Sixty Days in a Submarine: The Pathophysiological and Metabolic Cost

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INTRODUCTION

At this moment, and indeed at any time of any day, between 10,000 and 15,000
men are living in groups of a hundred or so in steel hulls deep below the surface
of the sea. They are completely and continuously isolated from the outside
world, even from the air they would normally breathe, for periods of up to
sixty days and more. Some revert to normal life conditions for two or three
months before returning to their submarine existence, while others may spend
only a few days ashore between underwater cruises. Some of them will continue
to live this unnatural existence for a large part of their working lives, accumu-
lating as much as seven years of underwater existence in their lifetimes. There
are perhaps 100,000 active submariners in the world today, the number
increasing steadily, and all are sailors serving in the Armed Forces of their
respective countries. It is probable that this number will be considerably
amplified when the commercial potential of nuclear-powered underwater
transport, especially for bulk materials, has been realised.

Submarines have been in existence for many years, the first really effective
submarine having been used as long ago as 1775. However, until nuclear power
was successfully applied to an underwater vehicle, less than twenty years ago,
a submarine was only a submersible surface ship that needed access to the
surface air for some hours at least once every day to allow diesel generators
to be run in order to recharge its batteries; at the same time it could replenish
the air devitalised by the crew during the preceding dive. The advent of
nuclear power meant that at last a submarine could be designed primarily
for its underwater role, since the nuclear reactor requires no air to release its
power. Therefore, a submarine was developed which theoretically could
remain submerged for the life of its nuclear core, which might be a number of
years. This tremendous advance would have been nullified unless a means
could be devised to remove the need for frequent access to the surface to renew
the air for the crews' respiration. A sophisticated system of atmosphere control has been evolved to give a designed underwater endurance of 90 days, though operationally a typical patrol is of 60 days' duration.

The Royal Navy has two types of nuclear submarine. The Polaris submarine, carrying Polaris missiles and conventional torpedoes, is of considerable size, weighs about 8,000 tons, has a crew of about 150, and a volume of breathable air of about 4,000 cubic metres. The Fleet submarine, commonly called a Hunter-Killer, carries conventional torpedoes only, has a crew of 100 men, and, with a breathable volume of 2,000 cubic metres, is less than half the size of a Polaris boat. An important difference between the two from the biological angle is that the Polaris submarine is manned by two crews who take the boat on patrol alternately, while the Fleet submarine has only one crew which is always at sea with the boat. Much of the work to be discussed has been carried out in Polaris submarines because of the inherent advantages of crew availability between patrols and of the fact that Polaris submarines carry doctors who at all times can carry out investigations on patrol. It is possible, however, that any changes seen in Polaris submariners may be of greater significance to Fleet submariners, who have no long recovery periods between patrols at sea.

THE SUBMARINE ENVIRONMENT
The atmosphere control system in use in nuclear submarines is outlined in Fig. 1. It can be seen that the system comprises means of producing oxygen by the electrolysis of sea water, removing carbon dioxide by chemical scrubbing, removing carbon monoxide and hydrogen by catalytic oxidation, and removing dusts, aerosols and some toxic contaminants by active and passive filters and by electrostatic precipitation. It is important to realise that the air in any sealed enclosure will eventually reflect practically all the materials involved in its structure, and all activities carried out within it. In submarines under closed conditions, many hundreds of substances, some harmless, some very toxic, have been identified. Examples of the more important substances found, together with their sources, are given in Table 1. The problem of defining safe exposure levels for these substances is complicated, as maximum permitted levels derived over the years for use in industrial toxicology cannot be applied directly to submarines. The reason for this is that industrial exposure is generally limited to working hours, i.e. 8 hours a day, 5 days a week, whereas exposure in submarines is continuous, 24 hours a day, 7 days a week with no daily and weekly recovery periods.

Apart from the presence of toxic contaminants described above, many other factors in the submarine environment may have much more profound
effects on the physiology, biochemistry and metabolism of submariners. These are listed in Table 2. When attempting to attribute biological changes to these factors it is important to examine the interplay that may occur between the factors, and to consider that counteraction, addition, or synergism between effects may occur. For instance, carbon dioxide will shift the oxygen dissociation curve to the right, carbon monoxide will shift it to the left, and toxic contaminants may contribute in either direction. Another more complex interplay will occur in calcium metabolism where carbon dioxide, lack of sunlight, limited physical activity, demineralised drinking water and the rich diet will all contribute to the overall picture.

In the early days of the nuclear submarine programme, attention was paid to the possible effects on the health of the crew, of aerosols and positively and negatively charged ions in the air, particularly their effects on pulmonary physiology and the central nervous system. It is now accepted that these are of little direct consequence to submariners, and interest in them has declined, though the specific nature of the aerosols and ions found will still be of toxicological concern. Investigation of the microbiological aspects of the environment has produced some interesting findings concerned with simplification of flora as the patrol progresses, and changes in nasopharyngeal and skin colonisation related to faecal contamination. These changes are unlikely to be of significance in a metabolic context unless frank disease supervenes. Climatic factors may be of importance, particularly when air-conditioning systems fail or steam leaks occur, though even under normal conditions,
Table 1. Major atmosphere contaminants found in nuclear submarines and their sources

| Acrolein | Frying |
|----------|--------|
| Aerosols, various | Smoking, lubricating oil, cooking |
| Airborne ions | Electrostatic precipitators, electric sparks |
| Aldehydes | Electrical Insulation |
| Aliphatic-aromatic hydrocarbons | Paints, solvents, thinners, fuels |
| Ammonia | CO₂ scrubbers |
| Arsine-stibine | Battery gassing |
| Carbon dioxide | Exhaling, smoking, cooking |
| Carbon monoxide | Smoking, oils, cooking, lagging |
| Chlorine | Oxygen candles |
| Freon | Air conditioning plant, refrigeration units |
| Halogenated hydrocarbons | Solvents, adhesives |
| Hydrochloric and hydrofluoric acid | CO burners from freon, halogenated hydrocarbons |
| Metal fumes | Burning, welding, brazing |
| Methane | Organic decomposition, sewage tanks |
| Methyl alcohol | Duplicator chemicals, paint cleaners |
| Mercury | Batteries, thermometers, fluorescent lights |
| Nitrous gases | Diesel exhaust, CO burners |
| Ozone | Electric sparking, precipitators |
| Phosphorus compounds (and organic) | Lubricants, fuels (air compressors) |
| Sulphur compounds | Lubricants, fuels, plastics, rubbers |
| Sulphur dioxide | Diesel exhaust, sewage tank |

Table 2. Environmental factors of significance in submarines

1. Carbon Dioxide—1% level
2. Carbon Monoxide—25 ppm level
3. Limited physical activity
4. Relatively unlimited rich diet
5. No sunlight, artificial UV light
6. Close contact with aerosols and charged ions in air
7. Demineralised drinking water
8. Close physical and microbiological contact in crew
9. Continuously variable watchkeeping and lack of external zeitgebers altering biological rhythms
10. Lack of normal physical, psychological and sensory stimuli
11. Climatic factors within the submarine
12. Unknown factors, other than toxic contaminants

especially in tropical waters, some crew members work in excessive heat. The lack of normal physical, psychological and sensory stimuli may contribute to changes seen in parameters associated with the autonomic nervous system and steroid hormones; a similar contribution may come from the continued
presence of low level physiological stress, primarily due to carbon dioxide and carbon monoxide. It is considered unlikely that the watchkeeping system and the lack of external zeitgebers significantly affect the biochemical and metabolic parameters of the submariners, but the overall effect of the submarine environment on normal circadian rhythms is most important from a research point of view, where many of the changes being monitored are within the limits of diurnal variation. It is probable that all the factors that might affect the submarine environment have received consideration at one time or another, but the space programme has shown that unexpected effects may lead to recognition of factors not previously considered.

**Physiological, biochemical and metabolic findings**

The changes in normal characteristics that have been seen, or are thought to have been seen, in nuclear submariners are many and varied. Only those that appear to be of most significance in terms of the long-term health of submariners will be dealt with here.

**Acid-base status**

The continued exposure to about one per cent of carbon dioxide during a patrol produces the expected respiratory acidosis. Figure 2 shows the degree and time course of acidosis reported by different workers, in submarines on patrol and under simulated conditions. That compensation of the acidosis, as reflected by the blood pH, occurs is undisputed, but the time to compensation appears to vary depending on whether the measurements are made on venous, arterial, or arterialised blood. It is now generally accepted that adaptation to the hypercapnia, as reflected by return of the pH to control levels and by reduction in ventilatory response to further increases in the level of carbon dioxide, is complete in 3 to 5 days, no matter what the level of exposure to carbon dioxide (Clark et al., 1969). However, Schaefer et al. (1964), using venous pH measurements, showed that the time to compensation of the acidosis varied inversely with the concentration of carbon dioxide, and Schaefer (1961) proposed three tolerance levels for carbon dioxide toxicity on the basis of animal and human work. Messier et al. (1971) have recently confirmed, in a simulated space voyage of 90 days’ duration where the ambient carbon dioxide was one per cent, using venous pH as an indicator of respiratory acidosis, that compensation takes some three to four weeks at these low levels of carbon dioxide. There is no doubt, however, as shown in all investigations, that compensation does occur well within the 60 days of a patrol, and the acidosis itself is therefore unlikely to be of significance to the
long-term health of the submariner, though the methods by which compensation is achieved may be of considerable significance.

Other reported factors of importance in acid-base status include an increase in alveolar $P_{CO_2}$ by up to 6 mm Hg which remains throughout the exposure period and shows further increases in the post-exposure period before returning to normal levels (Schaefer et al., 1963a; Pingree, B., 1971, personal communication); an increase in urinary excretion of bicarbonate ion after the venous pH has returned to normal with a sudden increase in the immediate recovery period (Schaefer et al., 1964); and a considerable rise in urinary hydrogen ion excretion during the middle third of a 50-day exposure to 0.8 per cent
CO₂, thought to represent an inefficient hunting mechanism in renal compensation for the excess CO₂ load (Gray et al., 1972).

The increased Paco₂ throughout the exposure raises the question of what happens to the excess carbon dioxide load to which the body is subjected. The urinary bicarbonate excretion and total titratable acid levels reported appear to bear some relationship to renal compensation of the acidosis, and it is suggested that during adaptation to the hypercapnia, carbon dioxide is being stored mainly in the bones, and when the body stores are saturated the excess carbon dioxide is excreted via the urine, and the blood pH returns to normal. On return to normal air, the stored CO₂ is rapidly released from the stores and excreted by the lungs and kidneys. There is evidence to support this hypothesis from submarine investigations and in the general literature (Davies, 1972a).

Calcium, Phosphorus and Magnesium Metabolism
As might be expected, changes in calcium, phosphorus and magnesium metabolism that are almost certainly due primarily to the carbon dioxide exposure can be seen. The changes in serum levels reported by Schaefer et al. (1963b) at 1·5 per cent CO₂, and by Gray et al. (1969, 1972), at about 0·8 per cent CO₂ are minor variations in calcium related to blood pH, and an overall slight increase in calcium and magnesium during the exposure period. The inorganic phosphate levels show little overall change apart from a sharp rise on initial exposure to the raised carbon dioxide. The serum changes, though small and within the normally accepted ranges, can be related to the phases of pH compensation previously described but, because of the very efficient homeostatic mechanisms associated with the serum levels of the substances, they are a poor indicator of the major changes in calcium, phosphorus and magnesium metabolism that may be occurring. Turning to the urinary excretion patterns, one sees a much more significant picture. Figure 3 shows the urinary calcium excretion rates reported by Schaefer et al. (1963b), Gray et al. (1972) and Peck (1971).

Soon after exposure starts there is a marked drop in the excretion of calcium particularly, and also of magnesium, and the rate of excretion remains at about half its previous level throughout the whole patrol period. The most significant feature is that calcium and magnesium excretion remain low for an as yet undetermined time when the submariners return to their normal environment. There is little overall change in phosphorus excretion during or after exposure. The important questions then arise of whether this represents calcium and magnesium retention, and if so, where they go and why they do not return to normal after submarine exposure ceases. It is unfortunate that oper-
national conditions in these investigations did not permit relevant faecal measurements to be made, and though the diets of the submariners were examined and no major changes in calcium ingestion were found, proper balance studies could not be carried out. The relationship between calcium intake and urinary excretion in health is confused; it has been stated (Moore-Ede et al., 1972) and shown (Marshall et al., 1972) that urinary calcium excretion is directly related to calcium ingestion; on the other hand, it has also been shown that it is practically independent of dietary calcium (Fourman and Royer, 1968; Davis et al., 1970). No further interpretation of the results found in submariners can therefore be made until full metabolic studies in an environmental chamber now being built at the Institute of Naval Medicine have been carried out. What is evident, however, is that, even if there is no absolute retention of calcium or magnesium, a change in metabolism has occurred as the route of excretion has changed and remains changed for an unknown period of time. The reasons for and the consequences of both these changes must be fully examined. It seems most likely that the cause of the decreased urinary excretion is multifactorial, and though chronic hypercapnia is probably the most important factor, the lack of sunlight and consequent lowered production of Vitamin D, reduced physical activity, and even the consumption of demineralised drinking water may all play a part. If the metabolic changes described

Fig. 3. Urine calcium output under chronic carbon dioxide exposure.
prove to be an unacceptable risk to submariners, it may be possible that some preventive measures can be taken in addition to improving conditions by reducing the patrol carbon dioxide levels, which will be very expensive. Drake (1969) showed that daily administration of magnesium oxide to the crew may remove the decreased calcium excretion seen in untreated control subjects, and Dent et al. (1964) showed that administration of cellulose phosphate would reduce calcium absorption.

**Water and Electrolyte Balance**

Little work has yet been carried out on water and electrolyte balance at these low levels of chronic hypercapnia. There is a degree of water retention (Davies, 1972b), and a decrease in urinary volume (Schaefer et al., 1964). Reduced excretion of water has also been seen in chronic hypercapnia accompanying chronic obstructive airways disease (White and Woodings, 1971). Variations in serum levels and urinary excretion of sodium, potassium and chloride occur at 1·5 per cent carbon dioxide associated with changes in the pH of blood and urine (Schaefer et al., 1964), and a reduction in plasma potassium with a slight negative potassium balance have been recorded in two studies (Schaefer et al., 1964; Messier et al., 1971).

**Metabolic Hormones**

No investigations into the hormonal control of calcium, magnesium and phosphorus metabolism under submarine conditions have yet been carried out. Schaefer et al. (1963b) stated, and more recent studies confirm this opinion, that there was no evidence of parathormone effect in the changes in calcium and phosphorus metabolism demonstrated. Studies in animals at 1·5 per cent CO$_2$ have shown an increase in adrenocortical activity, a reduction in liver and muscle glycogen stores (King et al., 1955), and an increase in urinary oxosteroid excretion (Schaefer, 1964). A reduction in the adrenaline content of the adrenal medulla and signs of adrenal exhaustion after 17 days at 3 per cent CO$_2$ have also been seen (Schaefer et al., 1949). All these changes correlated with raised Pco$_2$ rather than with variations in blood pH, indicating that the former is the more important stressor under submarine conditions.

**Haematological Parameters**

There are many studies of blood changes in chronic hypercapnia, mostly at relatively high levels of carbon dioxide, which are not strictly applicable to normal submarine conditions. Changes in blood parameters due to submarine levels of chronic hypercapnia would be expected only after very long exposure.
periods, and to date no convincing evidence has been produced to show changes attributable to carbon dioxide exposure at 3 per cent or less (Glatte et al., 1967). However, when the submarine environment as a whole is considered, and particularly the length of time the career submariner is exposed to it, haematological changes might be expected. Schaefer et al. (1964) found a slight decrease in red cell counts and haemoglobin at 1.5 per cent carbon dioxide which they attributed to the chronic hypercapnia. In operational submarines, other factors apart from hypercapnia may affect blood parameters, particularly carboxyhaemoglobinemia from raised carbon monoxide levels produced mainly by the normally unlimited smoking allowed.

The blood changes that have been found in Royal Navy nuclear submariners are increases in haematocrit with haemoglobin levels up to 20 g per cent and normal red cell counts; increased mean red corpuscular volumes up to 100 cubic microns; and increases in eosinophil counts, 5 per cent of nuclear-experienced submariners showing more than 1,000/mm³ (Morris, 1972).

The eosinophilia is surprising because the increased adrenal activity and the hypercapnia might both be expected to induce an eosinopenia.

The red cell changes are unlikely to be due mainly to chronic hypercapnia.

![Average values in nuclear submariners](image-url)
Figure 4, showing carboxyhaemoglobin levels found in nuclear submariners related to their smoking habits and to the ambient carbon monoxide levels in the submarine, indicates that this is a much more likely cause of the changes. Two factors of considerable significance to the submariner can be seen. The medium and heavy smokers, already burdened with 4 or 5 per cent carboxyhaemoglobin by their smoking habit, carry an added load of up to 5 per cent produced by the ambient level of carbon monoxide in the submarine. More importantly, perhaps, the non-smokers are also prejudiced by increased carboxyhaemoglobin levels, especially at an ambient level of 25 ppm which is the currently accepted maximum permitted level for submarine exposure. In fact, the present ambient levels of carbon monoxide experienced in Polaris submarines are around 10 ppm and, as can be seen, this considerably reduces the carboxyhaemoglobin load in the non-smoker.

There is conflicting evidence concerning the levels of carboxyhaemoglobin that can be borne before deleterious effects on the central nervous system are seen, but from the submariners’ point of view it is considered that significant deficiencies in mental performance have not been proven at less than 10 per cent carboxyhaemoglobin. Concern is felt, however, about the mounting evidence that cardiovascular damage may occur over long periods of time at the levels of carboxyhaemoglobin found in submariners (Lightfoot, 1972). It is becoming apparent that continuous carboxyhaemoglobin burdens of around 5 per cent carry a significant cardiovascular risk, and it may be necessary in the future to reduce the submarine maximum permitted level for carbon monoxide to 10 ppm to protect at least the non-smokers in the crew.

**CONCLUSIONS**

Having looked at the major changes occurring in submariners due to their service in nuclear submarines, attention must now be turned to the question of the effects of these changes on health. Only time and careful epidemiological studies, which it would be inexcusable to wait for before acting, will show the consequent penalties, if any, of living for long periods of time with the mild degree of hypercapnia, retention of, or changes in, metabolism of calcium and magnesium, altered water balance, abnormal carboxyhaemoglobin load and red cell hyperchromic macrocytosis, which are known to be present. Added to these will be a certain amount of adrenal hyperactivity and respiratory accompaniments to the hypercapnia of, for instance, increased tidal volume, increases in physiological and anatomical dead spaces, and changes in ventilatory response to increased carbon dioxide (Schaefer et al., 1963a). A potential microbiological hazard is also present (Medical Research Council,
1969) and the degree of eosinophilia present may reflect alterations in immunological status.

The major health hazards would appear to be associated with the renal and cardiovascular systems and the blood. Chronic hypercapnia due to levels of carbon dioxide not greatly in excess of those found in nuclear submarines has been associated in animals with frank nephrocalcinosis (Meessen, 1948; Schaefer, 1961), and reduced urinary excretion of magnesium has been shown to be important in the causation of experimental nephrocalcinosis (Gyory et al., 1970). The relationship between hypercapnia, carbonic anhydrase metabolism and urinary citrate has yet to be examined in submariners and may well produce some interesting results. Disease processes to be watched for in these contexts include hypertension of renal origin and the development of nephrolithiasis. Cardiovascular effects could be amplified by the imposition of the carboxyhaemoglobin load described, but coronary artery and cerebrovascular disease are more likely from this cause. Among other possibilities are chronic lung disease and haemopoietic abnormalities, and it is interesting to note here that a few cases have been seen in submariners of recurrent pleural effusion of unknown aetiology, and of polycythaemic conditions including frank polycythaemia vera, though the incidence of such diseases is so far not greater than might have been expected in a similar non-submariner population.

There is no evidence at present to show that the nuclear submariner is less healthy than his surface Navy or civilian counterpart (Davies, 1971), but the nuclear submarine programme is not yet old enough for any true increased incidence of disease to have become apparent. A very careful epidemiological watch will have to be kept in order to detect such increases, and prospective health studies are under way in both the United States Navy and the Royal Navy for this purpose. Additionally, a comprehensive preventive medicine programme has been instituted for nuclear submariners (Lambert, 1970), and careful investigation of environmental factors, properly designed epidemiological surveys, and the timely institution of preventive measures should preserve the health of the nuclear submariner at its existing high standard.

**SUMMARY**

The human habitability problems associated with the introduction of nuclear power into submarines, and the physiological, biochemical and metabolic changes consequent on long, continuously-submerged patrols are described. The environmental factors contributing to such changes, particularly raised ambient carbon dioxide and carbon monoxide levels, are discussed, together with the disease processes that might arise from such factors. It is concluded
that the existing good state of health of the nuclear submariner can be maintained by continued investigation of the effects of the environment and by an adequate preventive medicine programme.

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