TECHNICAL COMMUNICATION

Thermal status of saturation divers during operational dives in the North Sea

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Mekjavić IB, Golden FstC, Eglin M, Tipton MJ. Thermal status of saturation divers during operational dives in the North Sea. Undersea Hyper Med 2001; 28(3):149–155.—The principal aim of the present study was to monitor the core temperature (T_c) of a population of saturation divers conducting routine deep dives at different locations in the United Kingdom sector of the North Sea and to assess whether current dive procedures are adequate in preventing deleterious decreases in T_c. A total of 30 divers, with an average (SD) of 19.3 (6.6) yr of experience as saturation divers, participated in the study. The survey included 59 dives conducted at six locations (Scott Field, Norfra Pipeline, Hudson Field, Pierce Field, Forties Field, and Bruce Field) from four Diver Support Vessels (Rockwater 1, Semi 2, Bar Protector, and Discovery). The depth of the dives monitored ranged from 54 to 160 meters of seawater (msw), and the duration of the dives from 31 min to 7 h 30 min. before each dive, divers were requested to ingest a radio pill and strap a data logger to their abdomen. Upon returning to the chamber within the Diver Support Vessel following a dive, they provided subjective ratings of thermal perception (7 point scale) and thermal comfort (4 point scale) for the period just before, during, and immediately after the dive. In 55 dives, T_c of saturation divers working at depths to 160 msw for up to 6 h with water temperatures ranging from 4° to 6°C increased above the pre-dive core temperature of 37.4° (0.62° ± 0.6°C). In four dives there was a decrease in T_c: 2 divers had a 0.2°C fall in T_c, and 2 bellmen had a decrease of 0.4° and 1.0°C. The subjective responses of divers indicated that they were thermally neutral (neither warm nor cold) and comfortable before and immediately after the dives. The current practice of providing thermal protection with hot water suits to saturation divers working in the North Sea is adequate for preventing the risk of hypothermia and maintaining thermal comfort.

hypothermia, cold immersion, hot water suits, diving, telemetry

Hypothermia has been implicated, either directly or indirectly, as a major cause of many diving fatalities (1–7). At the outset of offshore exploration, hypothermia was considered one of the major factors hindering diver performance (8), which could lead to loss of consciousness (1) and ultimately death (7, 9). Although laboratory tests (10) have suggested that the heat provided by hot water suits is capable of offsetting the high heat loss, several reports have suggested that hypother-mia remains prevalent among saturation divers in the North Sea (3–7). Keatinge et al. (6) measured the urine temperature of divers returning to the diving bell fol-lowing routine dives and reported alarmingly low tem-peratures, indicative of mild-to-moderate hypothermia. In the absence of any visible signs of shivering or percep-tion of cold by the divers, it was concluded that satura-tion divers are susceptible to "symptomless hypothermia" or "undetected hypothermia". This has been attributed to divers' altered temperature perception and consequent inability to detect core temperature cooling (11). This is critical because in such situations, the diver must adjust the water temperature to a level which minimizes skin surface heat loss, and also the temperature of the breathing gas to minimize respiratory heat loss. Impaired temperature perception (12,13) has also been implicated in the occurrences of "chilling" and "scalding" reported among divers.

In view of the discrepancy between field observations and controlled laboratory studies, the present study monitored core temperature of saturation divers during operational dives in the North Sea. In contrast to previous studies, which were limited by the available technology at the time, a Diver Thermal Monitoring System was developed (14), which enabled continuous recording of deep body and surface temperatures during a complete work shift on the sea bed.

The present study examined the thermal protection provided by current divers' suits with auxiliary hot water heating.

METHODS

To ensure that the survey was representative of diving operations throughout the North Sea, field measurements were conducted on four Diver Support Vessels (DSV) operating in six locations in the United Kingdom (UK) sector of operations in the North Sea (Table I) from

Table 1: Characteristics of Dives Monitored

Location	Diver Support Vessel	No. of Dives Monitored	Maximum Depth, msw	Maximum Duration, h:min
Scott Field	Rockwater 1	4	131	6:40
Bruce Field	Rockwater 1	11	122	6:00
Hudson Field	Rockwater 1	3	160	5:20
Norfra Pipeline	Bar Protector	3	58	3:55
Pierce Field	Semi 2	26	82	7:30
Forties Field	Discovery	13	124	5:59

Table 2: Divers' Physical Characteristics

		Age, yr	Height, m	Weight, kg	S.A., m^2	Body Fat (15), %	Experience, yr
Mean		41.3	1.79	83.90	1.95	24.00	19.30
±SD		5.6	0.07	9.26	0.40	3.75	6.60
Range:	min	27	1.65	70.00	1.78	15.10	4.00
	max	48	1.93	97.00	2.24	31.00	33.00

November 1997 to May 1998.

Subjects: Thirty professional divers participated in the study ranging in age from 27 to 48 yr (mean ± SD = 41.3 ± 5.6). The divers' physical characteristics are given in Table 2. They each received detailed information regarding the protocol and gave their written informed consent before participating in the study. The protocol was approved by a local Ethics Committee.

Protocol: All divers were saturated in a trimix environment in hyperbaric chambers aboard DSVs. They were in saturation for a maximum of 28 days and conducted dives on a rotational basis. Divers dived in groups of three, one diver acting as the "bellman" and the remaining two conducting the open water dives. A minimum of 12 divers were normally in saturation, providing a total of four dive teams. Diving was conducted on a continuous basis (24 h), thus each dive team completed one dive per day (24 h).

During the dives, divers were provided with external heating. Hot water was pumped from the boiler on the DSV to the diving bell via an umbilical, and from there to a manifold on the divers' suits. High-pressure pumps delivered to the bell a steady flow of hot water at a maximum rate of 45 liter $\cdot$ min^{-1}. This flow of hot water was then partitioned between the two working divers in the water. Before being fed via an umbilical to the working divers, the water could also be circulated through a heat exchanger in the bell, providing heating for the bellman. The umbilical delivering hot water to the divers was connected to an external manifold on the divers neoprene wetsuit, and from there the hot water was distributed throughout the suit via a network of tubes. One tube ran the length of the back and the remaining tubes along each length of the limbs. The tubes had small perforations along their length, providing outlets for the hot water. At depths of 130 meters of seawater (msw) with water temperatures of 4°C, seawater heated to 55°C onboard the DSV reached the divers at 38°C. In the event that the heating was too excessive, the divers had the option of reducing the flow of hot water through the suit by manually adjusting a valve on a manifold protruding from the suit. Temperature sensors provided dive control on the DSV with water temperature at the boiler on board the vessel.

The diving procedures for all dives were similar, irrespective of the vessel and dive location. All dives were conducted in the UK sector of the North Sea, and the procedures and regulations of the Health and Safety Executive (UK) were strictly adhered to. Divers conducted a maximum of one dive in any 24-h period. Maximum duration of any open water dive was 6 h. In the event that they had to wait for equipment or engineering advice from the surface, they would return to the bell. In such situations, which were rare, their cumulative open water exposure was 6 h over an 8-h period. The length of the anticipated stand-by period would determine whether the divers either returned to the DSV and waited for further instructions in the transfer lock of the hyperbaric facility, or waited in the bell at depth.

Instrumentation: Measurements of gastrointestinal (T_c) and suit microclimate (T_{suit}) temperatures were made with a Temperature Monitoring System (Biomed d.o.o., Ljubljana, Slovenia) comprising radio pills and data logger (14). At least 1 h before their dive, calibrated radio pills and data loggers were transferred into the chamber through the medical lock. The logger was worn

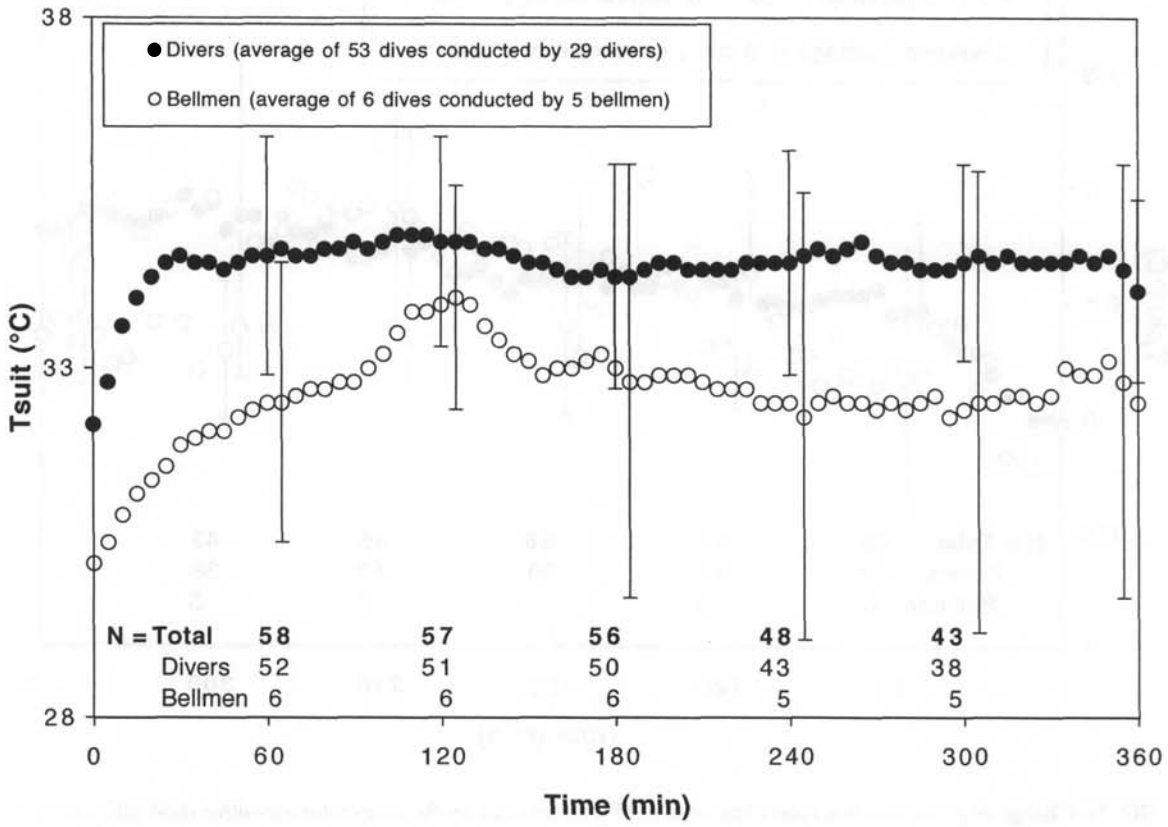

FIG. 1—Temperature within the microclimate of wet suits (T_{suit}) of divers (*closed circles*) and bellmen (*open circles*) working in open water at depths ranging from 54 to 160 msw for up to 6 h in the U.K. sector of the North Sea. Average (SD) T_{suit} at the onset of the dive was 32.2 (1.4) for divers and 30.2 (2.9) for bellmen. The numbers (*N*) indicate the total number of dives (by divers and bellmen) represented by the average data points at min 60, 120, 180, 240, and 300.

by the divers in a pouch strapped to the abdomen. Radio signals emitted by the temperature-sensitive radio pill were received by the logger, and stored in memory for subsequent transfer to a PC on board the DSV. Thermistors embedded in the sides of the logger provided information regarding the temperature of the suit microenvironment. Since the suit microenvironment was continuously flushed with water, T_{suit} reflected the skin temperature of the abdomen.

Divers provided subjective ratings of thermal perception (7-point scale: 1 = cold, 2 = cool, 3 = slightly cool, 4 = neutral, 5 = slightly warm, 6 = warm, 7 = hot) and thermal comfort (4-point scale: 1 = comfortable, 2 = slightly uncomfortable, 3 = uncomfortable, 4 = very uncomfortable) before and during the dive.

Analysis: Pre- and post-values of T_{pill} and T_{suit} were compared with a Student's paired *t* test. The level of significance was chosen as 0.5. Divers' subjective ratings regarding temperature perception and thermal comfort before and immediately after the dives were compared with a Wilcoxon signed rank test.

RESULTS

Of the 59 dives monitored, 30 were conducted at depths greater than 100 msw and 29 at depths shallower than 100 msw. During six of the dives monitored, the diver being monitored was the bellman (of these, 2 dives >100 msw and 4 dives <100 msw), whereas the remaining data corresponds to divers working in the open water (of these, 28 dives >100 msw and 25 dives <100 msw). All dives monitored were asymptomatic.

Suit microenvironment temperature (T_{suit}): In all the dives monitored the hot water suits functioned properly, allowing the divers to regulate the temperature of the suit microenvironment. As shown in Fig. 1, T_{suit} increased ($P < 0.05$) from 32.2° ± 1.4°C at the onset of the dives to 34.7° ± 1.7°C within 1 h of the dive.

Bellmen were not connected to the hot water supply, and thus their suit microenvironment temperatures were maintained at lower levels, as shown in Fig. 1. Their T_{suit} was on average between 32° and 34°C, with some bellmen maintaining suit temperature as high as 37.3°C. Changes observed in bellmen's T_{suit} during the dives were not significant.

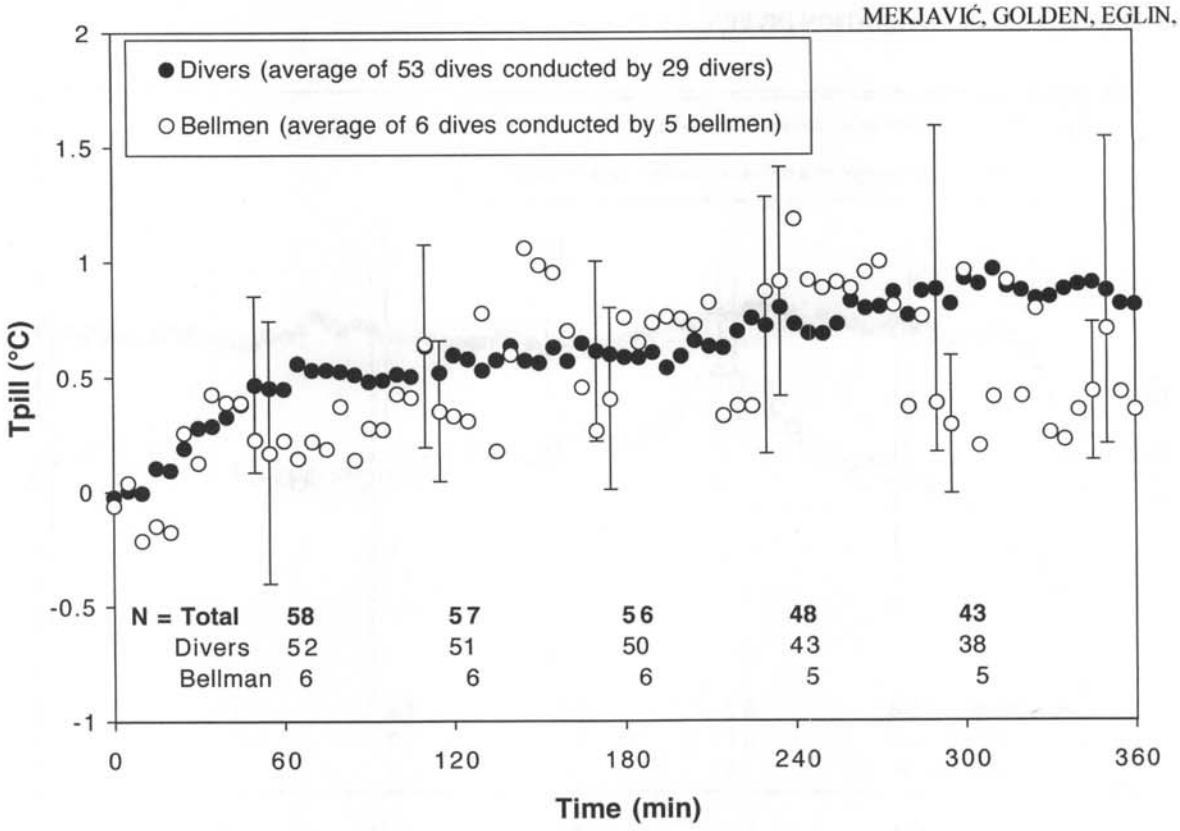

FIG. 2—Change in gastrointestinal (core) temperature (T_c) as recorded by the temperature-sensitive radio pill, relative to pre-dive levels of divers (*closed circles*) and bellmen (*open circles*) working in open water at depths ranging from 52 to 162 msw for up to 6 h in the U.K. sector of the North Sea. Average (SD) T_c at the onset of the dive was 37.4 (0.6) for divers and 37.0 (1.4) for bellmen. Numbers (N) indicate the total number of dives (by divers and bellmen) represented by the average data points at min 60, 120, 180, 240, 300.

Gastrointestinal temperature (T_c): Divers' core temperature, as measured by the radio pill, increased significantly ($P < 0.001$) from average pre-dive levels of 37.4° ± 0.6°C by 0.8° ± 0.7°C during the 6-h dives (Fig. 2). In contrast, there was no significant change in the core temperature of the bellmen (Fig. 2) during the 6-h dives.

It is evident from the characteristics of the dives monitored (Table 3), that in only 4 of the 59 dives did T_c decrease below the pre-immersion level. Two divers (dive numbers 10 and 51 in Table 3) experienced a 0.2°C decrease in core temperature. In two dives (dive numbers 15 and 34 in Table 3) the bellmen had a 0.4° and 1.0°C drop in T_c.

Thermal comfort: Divers' (n =39) subjective ratings of temperature perception and thermal comfort indicated that they were thermally neutral (median rating of 4 on 7-point temperature perception scale) and comfortable (median rating of 1on 4-point thermal comfort scale) before the dive. There was a tendency, albeit not significant, for the divers to become slightly warm (median rating of 5 on temperature perception scale) and slightly uncomfortable (median rating of 2 on thermal comfort scale) during the 6-h dive. In contrast, the bellmen (n = 4) reported being thermally neutral (median rating of 4) and comfortable (median rating of 1) before and during the dives.

DISCUSSION

The principal finding of the present study is that saturation divers working at depths to 160 msw for up to 6 h, in water with average temperatures of 4°C, do not experience any substantial decreases in body temperature. The hot water perfused suits currently being used by deep sea divers in the North Sea safeguard against hypothermia. There was no evidence of any impaired thermal perception, and thus behavioral thermoregulation. The tendency, though not significant, for the divers reporting becoming slightly warm and uncomfortable during the dives may be attributed to the significant increases in T_c and T_{suit}. No scalding or chilling was experienced by the divers during the use of the hot water perfused suits.

A decrease in T_c was observed in only 4 of the 59 dives. In two divers, the observed drop of 0.2°C over 4 h 42 min (dive no.10) and over 5 h 56 min is negligible, as such variations may be attributed to the circadian variation in body temperature. The largest decrements in Tc

Table 3: Characteristics of Divers Monitored

Dive, No.	Diver	Depth, msw	Duration, h:min	ΔTpill, °C	Temperature Perception			Thermal Comfort		
					pre-dive	per dive	post-dive	pre-dive	per dive	post-dive
1	1	131	6.40	0.2						
2	2	131	6.05	0.5						
3	3	131	6.05	1.3						
4	4	131	5.00	0.1						
5	5	54	3.55	0.4	4	4	6	1	2	2
6	6	57	.. 3.53	0.2	4	4	4	4	4	4
7	7	58	3.31	0.1	5		4	1	2	1
8	8	160	5.20	0.2	4	5	3	1	1	1
9	9	160	0.31	0.5						
10	8	160	4.42	0.2	4	5	3	1	1	1
11	10*	80	7.30	0.7	4	2	3	1	3	2
12	11	82	5.37	1.8	4	5	4	1	1	1
13	10	80	5.55	0.4	4	4	3	1	2	2
14	12	82	6.0	0.5	7	3	4	3	3	1
15	10*	80	5.59	0.4						
16	13	82	3.50	0.1	4	4	4	1	2	2
17	14	80	5.48	0.4	5	5	5	1	1	1
18	10	82	5.53	2.3						
19	12	80	5.59	1.1	4	4	4	1	1	1
20	15*	80	6.55	1.1						
21	16	82	5.51	0.7	6	7	7	2	3	3
22	15	82	3.11	0.6	3	5	4	1	2	1
23	13	82	5.11	2.0	3	6	4	1	2	2
24	2	80	4.23	0.2	5	6	4	2	2	1
25	12	82	6.00	1.3	4	4	4	1	1	1
26	3	80	2.36	1.3						
27	5	60	5.29	1.4						
28	15	82	6.00	2.2	3	5	4	1	1	1
29	18	80	5.36	1.1						
30	13	80	6.00	0,6	4	4	4	1	2	2
31	3	80	5.35	1.3	5	6	5	1	1	1
32	14	82	5.08	0.0						
33	12	80	5.40	1.3	4	4	4	1	1	1
34	2*	82	6.24	-1.0	5	4	3	1	1	1
35	15	82	5.59	2.3						
36	13	82	5.20	0,8						
37	19	123	5.59	0.5	4	7	3	1	2	2
38	20	122	5.51	0.5	5	4	3	1	2	1
39	21	124	1.41	0.1	5	6	5	2	1	2
40	22	122	5.15	0.4	4		4	1		1
41	23	123	5.47	1.3	4		4	1		1
42	24*	122	5.50	0.5	4	4	4	1	1	1
43	25	123	4.32'	1.0	3		4	2		1
44	26	123	3.29	0.5						
45	27	122	5.48	1.2	4	7	4	1	2	1
46	20	121	4.43	1.4	4	3	4	1	1	1
47	23	121	3.46	0.5						
48	22	123	3.05	0.1	3		4	1		1
49	25*	123	3.35	1.1	4		4	1		1
50	28	122	6.00	0.9						
51	12	122	5.56	-0.2						

Table 3: Characteristics of Divers Monitored, *continued*

Dive No.	Diver	Depth, msw	Duration, h:min	ΔTpill °C	Temperature Perception			Thermal Comfort		
					pre-dive	per dive	post-dive	pre-dive	per dive	post-dive
52	4	119	5:56	1.7	5	5	4	1	1	1
53	17	119	6:00	0.5	5	6	4	1	1	1
54	20	118	6:00	1.0	4	6	4	1	3	1
55	17	118	5:59	1.3						
56	29	118	5:53	0.3	4	5	4	1	2	1
57	6	121	5:59	0.8						
58	30	120	6:00	0.2	4	5	5	1	2	1
59	4	118	5:41		4	4	3	1	1	1

Notes: *Asterisks* indicate that the diver monitored was the bellman. Duration of dives for bellmen refers to time interval between bell lock-off and lock-on. Subjective ratings of temperature perception and thermal comfort were not always obtained.

were observed in two bellmen. They experienced a 0.4° and 1.0°C decrement in T_c over 5 h 59 min and 6 h and 24 min, respectively. That the largest decrement in T_c was observed in bellmen may be attributed to two factors. 1) bellmen were not as physically active as the divers working in the water, thus they did not experience a work-induced increase in metabolic rate and the associated increase in heat production; and 2) bellmen did not deploy the hot water heating system within their suit and relied solely on the hot water heat exchanger in the diving bell.

The absence of shivering in previous studies of divers with urine temperatures at hypothermic levels may be attributed to either an effect of the hyperbaric heliox (helium–oxygen) or trimix (helium–oxygen–nitrogen) on the shivering response, or to an underestimation of core temperature on the basis of urine temperature. With regard to the former, inert gas narcosis (16) has been demonstrated to suppress shivering during compressed air diving. However, it is unlikely that such an effect can be attributed to the development of hypothermia in dives where divers breathe heliox or trimix gas mixtures, as helium does not exert a narcotic influence at depths of 200 msw.

A more likely explanation for the observed near-hypothermia of the divers returning to the diving bell is the manner in which core temperature was assessed. Påsche et al. (10) observed that urine temperature of divers completing experimental dives in cold water at 51 atm abs for up to 3 h was 0.3°–0.8°C lower than rectal temperature and concluded that urine temperature underestimates core temperature.

Much concern regarding divers' thermal balance was raised by the study of Padbury et al. (11) who reported considerable core temperature cooling in a series of 25 laboratory dives. In their study 14 divers exhibited a decrease (−0.49° ± 0.38°C), six an increase (+0.18° ± 0.12°C) and four no change in rectal temperature (T_{re}). The average change in T_{re} in their group of divers was from 37.55° ± 0.53°C (pre-dive) to 37.29° ± 0.61°C (post-dive). Interestingly, four of the divers started the dive with rectal temperatures, which would be considered mildly hyperthermic (range: 38° to 39.5°C). Thus, in 10 divers the observed decrements in T_{re}, for example from 39.5° to 39.0°C (difference: −0.5°C) or from 38.0° to 37.3°C (difference: −0.7°C), although large in magnitude, do not reflect a core cooling from euther-mic to hypothermic levels, but rather from hyperthermic to euthermic levels.

Since the publication of earlier reports regarding the occurrence of hypothermia among North Sea divers, diving procedures and practices have changed. This may also have contributed to an improvement of the divers' ability to maintain thermal balance, as evidenced in the present study.

We conclude, therefore, that during routine deep diving operations in the North Sea, the current diving procedures and the provision of hot water perfused suits is adequate in preventing hypothermia and maintaining thermal comfort of divers and bellmen.

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