Protection Provided Against the Initial Responses to Cold Immersion by a Partial Coverage Wet Suit

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The protection provided against the initial responses to cold water immersion by a partial coverage wet suit was assessed. Eighteen subjects performed three 2-min immersions into water at 5°C. During each immersion, the subjects wore either: a) cotton overall, b) trunk and arms "wet" immersion suit, or c) "dry" immersion suit. Results showed that the dry suit provided significantly ($p < 0.05$) greater protection against the initial cardiac and ventilatory responses to immersion than either the wet suit or cotton overall assemblies. The responses recorded in the wet suit were similar to, and in some cases did not differ from, the cotton overall. We conclude that immersion suit design and tests should consider all of the responses associated with accidental cold water immersion and not just those resulting in a fall in core temperature.

THE DEBATE over the type of protection for individuals at risk of immersion in cold water has always tended to revolve around the subject of hypothermia. This approach ignores other responses, which could not only help to differentiate between suits but might also be more important than hypothermia. In both chronological and real terms, the most immediate and, possibly, the greatest threat to life are the responses evoked almost immediately upon cold water immersion (2,11).

The term "cold shock" has been applied to such responses as tachycardia, intense peripheral vasoconstriction resulting in hypertension, an inspiratory "gasp" reflex, and uncontrollable hyperventilation, which significantly reduce breath-hold time and the arterial partial pressure of carbon dioxide (3,4,8,9). Such responses can constitute a serious threat to survival, particularly in individuals with underlying cardiovascular disease. For healthy individuals, the respiratory responses may be particularly dangerous, increasing as they do the chance of aspirating water. The risk of aspiration is further increased in choppy water, or following forced submersion in an inverted or sinking craft.

For some functions, such as the protection of helicopter passengers on short flights over cold water, it has been suggested (7) that relatively cheaper, more robust, and more durable trunk-and-arms wet suits replace dry suits to protect passengers against hypothermia following accidental cold water immersion. Allan, Elliott, and Hayes (1) have reported that this type of suit can provide adequate protection against hypothermia for 1 h in water at 5°C. However, the protection provided against the initial responses to cold immersion by such a garment has not been assessed.

With these points in mind, the protection provided against the initial responses to cold by a trunk-and-arms wet immersion suit was compared with that provided by a dry suit and by a cotton overall during a simulated helicopter underwater escape.

MATERIALS AND METHODS

There were 18 healthy male volunteers, aged 18–37, who acted as subjects for the experiment. The mean (S.D.) subject data were: age 25 (5) years, weight 75.3 (9.1) kg, height 181 (6) cm, %fat 13.5 (3.8). The volunteers were fully informed about the experiment in accordance with the code of ethics of the World Medical Association.

Each subject undertook three 2-min immersions, in water at 5°C, at the corresponding time on successive days. They wore a different clothing assembly during each immersion; the order in which these were worn was counterbalanced to reduce the influence of cold habituation. The clothing assemblies are shown in Fig. 1 and described below:

A) Cotton overall assembly: this included no specialised protective clothing and was comprised of swim-

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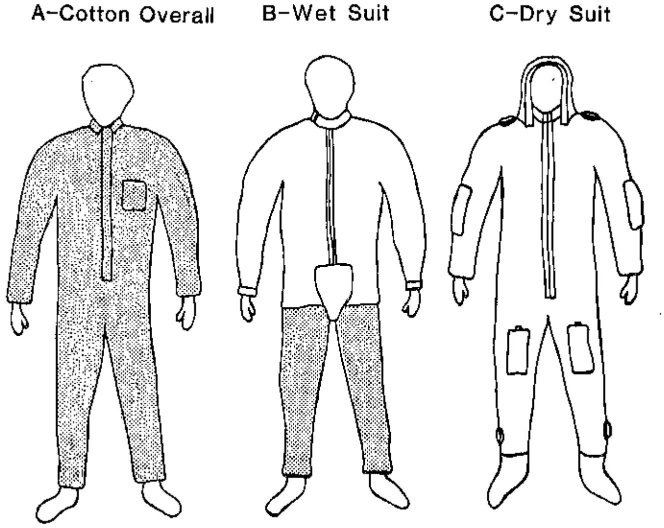

Fig. 1. The clothing assemblies.

ming trunks, cotton long-johns and vest, wool polo-necked pullover and socks, and a cotton overall.

B) Wet suit assembly: a trunk-and-arms wet suit (Dolphin wet suits, St. Albans, England) was worn over the cotton overall assembly. The wet suit was comprised of 5 mm foam neoprene over the torso and 3 mm over the arms. The jacket extended down to the groin and was secured at the front by a zip fastener. A neoprene flap attached to the back of the suit was passed between the legs and secured at the front by Velcro. The collar was also tightened by Velcro attached to a flap.

C) Dry suit assembly: an immersion suit (Multifabs GNX 430/27, Derby, England) was worn over the cotton overall assembly. The suit was constructed from a composite fabric incorporating a Gortex membrane and a Nomex outer layer. It had rubber wrist seals and a waterproof neck-to-groin zip fastener. A strip of neoprene foam inside a rubber neck collar constituted the neck seal when closed by the zip. This assembly was the only one of the three to include a hood; this was constructed from the same material as the rest of the suit. Although the hood included a thin foam neoprene face seal, it was not watertight.

The subjects were given the suit size that provided the best fit, that is, a tight-fitting wet suit, and a dry suit with close-fitting neck and wrist seals. A lifejacket (R.F.D. Type 102 Mk 2BA, Surrey, England) was worn over all of the clothing assemblies.

A simple immersion scenario was chosen to allow the differences between clothing conditions to be maximised. Only one subject performed the experiment at a time. Prior to immersion, the subject rested for 10 min in air at a thermoneutral temperature. During the rest period, the subject was seated and baseline measurements were recorded. At the end of this period, the seat was lowered at 0.2 $m \cdot s^{-1}$, by means of an electric winch, into a passenger cabin mock-up of a Bell 212 helicopter (Fig. 2). The seat came to rest in a position which corresponded to the middle seat of the central bench seat of the Bell 212, with the subjects completely submerged.

As the base of the seat came into contact with the water, the experimental clock was started. The subject was instructed to begin breath-holding as the water crossed his chin, approximately 5 s later, and to attempt to hold his breath until he had escaped from the helicopter mock-up and reached the surface of the water.

During submersion, the subject was restrained in the seat by a cross-lap seat belt and buckle (Irving Ltd, Herts., England). He assumed a standardised posture when seated, with the right hand holding the seat between the legs, and the left hand on the seat belt buckle.

At 20 s after the start of the experiment, a repeating high-pitched tone was emitted from an underwater audible alarm. This signalled the subject to undo the seat belt and escape from the cabin as quickly as possible. The 20-s period was an estimation of the time, during a

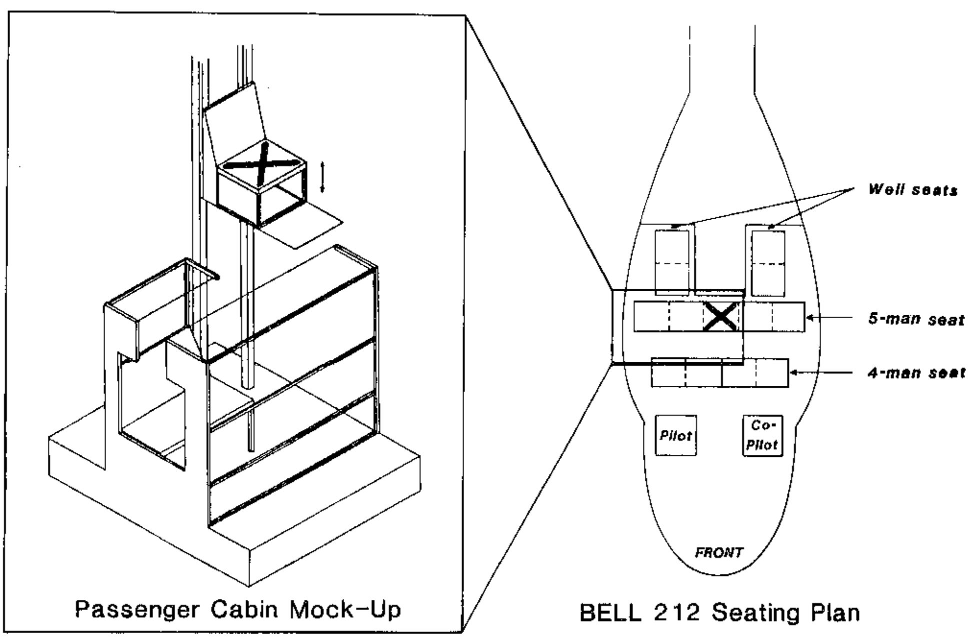

Fig. 2. The Bell 212 helicopter mock-up.

real helicopter ditching, when water turbulence and rotor blade activity may still be present, and it is thus inadvisable to attempt escape. This estimation was made following observation of individuals undertaking military and civilian helicopter underwater escape training.

On reaching the surface of the water, the subject inflated the lifejacket and rested until the end of the immersion period. Following immersion the subject undressed and rewarmed in water at 40°C.

Before their first immersion the subjects were allowed to familiarise themselves with the immersion procedure by performing underwater escapes in water at 25°C until their escape time ceased to vary by more than 0.5 s. Subjects refrained from smoking, eating or drinking for at least 3 h prior to experimentation.

Each subject remained on a mouthpiece and wore a noseclip throughout each experimental period. Oxygen consumption ($\dot{V}O_2$) was assessed by open-circuit spirometry where expired air was collected in a Douglas bag and analysed for oxygen and carbon dioxide concentrations (Beckman OM11 & LB2 analysers, IL, USA). The volume of expired air ($\dot{V}_E$) was measured by evacuating the Douglas bag through a dry gas meter (Harvard Apparatus Ltd., USA) which gave a digital readout of volume to 0.1 L. Douglas bags were collected for 4 min after 5 min of the rest period and for the first 2 min of immersion.

The inspiratory side of the respiratory tubing was connected to a pneumotachograph and integrator unit (P. K. Morgan, Kent, England). This allowed inspiratory volume ($\dot{V}_I$), respiratory frequency (f_R) and tidal volume (V_T) to be recorded throughout the experiments on a pen recorder (Gould Series 2600S recorder, OH, USA).

Breath-hold time (BHT) was determined by measuring the interval on the pen recorder between successive inspirations. In addition to holding his breath when submerged, each subject also performed a maximal voluntary breath-hold in air after 3 min of the rest period. The subject was instructed to take "only a slightly larger than normal inspiration" just prior to breath-holding. The volume of the breath taken was recorded.

The breath-by-breath end-tidal fractional concentration of carbon dioxide ($F_{et}CO_2$) was measured by continuously sampling expired air at the mouthpiece and analysing carbon dioxide concentration.

A hard wire 3-lead electrocardiogram (ECG) was obtained from all subjects throughout the experiments (Tektronic 408 monitor, OR, USA). This was recorded continuously on the pen recorder and used to calculate the heart rate of subjects during the last minute of the rest period and first minute of immersion.

Rectal temperature (T_{re}) was measured throughout each experiment by a rectal thermistor (Grants Instruments Ltd., CM probes, Cambridge, England) inserted 15 cm into the rectum and was recorded every 2 min during the experiment on a data logger (Grants Instruments Ltd., Squirrel data logger).

Skin temperature (T_{sk} was measured using skin thermistors (Grants Instruments Ltd., EU probes) attached by a single piece of adhesive tape at 10 sites: forehead, chest, lower arm, abdomen, back of hand, front of thigh, front of calf, foot, lower back, and back of thigh. These temperatures were recorded every 30 s on the data logger. Mean skin temperature ($\bar{T}_{sk}$) was taken as the unweighted average of the 10 skin temperatures (10).

The underwater tone, which informed subjects to make their escape, also automatically started a second experimental clock. This measured the time subjects took to unbuckle the seat belt and make their escape from the helicopter mock-up.

Water leakage into the dry suit during the experiment was determined by weighing the fully clothed subjects before and after immersion. Following immersion the excess water was wiped from the outside of the suit before weighing. The increase in suit weight due to external superficial water absorption was allowed for in the calculation.

Analysis of the data from the repeated measure design was conducted on a linear model with the main "effects" of subjects, clothing assemblies, condition order, time sequence, and the interaction between clothing assembly and time sequence. The significance of these terms in the model was assessed by analysis of variance. The Sheffé method of multiple comparison was used to investigate contrasts between assemblies at various times or between times.

RESULTS

Unless stated otherwise, results are quoted at the 5% level of significance. Mean data (+ range) for all subjects in each clothing assembly are presented in Tables I and II.

The $\bar{T}_{sk}$ and T_{re} of subjects did not differ significantly between conditions just prior to immersion. After 30 s of immersion, there was a significant reduction in $\bar{T}_{sk}$ in all conditions (Table II). The $\bar{T}_{sk}$ in the dry suit assembly

TABLE I. MEAN (+ RANGES) DATA AT THE END OF THE REST PERIOD (N = 18).

Variable	Cotton overall assembly	Wet suit assembly	Dry suit assembly
T_{re} (°C)	37.6 (37.1–38.5)	37.7 (36.9–38.5)	37.6 (36.9–38.3)
$\bar{T}_{sk}$ (°C)	30.8 (28.7–33.2)	31.1 (29.7–32.8)	31.5 (30.0–33.2)
f_H (Bts · min^{-1})	82 (55–121)	81 (52–103)	79 (53–95)
$\dot{V}_E$ (l · min^{-1})	14.1 (9.2–22.3)	12.3 (7.3–16.4)	11.5 (6.9–15.5)
f_R (Brths · min^{-1})	19 (13–29)	16 (10–23)	18 (13–29)
$\dot{V}O_2$ (l · min^{-1})	0.411 (0.306–0.682)	0.393 (0.279–0.464)	0.381 (0.306–0.463)
BHT (s)	45.0 (24.6–88.4)	43.0 (21.1–87.4)	42.7 (19.1–98.8)

TABLE II. MEAN (+ RANGES) DATA DURING COLD WATER IMMERSION (N = 18).

Variable	Cotton overall assembly	Wet suit assembly	Dry suit assembly
T_{re} @ 120 s (°C)	37.5 (37.1–38.5)	37.7 (36.9–38.3)	37.6 (36.9–38.3)
$\bar{T}_{sk}$ @ 30 s (°C)	18.2 (17.2–20.8)	19.8 (18.4–21.9)	27.3 (26.4–29.3)
f_H (0–60 s) (Bts · min^{-1})	102 (66–144)	100 (73–137)	89 (64–123)
$\dot{V}_E$ (0–120 s) (l · min^{-1})	56.6 (30–104.7)	51.8 (26.1–105.7)	24.9 (14.6–35.6)
f_R (0–60 s) (Brths · min^{-1})	44 (20–83)	40 (15–70)	21 (11–37)
$\dot{V}O_2$ (0–120 s) (l · min^{-1})	0.972 (0.728–1.420)	0.936 (0.749–1.218)	0.770 (0.583–0.935)
BHT (s)	9.5 (0.2–22.1)	12.2 (1.2–22.2)	19.2 (8.9–22.7)

was significantly higher than in the wet suit or cotton overall assemblies. The $\bar{T}_{sk}$ in the wet suit assembly was significantly higher than in the cotton overall assembly at this time.

Over the immersion period, an average of 1.1 L of water leaked into each dry suit; the pattern of undergarment wetting suggested that this leakage occurred primarily through the neck seal.

The BHT of subjects in air did not differ significantly between conditions. In water, the reaction and escape times of subjects also did not differ significantly between conditions, and averaged 0.64 s and 4.4 s, respectively, across all conditions. These times, meant that the total breath-hold time required to complete a successful underwater escape averaged 19.3 s.

The mean volume of the breath the subjects took before breath-holding in water was: cotton overall 1.4 L; wet suit 1.8 L; dry suit 1.8 L. In the dry suit assembly, 16 of the 18 subjects managed to hold their breath long enough to escape successfully (11% failure rate). When wearing the wet suit, 8 subjects managed to escape (56% failure rate). The BHT in this assembly was significantly shorter than in the dry suit assembly, but significantly longer than in the cotton overall assembly, in which five subjects managed to hold their breath long enough to escape successfully (72% failure rate).

The $F_{et}CO_2$ of the first expiration following breath-holding was significantly lower in all three conditions following breath-holding in water compared to air (cotton overall 4.12 cp. 5.85%, wet suit 4.56 cp. 5.79%, dry suit 5.52 cp. 6.06%). The $F_{et}CO_2$ was significantly lower after breath-holding in water in the cotton overall and wet suit assemblies compared to the dry suit assembly.

During the first minute of immersion, the f_R of subjects showed a significant increase in the cotton overall and wet suit assemblies compared to resting levels. When wearing the dry suit assembly, the f_R recorded during the same period was not significantly different from that measured during the rest period.

During the first 2 min of immersion, the $\dot{V}_E$ of subjects was significantly increased with all clothing assemblies. The $\dot{V}_E$ recorded in the dry suit was significantly lower than with the other two assemblies. The $\dot{V}_E$ recorded in the wet suit was significantly lower than in the cotton overall.

The $\dot{V}O_2$ during the first 2 min of immersion was significantly increased over resting levels with all clothing assemblies. In the dry suit, it was significantly lower than in both the wet suit and the cotton overall. No significant difference in the $\dot{V}O_2$ on immersion was found between the cotton overall and wet suit assemblies.

The heart rate of subjects was significantly increased over resting levels in all conditions on immersion. During the first minute of immersion, f_H when wearing the dry suit was significantly smaller than with both the wet suit and cotton overall assemblies, in which the f_H responses were not found to differ.

DISCUSSION

Several authors (5,15) have examined the relative merits of wet and dry immersion suits, and have concluded that in many circumstances there is little difference in the protection they provide against hypothermia. However, such studies consider only the core temperature response to cold water immersion, and ignore other hazardous responses to cold which an effective immersion suit should also prevent. The wet suit tested serves as a good example; although it has been shown to provide "adequate" protection against hypothermia (1), it provided little, or no greater, protection against the initial responses to cold water immersion than the cotton overall assembly.

In all of the clothing assemblies tested, subjects demonstrated a cold-induced reduction in their breath-hold time and a hyperventilation, plus an increase in respiratory frequency, heart rate, and oxygen consumption. The ranges shown in Table II demonstrate the wide individual variation in the size of these responses, and the hazardous level they can reach in some subjects. They are thought to be initiated by afferent stimuli arising at the peripheral cold receptors following a fall in skin temperature (6). As with the discharge of the receptors, the size of the responses is determined by the rate at which skin temperature falls ($r\Delta\bar{T}_{sk}$), the temperatures through which it falls, and the surface area of the body cooled. Thus, it is during the first seconds of immersion, when the $r\Delta\bar{T}_{sk}$ is most rapid, that the greatest responses are seen.

In theory, two ways in which clothing can help protect against these responses is to protect as much of the body as possible from a sudden fall in the skin temperature, or to reduce the $r\Delta\bar{T}_{sk}$ to levels where the magnitudes of the responses initiated are not hazardous. In practice, a dry suit might achieve either of these alternatives while a wet suit might only achieve the second.

The dry suit used in the present investigation provided some protection against the initial responses via both of the alternatives outlined above, even though the face and the hands were not covered by the suit and some leakage occurred. When wearing the dry suit, the $r\Delta\overline{T}_{sk}$ during the first 30 s of immersion (Tables I and II) was $0.14°C \cdot s^{-1}$ and was primarily caused by falls in the temperature of unprotected sites (forehead and hands). Indeed, if the unprotected skin sites are removed from the calculation of $\overline{T}_{sk}$, the $r\Delta\overline{T}_{sk}$ beneath the dry suit during the first 30 s is reduced to $0.035°C \cdot s^{-1}$; this fall was probably caused by a combination of conductive cooling and the water ingress noted above. In the dry suit, therefore, the $r\Delta\overline{T}_{sk}$ and the surface area cooled was limited to the extent that the average cardiorespiratory response to cold water immersion was less than 50% of that seen in the other two clothing assemblies.

While the subjects wore as tight a wet suit over the cotton overall assembly as they could, the $r\Delta\overline{T}_{sk}$ was not reduced to a level where the sizes of the initial responses differed greatly from those seen when the cotton overall assembly was worn (Table II). The $r\Delta\overline{T}_{sk}$ during the first 30 s of immersion was $0.38°C \cdot s^{-1}$ in the wet suit and $0.42°C \cdot s^{-1}$ in the cotton overall assembly.

Results suggest that the poor performance of the wet suit was probably due to two factors: the ineffectiveness with which it kept out water and its partial coverage construction, which provided protection for only the torso and arms.

With regard to the first factor, when only the sites covered by the wet suit are considered (chest, lower arm, abdomen, and lower back), the average of the skin temperatures at these sites fell during the first 30 s of immersion at the rate of $0.035°C \cdot s^{-1}$ in the dry suit, $0.32°C \cdot s^{-1}$ in the wet suit, and $0.41°C \cdot s^{-1}$ in the cotton overall assembly. Examining these skin temperature sites maximises the difference between the cotton overall and wet suit assemblies; although the $r\Delta\overline{T}_{sk}$ beneath the wet suit was approximately 20% slower in the cotton overall, it was still nine times the rate observed with the dry suit assembly.

The relative performance of the suits in the present investigation suggests that, on immersion in very cold water, even the most closely fitting wet suits will not provide nearly as much protection against rapid falls in skin temperature as a correctly fitting dry suit. There will, however, be some variation in the performance of both suits depending on the amount of underclothing worn; it is likely that the performance of a dry suit will improve, and that of the wet suit deteriorate, with an increase in the amount of underclothing worn.

A second factor influencing the performance of the wet suit is likely to have been its partial coverage design. In addition to the rate of temperature change, the size of the responses to cold has been reported to be influenced by spatial summation (12). Although some authors (9,12) have suggested that the torso is the most important body area for initiating responses to cold, others (14) have shown that the contribution of the limbs is also significant, particularly in the cardiac response to immersion.

The inferior performance of the wet suit assembly was probably due in part, therefore, to its failure to provide any protection to the legs. In practical terms, however, this factor is likely to be unavoidable because a whole-body wet suit would be uncomfortable to wear in many situations in air.

The problems created by the inability of individuals to breath-hold during cold water submersion could, to some extent, be avoided by providing some form of emergency breathing system. The use of such equipment does, however, require initial training, and introduces the risk of a pulmonary overpressure accident. In addition, it does little to attenuate the cardiovascular and subjective responses of individuals.

We conclude that when standards for immersion suit protection are established, consideration should be given to all of the responses associated with cold water immersion and not just to those resulting in a fall in core temperature. With regard to the cold shock responses, the wet suit concept may possess an inherent disadvantage compared with the dry suit.

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