REFLECTIONS ON HYPOTHERMIA

Przemysław Michniewski

Maritime Medicine Department, Military Medical Academy, Gdynia, Poland

ABSTRACT

The main factor determining a castaway's chances of survival in water is its temperature. The time of work in a cold environment, such as sea water, also limits the temperature gradient. This article presents algorithms and formulae estimating survival time and the ability of a person to endure immersion in cold water. Moreover, it touches upon an interesting topic regarding the impact of the thickness of subcutaneous fat tissue on thermoregulatory mechanisms of an organism. The analyses are partially based on the rich and tragic experiences and observations from marine operations carried out during World War II.
Key words: hypothermia, castaway diver, thermal protection.

ARTICLE INFO

PolHypRes 2014 Vol. 49 Issue 4 pp. 39 - 50

ISSN: 1734-7009 **eISSN:** 2084-0535

DOI: HTTP://DX.DOI.ORG/10.13006/PHR.49.4

Pages: 12, figures: 5, tables: 3.

page www of the periodical: www.phr.net.pl

Publisher
Polish Hyperbaric Medicine and Technology Society

Rewiev article

Date of approval for print in PolHyp Res.: 02.12.2014 r.

Originally published in Journal of Naval Health Service 1973r.

INTRODUCTION

Problems related to undercooling of organisms have been investigated by researchers for hundreds of years, particularly in relation to human utilisation of the aquatic environment. The group of people interested in this issue include seamen, swimmers, divers as well as other professional groups having contact with water, such as the army. Despite the rapid technological advancement, a human remaining in aquatic environment, especially in an emergency situation, is subjected to cold temperatures, which may be the direct cause of his death.

Below the author provides a slightly historical depiction of the problem of thermal protection and survival time in an environment characterised by a low temperature, which despite the passage of time continues to be valid to a significant extent. The article allows an understanding as to why castaway divers or soldiers still die when faced with a sudden emergency stay in cold water.

Bartosz Morawiec

TIME OF SURVIVAL OF CASTAWAYS IN COLD WATER ACCORDING TO THE HAMES-SMITH MONOGRAM

Rapid development of commercial fleets as well as the popularisation of water sports and sailing are unfortunately also the cause of an increase in the number of castaways requiring quick and effective rescue action. Our climatic zone is for most of the year characterised by such low water temperatures in both the sea and in lakes that the time for providing effective assistance is measured in dozens of minuts or even hours.

Despite the strict requirements imposed by international conventions in relation to rescue resources on ships, castaways do not always have the time and possibility to use them and are often found in water with nothing more than lifejackets or life-belts. Such incidents occurred on a mass scale during World War II in waters of the middle and north Atlantic during the attacks by Nazi aircraft and submersibles on the Allied convoys.

The main threat for this group of castaways was connected with death as a result of the organism being overcooled by cold water.

Today, Poland's marine rescue with regard to saving life at sea is mainly oriented towards undertaking actions in the region of the south Baltic, hence it seems appropriate to provide a brief description of this particular environment. Average temperatures of sea water for particular months in selected locations are presented in Table I.

Tab. 1.

Average temperatures of sea water according to months (8).

Place of measurement	Years	Temperatures in degrees Celsius											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Gdynia	1951-65	1.6	0.9	1.4	5.1	9.9	14.8	17.7	18.4	15.9	11.7	6.9	3.5
Hel	1951-65	1.9	1.0	1.5	4.5	8.7	13.9	17.3	18.1	15.8	12.0	7.7	4.0
Mielno	1951-65	1.3	0.9	2.3	6.4	10.8	14.7	17.5	17.6	15.5	11.2	6.5	3.1
Międzyzdroje	1951-65	1.0	0.6	2.0	6.2	11.4	16.3	18.6	18.5	16.1	11.5	6.7	2.9
Władysławowo	1951-65	1.2	0.8	1.8	5.5	9.6	13.6	17.3	17.4	15.0	10.8	6.3	3.0

The temperature of the surface water of the Baltic changes considerably depending on the season of the year. During winter, depending on water salinity, ice may appear in the bays and near the shore, and the water temperature may fall below 0°C.

The highest water temperatures are usually noted in August (18-19°C). The fluctuations observed during the year vary from -0.4 to 21.8°C. Thus, the water sports season in the Baltic is practically limited to the period from mid June to mid September. From the point of rescue possibilities it is necessary to assume that any vessel's failure during the entire year may lead to casualties among castaways due to exposure to cold.

In such a situation, the homoeothermal system of the human organism comes in contact with an aquatic environment to which it is not adjusted due to its distinguishing physical properties. The thermal conductivity of water reaches 53 kcal/m^2/h/cm/°C, whereas that of air is 2 kcal/m^2/h/cm/°C, and additionally the thermal capacity of water is four times that of air and the density 700 times greater. Therefore, heat dissipation from the surface of the body is 25 times more intense than in the air.

Although a normally dressed person is able to remain for a period of six hours in an air environment at a temperature of 4°C without injury to health or a drop in body temperature, in water having the same temperature this person will die as a result of hypothermia within 30-60 minutes (1, 4, 6, 9, 16).

The speed of accumulation of hypothermia-related symptoms is also connected with the fact that in water the warmth is taken from the entire immersed area of the body solely by conduction. In water with the temperature up to 15°C, the survival time of undressed people reaches from 1.5 to 2 hours, whereas for those normally dressed it is extended to 4.5 hours [6, 9].

Due to high individual differences in the tolerance of cooling in water related to age, sex, body build and acclimatisation, a series of monograms and formulae were prepared for the purposes of the navy and merchant shipping as well as the aviation and marine rescue services, which allow the prediction of the likely survival time of a castaway immersed in water.

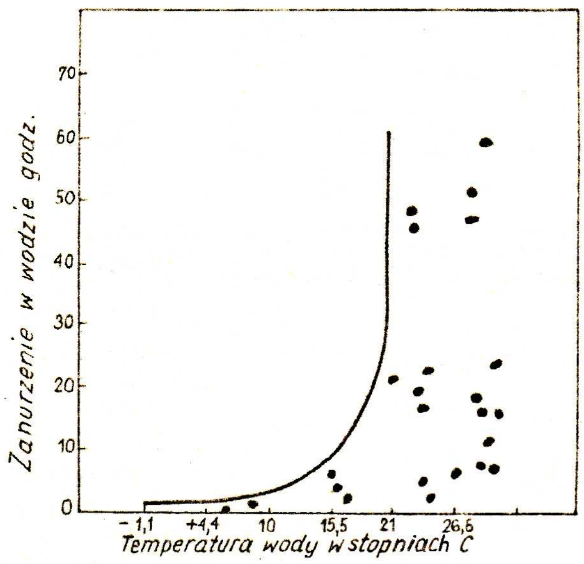

Fig. 1. Time of survival of castaways depending on the immersion time and water temperature. The black spots symbolise castaways who were rescued.

The survival time of castaways depending on water temperatures is presented in Fig. I prepared on the basis of studies of several authors, mainly those by Molnar carried out on material from World War II [1, 4, 6, 9, 13]. Research results allow the conclusion to be drawn that water temperatures of 20°C and higher are safe for young and healthy men (seamen), and prolong the survival time to ten hours.

In 1962, Barnett worked out a monogram on the basis of Molnar's research, providing a visual depiction of the zone characterised by a 100% mortality rate, the border zone and the safe zone depending on the time of staying afloat and water temperature, which is illustrated by Fig. II (16).

The above charts allow merely a rough determination of survival time, hence they were meant to serve mainly the professional medical, military and civilian staff. In 1962 Smith and Hames [15, 16] prepared a monogram allowing determination of the survival time of people in cold water with regard to their sex, age, body built and clothing, which is illustrated by Fig. III.

The method of proceeding with the monogram.

1. The defined water temperature (TW) and the insulating value of tissues and the clothing (It) is connected with a straight line to an intersection with the closest scale determining the value of heat released into the environment by means of conduction and convection per unit of area (Hc/A).
2. The values of heat emission Hc/A and production in the area unit M/A/ should be connected with a straight line and the intersection point with the neighbouring scale will allow to determine the so-called thermal deficiency D/A.
3. The value of the thermal deficiency D/A and the value related to the immersed part of the body A should be connected with a straight line, with the intersection point with the neighbouring scale indicating the total thermal deficiency value expressed in kcal/h/D.
4. The thermal deficiency value D should be connected with the body mass value (m) in order to determine the average fluctuations in body temperature within one hour (dO) at an intersection point with the neighbouring scale.
5. The value of deviation in the average body temperature dO is to be connected with the proper value on the scale of the time of exposure (t) and average body temperature (O).

Example (Fig. III). Dashed line. In water with a temperature of 4.0°C a naked man (I_t = 0.30 clo) loses 610 kcal/m^2/h. As a result of the exposure to cold and the intensified metabolic processes, the thermal productivity of the body reaches 400 kcal/m^2/h, which results in an occurrence of thermal deficiency of 210 kcal/m^2/h.

The area of the body immersed in water amounts to 1.75 m^2, thus the total thermal deficiency will amount to 365 kcal/h, which for a man with body mass of 75 kg will result in body temperature reduction by 6.0°C/h. With the average body temperature of 31°C endured for a period of ca. 1 h there is only a 50% chance of survival. Usually, such people will probably be incapable of physical movement; however, others will be able to survive longer than 1 hour and 50 minutes.

Generally, it is assumed that it is impossible to retain the thermal balance of an organism immersed in water possessing a temperature below 20°C.

Heat emission under such circumstances will exceed its production connected with the occurring spasms and muscular effort (swimming), as a result of which the body temperature will continue to drop until the person's death.

In water with the temperature close to 0°C the body temperature drops by 10°C per hour [5, 7, 10]. This is connected with the so-called "biological zero", i.e. the lowest temperature of the tissue at which its function inhibition is still reversible. The biological zero is equal to 29°C in relation to cerebral cortex, 27°C to subcortical centres, and 25-22°C to myelencephalon centres.

According to Molnar [9] there are no chances of survival with a body temperature drop below 23.8°C measured in the rectum.

Conclusions

1) By its distinctness of physical properties, the aquatic environment causes dramatic shortening of survival time in castaways.
2) Water temperature of less than 20°C does not allow the maintaining of the thermal balance of an organism.
3) Clothing and moderate movement prolong the survival time in water.
4) With water temperatures being close to 0°C death is to be expected before the lapse of 60 minutes.
5) The above average survival times depending on water temperature may be significantly shortened as a result of the state of the sea, waves, wind, i.e. the factors that may lead to a castaway's drowning due to hypothermia

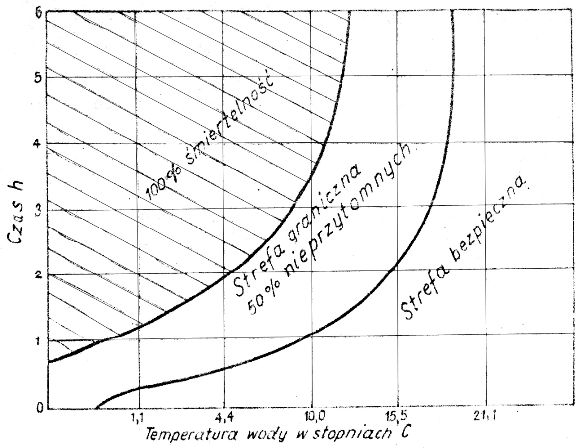

Fig. 2. The monogram drafted by Barnett, visually determining the zone of 100% mortality, the border zone and the safe zone depending on immersion time and water temperature.

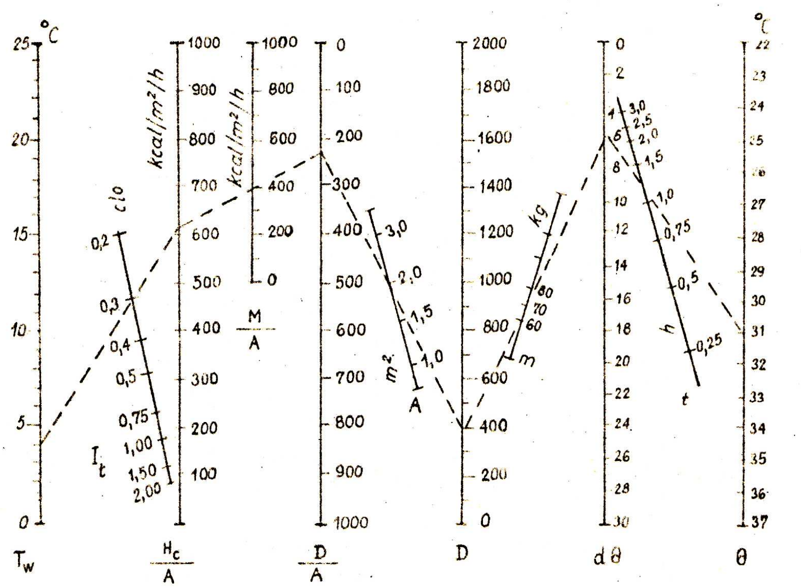

Fig. 3. Monogram used in the determination of the time of tolerance in the conditions of immersion in cold water (acc. to Smith and Hames). The CLO unit in the I_t scale corresponds to the thermal insulation provided by the clothing ensuring thermal comfort to a person at rest at the temperature of 21°C, relative humidity below 50% and air movement of 0.1 m/s. The value of thermal production by an organism is in such conditions equal to 50 kcal/m^2/h.

THE INSULATING ROLE OF SUBCUTANEOUS FAT TISSUE IN THE PROCESS OF AN ORGANISM'S THERMOREGULATION IN WATER

Doctors conducting research on the thermal effects of the aquatic environment on the thermal balance of swimmers or castaways have taken a long-term interest in the role of the fat tissue in the phenomenon of individually diversified tolerance to long-lasting exposures to cold water [1, 3, 4, 6, 13].

In 1898, Bordier conducted measurements of the thermal conductivity of tissues and discovered that the muscle tissue is characterised by 1.8 times higher thermal conductivity as compared with fat tissue. According to the tests carried out by Hardy and Soderstrem in 1938 [4], the thermal conductivity of animal tissues reach 0.00049 cal.cm/cm^2/s/˚C in relation to fat, and 0.00047 cal.cm/cm^2/s/˚C in relation to the muscles. In 1950, Hatfield and Pugh [4] performed in vivo measurement of the thermal conductivity of human tissues with the use of thermoelements in the form of needles inserted into the subcutaneous tissue and muscles. The results of these tests are presented in Tab. 2.

Tab. 2.

Thermal conductivity of standard human tissues and protective fats used by swimmers.

Tissues	Human tissues	
	Fat	Muscles
Average	0.000438	0.00092
Protective fats used by swimmers		
Anhydrous lanolin	0.0036	
Hydrous lanolin	0.00054	
Petrolatum	0.00049	

The value of thermal conductivity included in Tab. I has been expressed in cal.cm/cm^2/s/˚C, whereas conversion into kcal.cm/m^2/h/˚C requires multiplying by 3.6 x 10^3. As a result of the above studies, conclusions were drawn with regard to the insulating role of the fat tissue for an organism immersed in cold water. It should be emphasised, that according to the data from the last war concerned with castaways at sea, the role of subcutaneous fat tissue is not that obvious [10].

The deeper under the skin, the greater the increase in body temperature. In room temperature, already at the depth of 1 cm under the skin the temperature of tissues is approximated to general body temperature. In the situation when the skin is in contact with an aquatic environment with higher conductivity and thermal capacity, the deeper layers of the body will be more easily affected. In water with the temperature of 33˚C the conductivity of tissues at rest will reach 9-10 kcal/m^2/h/˚C in water with the temperature of 7˚C.

The thermal conductivity of water is equal to 53 kcal/m^2/h/cm/˚C, while that of air – 2 kcal/m^2/h/cm/˚C. Hence, the loss of temperature by skin immersed in water is 25 times more intense than it is the case with air. Moreover, nearly the entire heat exchange in water is realised via conduction and convection.

The effect of low temperature on a naked body in water is manifested by contraction of the blood vessels localised in the skin, thus causing a decrease in cutaneous blood flow and in the thermal conductivity of body tissues. In this situation the subcutaneous fat tissue, which is to a large extent devoid of blood, serves as a good thermal insulator, which may be compared to a wrung up sponge.

Temperature drop of the skin and subcutaneous tissue decreases the difference between the temperature of the skin and water. In effect, the temperature loss from the surface of the body becomes reduced.

This is schematically illustrated by Fig. 4.

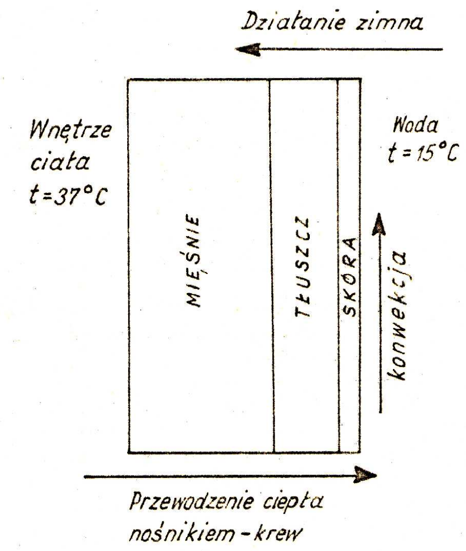

Fig. 4. Temperature loss by an organism immersed in water by conduction and convection. Temperature gradient: body-water =22˚C. The cold reduces the temperature of the skin and subcutaneous tissue, thus decreasing the temperature gradient and thermal conductivity of tissues while at the same time increasing their insulating property, mainly that of the fat tissues.

The struggle of the organism to preserve thermal balance in the conditions presented in Fig. 4 may take two routes:

a) An increase in thermal production through raised metabolism, physical effort, muscular tension and tremor;
b) A decrease in heat release as a result of vasospasms in body tissues, reduction in thermal conductivity of tissues and growth in the insulating value of subcutaneous fat tissue.

Commonly, in the conditions of cooling of an organism the above phenomena are concomitant, with physical effort being the only variable that may be consciously dosed.

Individual differences (training, acclimatisation, body build) are the reason that, for instance, competitors swimming across the English Channel are able to endure a 12-22-hour exposure to water with the temperature of 15.5˚C, whereas castaways are only able to survive for 4-6 hours in the very same conditions.

As a result of the works conducted by Pugh and Keating [1, 5, 6, 12, 13] it is possible to conclude that the resistance to cold of long-distance swimmers is first of all related to the thickness and insulating properties of subcutaneous fat tissue. Long-distance swimming requires high heat production of up to 10-15 kcal/min. both in slim and overweight swimmers: however, this factor did not protect slim people from a fast decrease in their body temperature and dropping out of the competition.

If in cold aquatic environments the cutaneous blood flow increases as a result of the work of muscles, then the heat loss may exceed its generation and cause a decrease in body temperature.

This occurs faster in slim swimmers and in low water temperatures. Intense swimming (an increase in heat production) may not only fail to improve the thermal balance of an organism, but also significantly shorten the time of the swimmers mobility. This fact is crucial in respect to castaways.

The low efficiency in the thermogenesis process of muscular tremor is a direct result of it being accompanied with an increase in the cutaneous blood flow, a decrease in the insulating properties of the fat tissue and, in consequence, a rise in thermal losses in water.

The range of average thickness of subcutaneous fat tissue of participants of swimming contests was equal to 6-10 mm as compared with the average value of 4 mm that was applied among the subjects of the so-called control group [12, 13]. Although this deviation seems small, it is possible to justify the opinion that the thickness of subcutaneous fat has a decisive meaning with regard to enduring cold water temperatures.

The insulating value of tissues is expressed as the inverse of kilocalories distributed on the area of one m^2 of immersed skin per temperature gradient with the value of 1˚C in relation to the temperature in the rectum (inside of the body) and water temperature.

Basic equations concerning heat flow indicate that the heat flow (H) through an insulation centre with the thickness of 1 cm per unit of area is equal to the difference of temperatures occurring on the brink of the centre (Δt) divided by the value of its thermal insulation [I]. [13]:

$$H=\frac{\Delta t}{I}$$

Let us assume that the heat flow value through subcutaneous fat tissue reaches 30 $kcal/m^2/h$, i.e. 0.00083 $cal/cm^2/s$ in an undressed person at rest in the conditions of full vascular constriction. The value of thermal insulation of human fat, which is an inverse of thermal conductivity of fat reaches $\frac{1}{0{,}0005}$ $cal/cm^2/s$ per each 1 cm of its thickness, thus:

$$\Delta t = 0.00083 \times \frac{1}{0{,}0005}\ ^{\circ}C/cm = 1.67\ ^{\circ}C/cm$$

In an undressed person at rest, a 1 cm thick subcutaneous fat layer would maintain the temperature difference of 1.67˚C. When heat production is ten times higher than at rest, for instance in swimmers, then the same thickness of the fat layer would be capable of enduring the temperature difference of 16.7˚C, or, to the contrary, a 1 mm thick fat tissue at the time of high energy release is equal to the thickness of 1 cm when the subject remains at rest.

Fat becomes efficient in heat insulation only when the speed of its permeation is sufficiently high. Such conditions are present in long-distance swimmers, where hard working organisms remain in immersion in cold water [12, 13].

The above reasoning has led to the proper evaluation of the role of the fat provided on the body with the purpose of protecting it against the cold (see tab. 2). The thermal conductivity of lanolin or petrolatum is comparable with the conductivity of fat in an organism, thus a 1 mm layer of lanolin distributed on the skin has the capacity to level the temperature difference of 1.67°C or is equal to an increase in water temperature by this value [10].

Pioneering research in this area was conducted by Pugh and others, as well as Keating and Cannon [1, 5, 12 & 13] on volunteers and participants in attempts to swim across the English Channel. Table 3 presents the physical characteristics of the subjects, with 1 and 2 representing the group of slim swimmers and 3 and 4 of those being overweight.

Tab. 3.

Physical properties of the subjects.

No.	Height cm	Weight kg	Area of the body m^2	Area of immersed body m^2	Lappet thickness
1	173	69	1.82	1.70	6.5-6.7
2	162.5	54.5	1.58	1.48	6.5-6.7
3	175	89	2.05	1.92	26.7-26.0
4	170	89	2.00	1.87	26.7-26.0

Fig. 5. shows graphic values of the thermal insulation of the body tissue of subjects whose physical characteristics were specified in Tab. 3.

Fig. 5 indicates that the value of thermal insulation of bodily tissues was the lowest at the highest water temperatures, however it should be noted that those lowest values of tissue insulation were nearly equal for all researched men, both slim and overweight.

With the reduction in water temperature the insulating value of tissues rose to the maximum level, which proved to be much higher in overweight people than in slim subjects and was reached by them at a lower water temperature.

Although the insulating value of tissues in overweight subjects increased to reach high values with a water temperature of 12°C, at lower water temperatures it significantly dropped. A decrease in the insulating value of tissues were in these conditions accompanied by cyclic increases in heat release.

This is caused by periodic vasodilation in water temperature below 10°C with direct impact of cold.

The dilation of vessels, even though periodic, greatly reduces the insulating properties of tissues (plethora) in overweight people at low water temperatures.

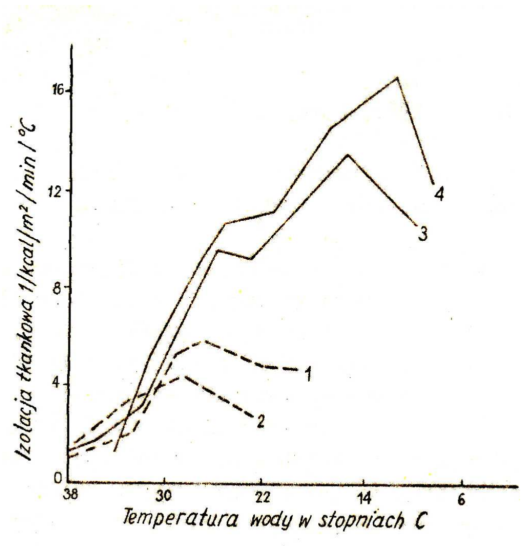

Fig. 5. The value of thermal insulation of fat tissue in slim (1, 2) and overweight (3, 4) subjects depending on water temperature.

Hence the conclusion that no quantity (thickness) of subcutaneous fat will allow an obese person to survive in water where the temperature is close to freezing point for an unspecified period of time without proper protective clothing.

In this respect humans differ from aquatic Arctic mammals such as seals, whales, walruses which are capable of surviving in water with temperature close to freezing over a long period of time.

BIBLIOGRAPHY

1) Cannon P., Keatinge W.: J.Physiol., 1960, 154:329
2) Durnin J., Passmore R.: Energetyka pracy I wypoczynku, PWN, W-wa, 1969.
3) Glaser E.: Nature, 1950, 23:1068.
4) Hatfield H., Fugh L.: Nature, 1951, 24:918.
5) Keatinge W.: J.Physiol., 1960, 153:166.
6) Keatinge W.: Survival in cold water. Blackwell Scient.Public., Oxford 1969.
7) Klonowicz S., Kozłowski S.: Człowiek a środowisko termiczne, PZWL, W-wa, 1970.
8) Lambertsen C.: Underwater physiology. Williams, Wilkins Co, Baltimore, 1967.
9) Molnar C.: J.A.M.A., 1946, 27:1046.
10) Mornar G.: J.A.M.A., 1946, 13:1046.
11) Nicholl G.: Survival at sea. Adlard Coles, London, 1960.
12) Pugh L., Edholm O.: Lancet, 1955, 8:761.
13) Pugh L. I wsp.: Clin.Sci.1960, 19:257.
14) Rocznik Statystyczny Gospodarki Morskiej, G.U.S.W-wa, 1971.
15) Smith B., Hames E.: aerospace Med. 1962, 33:834.
16) Whittingham P. w podr. A textbook of aviation physiology, pod red. J.Gilliesa, Pergamon Press, Oxford, 1965, str. 479.