RESEARCH ARTICLE

# Comparison of argon and air as thermal insulating gases in drysuit dives during military Arctic diving equipment development tests

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## ABSTRACT

**Introduction:** It is vital to protect divers from the cold, particularly in Arctic conditions. The insulating gas layer within the drysuit is crucial for reducing heat loss. The technical diving community has long claimed the superiority of argon over air as an insulating gas. Although argon is widely used, previous studies have shown no significant differences between the two gases. Owing to its lower heat conductivity, argon should be a better thermal insulating gas than air.

**Methods:** The study aimed to determine whether argon is beneficial for reducing heat loss in divers during development of military drysuit diving equipment in Arctic water temperatures. Four divers completed 14 dives, each lasting 45 minutes: seven dives used air insulation and seven used argon insulation. Rectal and eight skin temperatures were measured from which changes in calculated mean body temperature (MBT) were assessed.

**Results:** There was a significant reduction in area weighted skin temperature over time (0-45 minute) on air dives ($\Delta T_{skin} = -4.16°C$, SE = 0.445, $P < 0.001$). On argon dives the reduction was significantly smaller compared to air dives (difference between groups = 2.26°C, SE = 0.358, $P<0.001$). There were no significant changes in rectal temperatures, nor was a significant difference seen between groups.

**Conclusion:** Compared to air, argon may be superior as a drysuit insulating gas in Arctic water temperatures for some divers. Argon used as insulating gas can make diving safer and may diminish the risks of fatal diving accidents and occupational hazard risks in professional diving. ▮

KEYWORDS: Arctic; argon; cold; diving; immersion; insulating gas; inflation gas

## INTRODUCTION

Heat loss has always been an important consideration when diving in Arctic conditions. In Finland, the water temperature is 4°C throughout the year at 30 meters or deeper. During winter, the surface water freezes, and low water temperature directly under the ice layer is below 0°C. Heat loss is not only a matter of discomfort for divers, it impairs physical and cognitive performance [1,2], increases the risk of decompression sickness [3,4], and can lead to hypothermia. Prolonged exposure to cold can ultimately lead to major health impairments or even death.

Finnish military divers use drysuits when performing dive tasks. In addition to human physiological thermoregulation mechanisms such as skin vasoconstriction and shivering, there are means to reduce cooling during drysuit diving. These include insulating layers under the drysuit and special active warming systems. Such warming systems may be effective for short periods, but they can be unwieldy and clumsy, and they can cause burns to the skin [5]. Furthermore, they are susceptible to disturbances – e.g., equipment compressing against other devices, wrong buttons being engaged, batteries loosening – and there are indications that warming systems may increase the risk of hypothermia under certain conditions [6]. During military combat diving operations, it may be detrimental to use active warming components, since they can lead to a greater risk of being observed by the enemy due to the heat signature they generate.

In theory, argon is a better insulating gas than air because its heat conductivity is 17.72 $mW \cdot m^{-1}K^{-1}$, which is 31% lower than the heat conductivity of air (25.9 $mW \cdot m^{-1}K^{-1}$) [7]. Although the use of argon as a drysuit insulating gas is nothing new for the technical diving community, only two studies have compared argon and air as thermal insulating gases in drysuit diving [8,9]. Neither demonstrated a difference between the two gases in preventing heat loss [8,9].

The aim of this study was to compare argon and air as thermal insulation gases during Finnish Navy drysuit dives in Arctic conditions to determine whether the use of argon provides any beneficial effects on the thermal status of military divers or their operational abilities. For evaluation purposes, we used the area weighted skin temperature and the deep body temperature and calculated the change in each diver's mean body temperature (MBT) as a measure of body thermal balance, plus divers' self-reports of their operational ability.

## METHODS

### Subjects

Four physically fit male Finnish Navy divers (Table 1) volunteered to take part in testing new equipment as part of their normal operational exercises. Since this study was observational and descriptive, and the data were analyzed retrospectively from temperature measurements made during regular Naval diving equipment development tests, no ethics committee approval was required. However, the study protocol was approved by the research and development department of the Centre for Military Medicine. Body fat mass and muscle mass were measured with an InBody body composition analyzer.

### Diving equipment and drysuit insulating gas

The diving equipment used for all dives is presented in Table 2. Argon was used as the drysuit insulating gas in seven dives; air was used in seven dives. The certified 100% pure[10] argon was supplied by Woikoski Ltd (Hyvinkää, Finland). Air was taken from diving cylinders filled from a compressor that met the Finnish Navy's purity standard for breathing air [11].

### Procedure

All 14 dives were conducted over five days in January near the Arctic Circle. Each diver conducted the same number of dives with argon or air, thus acting as his own reference (dives in total for each diver (D): D1 – two dives, D2 – four dives, D3 – two dives, and D4 – six dives).

One diver performed two dives on the same day, with a surface interval of 196 minutes between the dives; otherwise, only one dive per diver per day was performed. During the tests, the air temperature varied from -23.0°C to -3.4°C. The river in which the dives were conducted was frozen, so a hole was cut through the ice layer to allow the divers to reach the water.

The dive equipment was put on with the assistance of staff members in a building with a consistent room temperature of 18°–19°C, and heat sensors were placed (see below) at the same time. Prior to each argon dive, excess air was vented from the drysuit by squatting and then refilling the suit with argon. At the same time the extremities were moved. This purge was repeated three times to ensure that the air in the drysuit was replaced with argon and that argon was distributed to all parts of the suit. The divers were warned not to exercise too vigorously, to prevent the buildup of heat before the dive and creating a bias in the data.

After preparations, the divers walked a distance of approximately 30 meters directly to the dive site and commenced the dive without further delays. The participants descended to the bottom of the river, where they remained motionless in a horizontal prone position for 45 minutes at a depth of 6 meters. Only hand and slow leg movements were permitted. The measured water temperature at the relevant spot was -0.5°C during all dives. There was a consistent water current at the spot where the dives were conducted, which increased heat loss during the dives.

### Measurements

The diver rectal temperature ($T_{rect}$) was measured with data storage tags (DST) Star-Oddi sensor. Skin temperatures were recorded with the ACR Smartreader Plus 8-system at eight standardized skin sites: forehead; right scapula; left upper chest; right upper arm; left lower arm; left hand; right anterior thigh; and left calf [12] every five minutes throughout the dives.

In addition to the temperature measurements, after every five minutes each diver reported their subjective evaluation of their operational performance ability, using a scale of 1 to 4: 1 – no ability at all to perform easy tasks; 2 – major drop in operational ability; 3 – some drop in operational ability; 4 – normal performance ability).

**Table 1**

| diver (number) | age (years) | height (meters) | weight (kg) | BMI ($kg/m_2$) | body fat mass (kg) | body muscle mass (kg) |
|---|---|---|---|---|---|---|
| 1 | 43 | 1.78 | 79.2 | 25 | 13.7 | 37.2 |
| 2 | 40 | 1.72 | 86.4 | 29.2 | 14.5 | 41.7 |
| 3 | 25 | 1.8 | 80.3 | 24.8 | 4.9 | 43.3 |
| 4 | 49 | 1.81 | 86.8 | 26.5 | 13 | 42.4 |

**Table 2**

| | |
|---|---|
| mask | Interspiro Mk. II |
| drysuit | Ursuit Heavy Light Cordura FZ |
| diving hood | Ursuit Ice Hood |
| gloves | Heat Holders |
| underwear | Ursuit Xtreme |
| socks | North Outdoor Extreme 70% merino wool |
| additional warmers | Ursuit elbow and knee warmers |
| underlay (polo shirt and trousers) | North Outdoor 100% merino wool |

### Statistic

Comparison of argon and air was made by noting the area-weighted skin temperature ($T_{skin}$) of the groups. Moreover, for evaluating the change in body temperature the $T_{skin}$ and the rectal temperature ($T_{rect}$) at the beginning of each dive as the zero point. MBT was then calculated using the following formula, modified from Burton's formula [13], for each measurement time:

$$\Delta MBT = \Delta T_{rect} \; x \; 0.65 + \Delta T_{skin} \; x \; 0.35$$

Where MBT = mean body temperature, $T_{rect}$ = rectal temperature, and $T_{skin}$ = area-weighted skin temperature [14].

$T_{skin}$ was calculated using the ISO9886 weighting coefficients [12].

For evaluating $T_{rect}$, $T_{skin}$ and MBT changes a linear mixed-effects model was performed with main effects and interaction between group and time. Both varying slope and varying intercept were fitted for ID. The analyses were made with the R program (R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria).

The difference in operational performance was compared using the Mann-Whitney U test.

## RESULTS

No diver had any complications or adverse effects during the tests. No drop in temperature to a physiological critical level [15,16] was recorded (Figures 1 and 2). The average measurements for $T_{rect}$ and $T_{skin}$ for the two groups of dives at different time points are presented in Figures 1 and 2. The relative changes in MBT over time are presented in Figure 3. Figures 4 A (chest) and 4 B (blade) show the temperature measurement results for each diver's first dive in both groups at 0, 15, 30 and 45 minutes. Table 3 shows temperature measurement results at each skin measurement sight in both groups at 0, 15, 30 and 45 minutes.

- **$T_{rect}$** – The model did not predict significant changes in temperature, nor was a significant difference between groups observed.
- **$T_{skin}$** – The model predicted a significant reduction in skin temperature over time (0-45 minutes) on air dives ($\Delta T_{skin}$ = -4.16°C, SE = 0.445, $P < 0.001$). On argon dives the reduction was significantly smaller compared to air dives (difference between groups = 2.26°C, SE = 0.358, $P < 0.001$).
- **ΔMBT** – The model predicted a significant temperature reduction over time (0-45 minutes) on air dives (ΔMBT = - 1.53°C, standard error (SE) = 0.153, $P < 0.001$). On argon dives the predicted reduction was significantly smaller compared to air dives (difference between groups = 0.77°C, SE = 0.117, $P < 0.001$).

No significant difference in self-reported/subjective evaluation of operational ability was seen between the groups. Only one diver (number 4) reported subjective diminishing of operational ability on the given scale from 4 to 3 during two dives (one at 25 minutes and the other at 35 minutes). Both of these dives were in the air group.

## DISCUSSION

To our knowledge, this study is the first to show the superiority of argon over air when used as a drysuit insulation gas. Albeit, because the number of dives was small and one diver contributed to the majority of our data, conclusions cannot automatically be made for all argon dives. More research should be done on a larger, more balanced group.

In addition to the objective temperature measurement data, the divers' subjective reports of operational ability are in line with the temperature measurements that indicate the superiority of argon. Although, not statistically significant, a subjective reduction in operational ability occurred in only two dives, both in the air group.

Using the deep body temperature (measured by a radio transmitter) as the only objective measurement during test

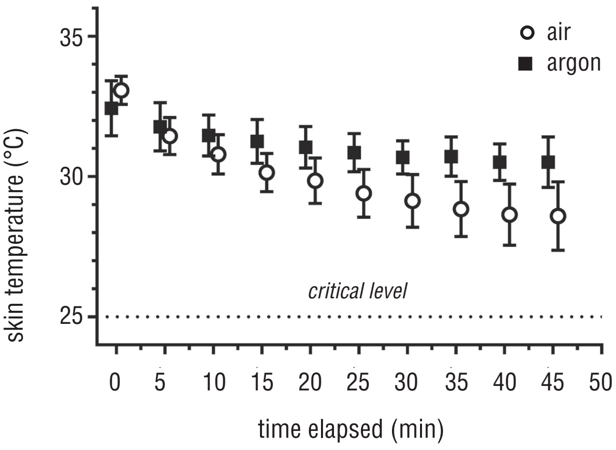

**FIGURE 1**

Area weighted average skin temperature [12] for argon (n = 7) and air (n = 7) dives in near-freezing fresh water; means and standard errors shown.

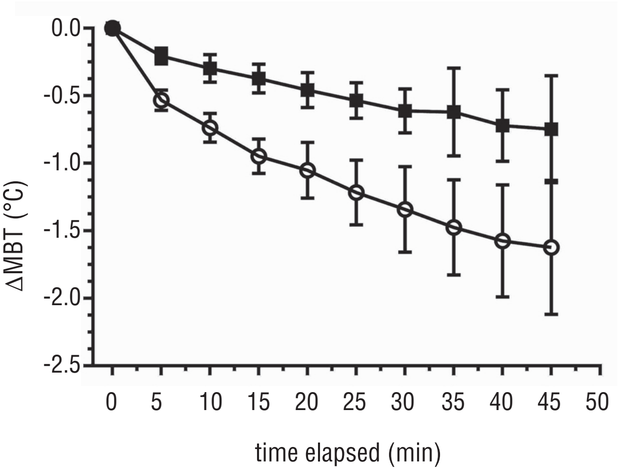

**FIGURE 3**

The change in calculated mean body temperature [12] (ΔMBT) for argon (n = 7) and air (n = 7) dives in near-freezing fresh water; means and standard errors shown.

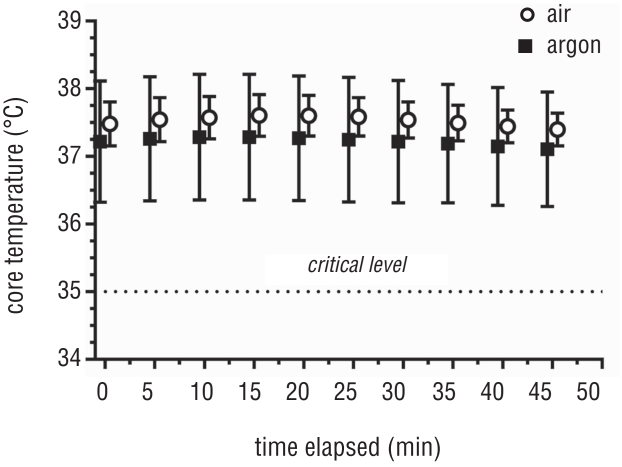

**FIGURE 2**

Rectally measured deep body temperature [12]; for argon (n = 7) and air (n = 7) dives in near-freezing fresh water; means and standard errors shown.

dives, no significant difference was seen between groups, as in Vrijdag's study [9]. Using skin temperature gives a more accurate view on the insulating properties of the drysuit gas. Moreover, a combination of deep body and skin temperatures provides a more accurate indication of the changes in body temperature than a single deep body site. Estimating MBT from these temperature measurements has been shown to be precise and accurate[17], although it does not segregate how much of the change in temperature is due to heat loss and how much is due to heat production. Moreover, at 13°C, the water temperature in that study was relatively warm for drysuit diving, which would partly explain why no significant difference was found between the two groups.

The other previous study by Risberg and Hope did measure both rectal and skin temperatures in water temperatures from -1°C to + 4°C [8]. In that study, the subjects also performed multiple drysuit flushing and squeezing procedures, thus ensuring that the air was replaced with argon before the dives. No physiologically significant differences were found between the two groups. As discussed in the paper, the divers' horizontal prone position during the tests led to the suit pressing against the divers' skin on the downward-facing parts of the body, and thus there was only a thin layer of gas between the skin and the surrounding cold water [8]. This may explain why there was no significant difference between the argon dives and the air dives in that study.

In the present study, the subjects also performed their dives in the horizontal prone position, but the subjects wore a thicker layer of clothing under the drysuit. This caused the suit to remain a good distance away from the skin at all times during the dives. The divers used additional elbow and knee warmers for the same reason, as well as undergarments made from merino wool, which is a porous material that holds gases well. The suit was large enough to ensure that the clothes fitted comfortably under the suit, enabling the use of sufficient insulating gas to prevent the drysuit squeezing against the body.

There are a few disadvantages to using argon as a drysuit insulating gas. It is the most common noble gas in the atmosphere, so production costs are not great.

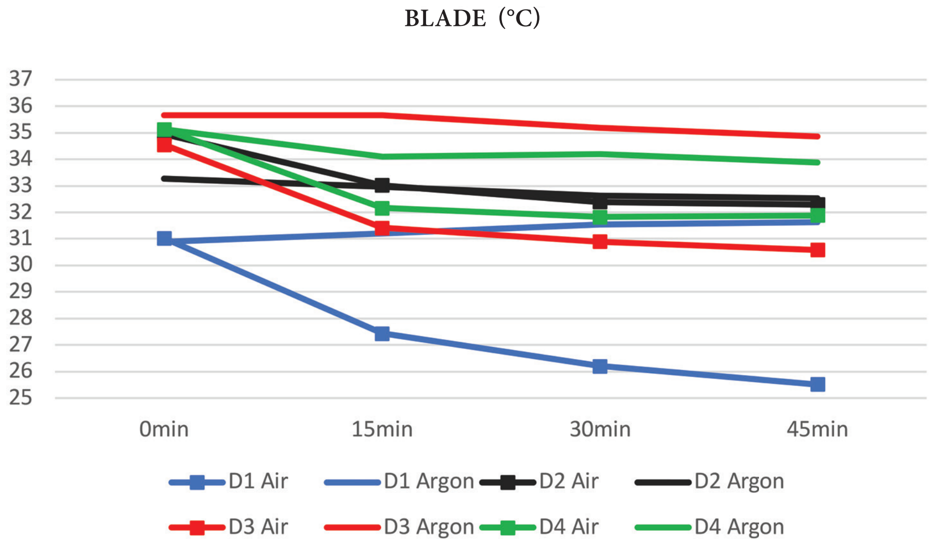

**Figure 4A**

Skin temperature (°C) measured from blade for all four divers' first dive with air and with argon. Diver number (D1-4).

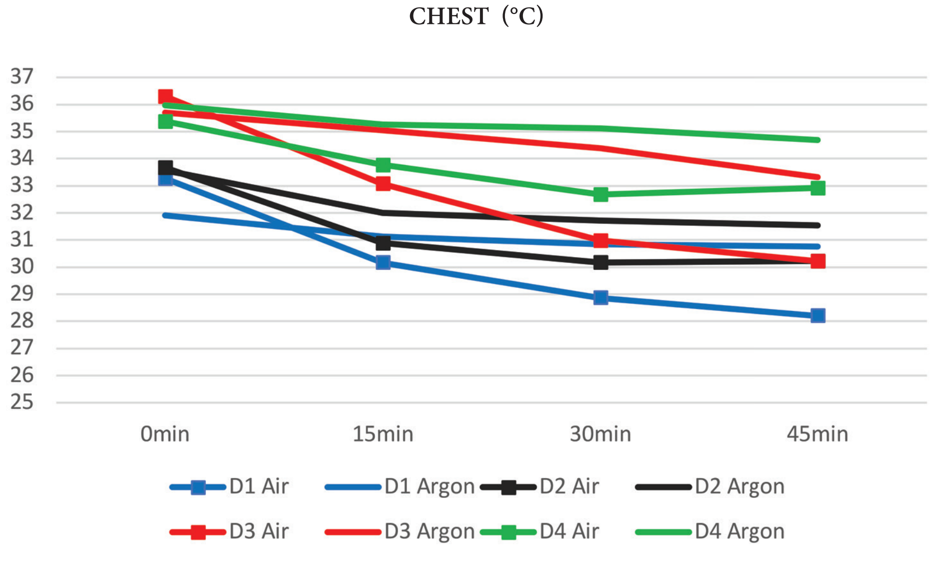

**Figure 4 B**

Skin temperature (°C) measured from chest for all four divers' first dive with air and with argon. Diver number (D1-4).

However, with more frequent use, economic and logistical factors must be taken into account. Argon requires its own gas cylinder, and the possibility of confusing the cylinder with another dive cylinder of breathing gas could lead to fatal dive accidents from hypoxia. However, this risk is more theoretical than real in well-functioning diving communities with good training routines. Additionally, with argon there are risks that must be addressed depending on the situation. Argon can cause urticaria and vestibular dysfunction [18] although these risks are minimal. To benefit from argon, it must be ensured that the suit is not squeezed against the body. This can be achieved with a sufficiently thick layer of clothing under the drysuit, as noted in the present study, combined with a thorough suit flushing routine. While the added layer of clothing can restrict the diver's mobility and buoyancy control, the amount and weight of the clothing used by the subjects in this study was fairly standard for diving in Arctic conditions.

The significantly lower drop in both $T_{skin}$ and $\Delta$MBT in the argon group gives support to the hypothesis that some divers could actually benefit from diving with argon as drysuit insulation gas. The risk of hypothermia in the Arctic environment [1-4] is much greater than the minimal risk of using argon as insulating gas [18]. Therefore, even a minor improvement in thermal insulation could be beneficial. In most DCS cases in Arctic conditions, cold is at least a contributing factor [4]. Our subjects were underwater for 45 minutes. Technical divers often perform much longer dives in similar conditions. In addition, as divers go to deeper depths, helium is sometimes added to the breathing mixture to prevent/limit nitrogen narcosis. However, helium has a poor thermal coefficient and contributes to heat loss. In these dives the replacement of drysuit gas with argon is even more necessary, as heat conduction of helium is higher than that of air.

## LIMITATIONS

Firstly, the divers were not blinded to the gas used, meaning that the subjective reports of operational ability cannot be seen as evidence for the superiority of argon.

Secondly, the study was conducted as a field study, and thus the measurements were not made in standardized laboratory conditions, as in wet chamber tests. On the other hand, the temperatures and water current at the measured diving site were constant throughout the test period. Moreover, the subjects performing the dives were of different ages, and had different fat percentages and muscle masses. The latter-mentioned factors were taken into account by having each diver in the argon group serve as his own control in the air group.

Thirdly, the study had only a small number of subjects and dives. A great part of the data came from one diver. On the other hand, a small number of subjects is not unusual in similar physiological studies of extreme environments. The fact that one diver contributed to the data more than the others means that the conclusions cannot automatically be drawn to all possible argon divers. Possible adaptation to cold during the five days of diving was not been taken into account during the tests. There is some evidence that continuous exposure to cold may improve the body's heat-regulating mechanisms [18]. This phenomenon would, however, diminish the differences between the two groups, not increase them.

Fourthly, in the argon group $T_{rect}$ shows wide confidence intervals. This could be explained partly by the fact that before the argon dives but not before the air dives the subjects carried out a vigorous suit flushing procedure. Muscle work before diving, albeit minor and for a short time period, could have affected the distribution of blood in the body. Although this might confound the results, it should actually lead to a greater $\Delta$MBT for the argon dives – muscle work leading to increased peripheral blood flow and greater heat loss through conduction.

## CONCLUSIONS

Area weighted skin temperature and mean body temperature fell significantly less in the argon group compared to the air group during 45-minute dives in near-freezing water. Contrary to previous studies, our results actually indicate that some divers may benefit from using argon as insulating gas. Reducing heat loss during diving decreases the risks of hypothermia and decompression sickness and affects both physiological and cognitive skills positively; this in turn makes diving safer and diminishes the risks of fatal diving accidents and occupational hazard risks in professional diving. However, to benefit from argon's properties, a sufficiently thick layer of clothing should be worn under the drysuit to avoid the suit pressing against the body and displacing the gas layer. Moreover, a proper argon flush and squeeze procedure should be repeated at least three times to ensure argon has replaced all the air in the suit.

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