.2.3 Intra-abdominal temperature, t_{ab}

2.2.3.1 Principle of the method

A temperature transducer is swallowed by the subject. During its transit through the intestinal tract, the temperature recorded will vary according to whether it is located in an area close to large arterial vessels or to organs with high local metabolism or, on the contrary, near the abdominal walls.

2.2.3.2 Interpretation

When the transducer is located in the stomach or the duodenum, temperature variations are similar to those of t_{es} and the difference between the two temperatures is very small. As the transducer progresses inside the intestine, the characteristics of the temperature come closer to those of t_{re}. Therefore, the interpretation will depend on the time elapsed since the swallowing of the transducer and on the speed of the gastro-intestinal transit for the given subject.

In the present state of knowledge, t_{ab} seems to be independent of ambient climatic conditions, except for strong radiant heat impinging on the abdomen.

2.2.4 Oral temperature, t_{or}

2.2.4.1 Principle of the method

The transducer is placed underneath the tongue and is therefore in close contact with the deep arterial branches of the lingual artery. It will then provide a satisfactory measurement of the temperature of the blood influencing the thermoregulation centres.

The temperature measured nevertheless, depends on the external conditions. When the mouth is open, thermal exchanges by convection and evaporation on the surface of the buccal mucus membrane contributes to a reduction in the temperature of the buccal cavity. Even when the mouth is closed, the temperature can be significantly lowered as a function of a reduction in the cutaneous temperature of the face, or raised if the face is exposed to strong radiant heat.

2.2.4.2 Interpretation

When the measurement conditions are met, t_{or} is very similar to t_{es}. With the subject resting and in environments in which air temperature is greater than 40 °C, t_{or} can overestimate t_{es} by 0,25 °C to 0,4 °C. With the subject working, the concordance between t_{or} and t_{es} is only established for muscular effort levels not exceeding 35 % of the maximal aerobic power of the subject.

2.2.5 Tympanic temperature, t_{ty}

2.2.5.1 Principle of the method

The thermal transducer is placed as close as possible to the tympanic membrane whose vascularisation is provided in part by the internal carotid artery which also irrigates the hypothalamus. As the thermal inertia of the eardrum is very low, due to its low mass and high vascularity, its temperature reflects the variations in arterial blood temperature which influence the centres of thermoregulation.

However, as the tympanic membrane is also vascularised by the external carotid aretery, its temperature is influenced by the local thermal exchanges existing in the area vascularised by this artery.

2.2.5.2 Interpretation

t_{ty} varies in a similar fashion to t_{es} during rapid variations in the thermal content of the core, whether these are of metabolic origin or caused by the environment. The observed difference between these two temperatures or between t_{ty} and t_{re} is however influenced by local heat exchanges around the ear and the cutaneous surface of the head.

2.2.6 Auditory canal temperature, t_{ac}

2.2.6.1 Principle of the method

The transducer is, in this case, located against the walls of the auditory meatus immediately adjacent to the tympanum. These are vascularised by the external carotid artery and their temperature is affected both by the arterial blood temperature at the heart and by the cutaneous blood flow around the ear and adjacent parts of the head. A temperature gradient is thus observed between the tympanum and the external orifice of the auditory meatus. This gradient can be reduced by insulating the ear adequately from the external climate.

2.2.6.2 Interpretation

The interpretation principles are very similar to those presented for the tympanic temperature. The auditory canal temperature therefore undergoes variations parallel to those of t_{es}, in the same way as t_{ty}.

However, the positive deviations in hot environments or the negative ones in cold climates from t_{es} are systematically greater than for t_{ty}. Therefore, t_{ac} may rather be considered as an indicator of the combined temperatures of the core and of the skin, than of an indicator of the core temperature only.

This temperature measuring site is accepted by some as a necessary compromise between the precision of the estimation and the practicability for the subject and the observer.

2.2.7 Urine temperature, t_{ur}

2.2.7.1 Principle of the method

The bladder and its content may be considered as being part of the core of the body. Therefore, the measurement of the urine temperature during its discharge can provide information concerning the body core temperature t_{cr}. The measurement is made by means of a temperature transducer inserted in a collecting device. By definition, the measurement possibilities are dependent on the quantity of urine available in the bladder.

2.2.7.2 Interpretation

Urine temperature varies approximately as t_{re}, except the time constant is somewhat greater and its actual value is systematically lower than t_{re} by 0,2 °C to 0,5 °C.

3 Skin temperature, t_{sk}

3.1 General

Skin temperature varies widely over the surface of the body and especially when the ambient conditions are cold. For this reason, a distinction should be made between

— the local skin temperature, t_{sk}, measured at a specific point of the body surface

— the mean skin temperature, $\overline{t_{sk}}$, on the entire surface of the body, which cannot be easily measured directly but can be estimated by weighting an ensemble of local skin temperatures according to the area they characterize.

By itself, $\overline{t_{sk}}$ does not make it possible to evaluate the thermal physiological strain. It constitutes however an important criterion for the appraisal of thermal comfort.

3.2 Principle of the method

For a nude subject, the temperature at a given point of the body surface may be measured from a distance by means of an infrared radiation transducer. This technique gives the mean temperature of the area, small or large, of the skin which is intercepted by the transducer. Otherwise, the temperature is measured by contact with a temperature transducer fixed on the skin.

3.3 Interpretation

Skin temperature is influenced by the following factors:

a) the thermal exchanges by conduction, convection, radiation and evaporation at the surface of the skin;

b) the variations of skin blood flow and of the temperature of the arterial blood reaching the particular part of the body.

In dry environments, skin temperature responds, with a time constant of about 3 min, to variations of ambient air temperature, radiation and air velocity.

The number of measuring points should be determined according to the desired degree of precision, the ambient conditions, the technical requirements and the degree of annoyance tolerated by the subject.

As temperatures at the surface of the body are very heterogenous in ambient conditions close to thermal neutrality and in cold environments, weighting schemes with many measuring points should be used. In very cold conditions, measurement of one or more finger and toe temperatures on both sides of the body may be required for safety reasons. In warm and hot ambient conditions, except in the presence of highly asymmetric radiation, local skin temperatures tend to be homogeneous, so that the weighting scheme using few measuring points can be used with accuracy.

4 Assessment of thermal strain on the basis of heart rate, HR

4.1 General

Heart rate, HR, over a time interval Δt (in minutes) is defined as follows:

$$\mathrm{HR} = n/\Delta t$$

where n is the number of heart beats observed during this time interval. It is expressed in beats per minute (bpm). This value is usually counted for a time interval of 1 min.

At any given time, the heart rate HR can be considered as the sum of several components which are not independent of each other:

$$\mathrm{HR} = \mathrm{HR}_0 + \Delta\mathrm{HR}_M + \Delta\mathrm{HR}_S + \Delta\mathrm{HR}_T + \Delta\mathrm{HR}_N + \Delta\mathrm{HR}_E$$

where

HR_0 is the heart rate of the subject, on average, at rest while sitting, under neutral conditions, that is, when the metabolic rate is equal to 58 W/m^2;

$\Delta\mathrm{HR}_M$ is the increase in heart rate linked with work metabolism;

$\Delta\mathrm{HR}_S$ is the increase connected with static exertion;

$\Delta\mathrm{HR}_T$ is the component connected with the thermal strain experienced by the subject;

$\Delta\mathrm{HR}_N$ is the component due to psychological factors: this component, often observed in the subject at rest, tends to disappear on exertion;

$\Delta\mathrm{HR}_E$ is the residual component connected with rhythm of breathing, circadian rhythm, etc. The respiratory component disappears to a large extent when the calculation of HR is made over a period of 30 s or more, while the circadian component may be disregarded here.

In the context of this International Standard, only the component $\Delta\mathrm{HR}_T$ will be examined.

4.2 Principle of the method

In an actual work situation, the component $\Delta\mathrm{HR}_T$ can only be assessed if heart rate at rest HR_0 has been measured and if the other components can be disregarded.

When muscular work is stopped, heart rate starts decreasing rapidly. After several minutes, the ΔHR_M and ΔHR_s components due to work have practically disappeared leaving only the component ΔHR_T from thermal origin. The trend of HR deceleration thus shows a break after a certain recovery time and the thermal component at the end of the working period can be estimated by:

$$\Delta HR_T = HR_r - HR_0$$

where

HR_r is the rate recorded at the time of the break in recovery deceleration trend;

HR_0 is the heart rate at rest in a thermally-neutral environment.

The recovery time up to the break is on average 4 min. It can be longer if the metabolic rate during the previous working period was very high. Therefore, it is necessary to measure HR either every 30 s or continuously during the first minutes of recovery and to observe directly the breaking point in the deceleration trend of HR.

4.3 Interpretation

The increase in heart rate of thermal origin ΔHR_T is very strongly related to the increase in t_{cr}. The increase in HR for an increase of 1 °C in t_{cr} is called thermal cardiac reactivity and is expressed in heart beats per minute per degree Celsius (bpm/°C). Interindividual variations of thermal reactivity are very important. Even for the same subject, it varies according to the type of exertion made (and thus the muscular group involved) and according to whether the thermal stress is exogenic (due to the climate) or endogenic (due essentially to the metabolism). This interpretation must take these factors into account.

5 Assessment of physiological strain on the basis of body mass variation, Δm, due to sweating

5.1 Principle of the method

The gross body mass loss of a person during a given time interval is the difference between the body masses measured at the beginning and at the end of this interval. The gross body mass loss, Δm_g, is the sum of several components.

$$\Delta m_g = \Delta m_{sw} + \Delta m_{res} + \Delta m_0 + \Delta m_{wat} + \Delta m_{sol} + \\ + \Delta m_{clo}$$

where

Δm_{sw} is the mass loss due to sweat loss during the given time interval;

Δm_{res} is the mass loss due to evaporation in the respiratory tract;

Δm_0 is the mass loss due to the mass difference between carbon dioxide and oxygen;

Δm_{wat} is the mass variation of the body due to intake and excretion (urine) of water;

Δm_{sol} is the mass variation of the body due to intake (food) and excretions (stools) of solids;

Δm_{clo} is the mass variation of the clothing due to variation of clothing or to sweat accumulation in the clothing.

In the context of this International Standard, the sweat loss, Δm_{sw}, and the net water balance of the body are considered.

5.2 Interpretation

In a warm environment, the sweat loss can be considered as an index of the physiological strain from thermal origin, including not only the sweat that evaporates at the surface of the skin but also the fraction dripping from the body surface or accumulating in the clothing. The net water balance ($\Delta m_{sw} + \Delta m_{res} + \Delta m_{wat}$) is to be considered in relation to the risk of dehydration of the body. A regular intake of small volumes of water, over the entire exposure period, will be able to balance about 75 % of the water loss: this can be assumed to be the case for acclimatized workers. In case of non-acclimatized workers, on the contrary, the periodicity, the volume and the quality of water intake can be inadequate and it is advisable to consider that the water loss is not compensated at all.

In comfortable or cooler conditions, the sweat loss and the body water balance are reduced and are of little use. Δm_{sw} can however be compared to the value predicted as a function of the metabolic rate to assess the degree of comfort of the situation.

Annex A
(informative)

Comparison between the physiological methods of evaluation of thermal strain

Table A.1 describes the technical requirements for the different methods of physiological measurement of thermal strain. The comparison criteria are the following:

1) Complexity of the instrumentation

0: simple

1: should correspond to some requirements

2: complex

2) Technical requirements for the measurement procedure

0: simple technique

1: requires a competent person

2: requires medical surveillance

3) Continuity of the measurement

C: continuous or discontinuous measurement

D: discontinuous measurement

4) Work interference

0: limited to the time of the measurement

1: moderate work interference

2: strong interference with the normal process of work

5) Physical annoyance for the person

0: very slight and limited to the duration of the measurement

1: limited, except if the technique is not optimal

2: of a psychological nature without physical annoyance

3: moderate physical annoyance

6) Health hazards for the person

0: no hazard

1: potential hazard if technique not optimal

2: potential hazard if anatomical abnormality of the person

7) Cost

0: very low

1: moderate

2: medium to high according to the system used

3: high

Table A.2 compares the different methods concerning their relevance and difficulty of interpretation for the appraisal of the thermal strain.

1) Relevance in the fields of cold, moderate and hot conditions

−: not relevant for the assessment of thermal strain

+: relevant

2) Requirements concerning the interpretation of the data

0: direct interpretation

1: interpretation requiring basic training

2: interpretation requiring specialized competence

Table A.1 — Technical requirements for the different methods of physiological measurement of thermal strain

Physiological parameter	Instrument complexity	Technical requirement	Continuity of the measurement	Work interference	Physical annoyance	Health hazard	Cost
	1	2	3	4	5	6	7
t_{es}	2	2	C	1	3	2	1
t_{re}	0-1	0	C	0	2	1	1
t_{ab}	2	1	C	0	2	2	3
t_{or}	0-1	0	C	0	0	0	0
t_{ty}	2	2	C	1	3	2	1
t_{ac}	1	1	C	1	3	1	1
t_{ur}	1	0	D	0	2	0	0
HR							
pulse[1)]	0	0	D	0	0	0	0
ECG[2)]	2	1	C	0-1	0-1	0	2
t_{sk}							
contact	1	1	C	1	1	0	2
no contact	2	1	D	0	0	0	3
Sweat loss	1	0	D	1	1	0	1

1) This refers to the recording of the pulse rate at the wrist.

2) This refers to the continuous recording of the electrocardiographic signal.

Table A.2 — Relevance and difficulty of interpretation of the different physiological parameters

Physiological parameter	Relevance			Interpretation
	cold	moderate	warm	
t_{es}	+	—	+	1
t_{re}	+	—	+	1
t_{ab}	+	—	+	1
t_{or}	—	—	+	1
t_{ty}	—	—	+	1
t_{ac}	—	—	+	1
t_{ur}	+	—	+	1
HR	—	—	+	2
t_{sk}	+	+	+	2
Sweat loss	—	+	+	1