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# High altitude dives from 7000 to 14,200 feet in the Himalayas

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Sahni TK, John MJ, Dhall A, Chatterjee AK. High altitude dives from 7000 to 14,200 feet in the Himalayas. Undersea Biomed Res 1991; 18(4):303–316.—Indian Navy divers carried out no-decompression dives at altitudes of 7000 to 14,200 ft (2134–4328 m) in the Nilgiris and Himalayas from May to July 1988. Seventy-eight dives on air and 22 dives on oxygen were carried out at various altitudes. The final dives were at Lake Pangong Tso (4328 m) in Ladakh, Himalayas, to a maximum of 140 feet of sea water (fsw) [42.6 meters of sea water (msw)] equivalent ocean depth in minimum water temperature of 2°C. Oxygen diving at 14,200 ft (4328 m) was not successful. Aspects considered were altitude adaptation, diminished air pressure diving, hypothermia, and remote area survival. Depths at altitude were converted to depths at sea level and were applied to the Royal Navy air tables. Altitude-related manifestations, hypoxia, hypothermia, suspected oxygen toxicity, and equipment failure were observed. It is concluded that stress is due to effects of altitude and cold on man and equipment, as well as changes in diving procedures when diving at high altitudes. Equivalent air depths when applied to Royal Navy tables could be considered a safe method for diving at altitudes.

altitude diving, acclimatization, equivalent depth, decompression, hypoxia, hypothermia, equipment failure

The aim was to establish a record dive at 14,200 ft (4328 m) in Lake Pangong Tso in the Northern Tip of Ladakh state in the Himalayas. The task involved the preparation of men and equipment to move across the subcontinent from the Diving Training School located at Cochin in the southern tip of India to the remote areas of Ladakh, living in these areas, acclimatizing to high altitudes, and then to carry out diving with equipment and procedures not tested at these heights. The only route to the lake is a treacherous dirt track from Leh, the capital of Ladakh 80 miles (130 km) away and involves crossing a snowbound pass at 17,500 ft (5334 m). Air communication is unreliable due to the cross currents in these mountains, overshadowed by clouds, and being snowbound most of the year. Food and shelter are sparse, temperatures low, and human efficiency reduced. A total of 32 preparatory dives at 7000 ft (2134 m) at Pykara Dam in the Nilgiri Hills were carried out. Subsequently, 22 dives at 7000 ft (2134 m) in Lake Manasbal, 16 dives at 11,000 ft (3353 m) in Leh, and finally 30 dives at 14,200 ft (4328 m) in Lake Pangong Tso were carried out. Dives on air were with breathing apparatus self-contained compressed air (BASSCA) following no-decompression schedules, and with Oxyger 57 on 100% oxygen. At 14,200 ft (4328 m) oxygen diving was attempted on two occasions but abandoned due to discomfort of the divers.

## METHODS

### Adaptation to high altitude

To overcome the effects of high altitude the following steps were taken. A high standard of physical fitness was ensured by carrying out a 10-day physical work-up including diving at Pykara Lake (2134 m) in southern India. This stay also proved valuable in assessing requirements in terms of spares, stores, food, medical equipment, etc. Planning was done in minute detail because the final dives would be in areas where no support, supplies, or spares could be expected. Stringent physicals followed at Cochin which included stress ECG, chest x-ray, pulmonary function tests, and exposure to a simulated altitude of 18,000 ft (5486 m) on air in a hypoxic aviation chamber for 30 min. Baseline peak expiratory flow rate (PEFR) using the miniature Wright peak flow meter was recorded. This was repeated on ascending to higher altitudes and used as an index to severity of onset of acute mountain sickness (AMS) (1, 2)

Acclimatization to reduced partial pressure of oxygen at altitude was considered the most important aspect to prevent hypoxia. Adaptability to severe hypoxia has been demonstrated by Reinhold Messner and Peter Habler when they ascended Mount Everest (8848 m) without oxygen supplements (3, 4). Despite acclimatization, work capacity is greatly reduced with altitude (5). Increase in mean reaction times at altitudes has also been attributed to hypoxia (6). On the basis of the experience of other workers (1), it was decided that a 6-day acclimatization each at Leh (3353 m) and Pangong Tso (4328 m) would be sufficient. Acclimatization would consist of strict rest on the first day followed by gradually increasing exercise before actually diving. Leh (3353 m) is in the Zanskar Range of mountains, in northern India, on the River Indus. Acclimatization here lasted for 6 days as planned. However, at Pangong Tso (4328 m), it was reduced to 4 days due to onset of bad weather and the men feeling sufficiently acclimatized. This acclimatization schedule would also adequately allow the excess nitrogen accumulated in body tissues during ascent to reach equilibrium with the reduced ambient pressure before diving (7).

Mild anoxia causes polyuria, and oliguria occurs with severe anoxia. Victims of AMS are known to become oliguric on arrival at altitude (1), hence urinary output was monitored. In addition, adequate intake of fluids was ensured to prevent dehydration, hemoconcentration, and risk of thrombi, because 3–4 liters of water loss per day can occur in the Himalayas (3). All members were familiarized with symptoms of AMS, which are well documented. The mountaineering principle of "sleep low: work high" was followed, so that the duration of stay at low oxygen pressures was restricted to the working period only (work high) and higher oxygen pressures available during hours of rest (sleep low). Also the "buddy system" familiar to divers and mountaineers was followed. Evacuation to lower altitude (with higher $P_{O_2}$) causes a reversal of effects due to high altitude. Planning for such a requirement was also made.

The final team comprised 8 divers, 1 technician, 1 diving medical assistant, and 1 physician (specialist in diving medicine). Six and a half tons of equipment traveled nearly 4500 km (2770 miles) across the most difficult terrain in the world to be available for diving at Pangong Tso in the Himalayas.

### Diving at diminished atmospheric pressure

Decompression tables to a maximum height of 18,000 ft (5486 m) were calculated on the basis of equations by Smith (7). Tables 1 and 2 are in feet and meters, respectively. Modified decompression stops had been calculated for use in emergency since no decompression dives were planned.

The Royal Navy diving tables were used throughout since we had been using these tables at Pykara (8). Also work at our institute and of other authors has confirmed the British tables to be more conservative (9, 10). Maximum diving depth and time at each altitude would not exceed an equivalent ocean depth of 45 msw (147.6 fsw) for 8 min since this was the limit for no-decompression dives in the British air tables. A decompression stop for 3 min could be added for additional safety (11). Other aspects that have to be considered while diving at altitude are change in buoyancy, equilibrium of tissue if air travel occurs before or after diving, and doubling of pulmonary gases in shallower depths (12). Table 3 is a calculation of ascent rates and pressure gradients at various altitudes. On surfacing, air starvation and breathing difficulty can occur due to the change from high partial pressure of oxygen during diving to very low partial pressures in the atmosphere at high altitudes.

Air diving was carried out at Lake Pykara (2134 m), Manasbal (2134 m), Leh (3353 m), and Pangong Tso (4328 m). Oxygen diving in pairs for 30 min was carried out at all the above sites except Pangong Tso, where it was abandoned after two attempts by two pairs of divers. Diving at Manasbal and Leh was restricted to 40 and 30 ffw (feet of fresh water) (12.2 and 9.15 mfw [meters of fresh water]), respectively, because that was the maximum available depth. At Manasbal, divers had the additional risk of weeds that infested the whole lake. Equivalent air depth and ascent rates were read off Tables 1–3 and then superimposed on the British Navy diving tables. A prophylactic stop at 2 mfw (6.5 ffw) for 3 min was not practiced due to additional risk of hypothermia.

The diving scenario was as follows: 2 Gemini craft were in the water at any given time; one formed the diving platform and the other, medical support. Emergencies would be placed in the Gemini and rushed to the shore, first aid being given en route by the physician and the diving medical assistant. A portable recompression chamber with facility for oxygen therapy and two stretchers prepared for hypothermia were kept ready on the shore whenever diving was in progress. If required, hypothermic divers while being warmed could be recompressed in the chamber. Diving was invariably carried out in the warmest part of the day and to exact depths on a cable anchored to the floor of the lake. This eliminated errors due to altered depth gauge readings (7, 8, 12). A supervisor kept a strict watch on diving time and logged it. To our knowledge, the equipment we were using had not been used at these altitudes, hence functioning of the diving sets was checked 3 times, once in the morning, before

**TABLE 1**
EQUIVALENT OCEAN DEPTHS FOR DIVES AT ALTITUDE (EO)

| Altitudes, × 1000 ft* | | 0 | 1 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Depth | | Equivalent Ocean Depths in fsw | | | | | | | | | | | | | | |
| ffw | mfw | | | | | | | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 3.05 | 10 | 10 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 20 | 20 | 20 | 20 | 20 | 20 |
| 20 | 6.1 | 20 | 20 | 25 | 25 | 30 | 30 | 30 | 30 | 35 | 35 | 35 | 35 | 40 | 40 | 40 |
| 30 | 9.15 | 29 | 30 | 40 | 40 | 40 | 50 | 50 | 50 | 50 | 50 | 50 | 55 | 55 | 60 | 60 |
| 40 | 12.2 | 39 | 40 | 50 | 50 | 60 | 60 | 60 | 60 | 70 | 70 | 70 | 70 | 75 | 75 | 80 |
| 50 | 15.2 | 49 | 50 | 70 | 70 | 70 | 70 | 80 | 80 | 80 | 80 | 90 | 90 | 90 | 95 | 100 |
| 60 | 18.3 | 59 | 60 | 80 | 80 | 80 | 90 | 90 | 90 | 100 | 100 | 100 | 105 | 110 | 115 | 120 |
| 70 | 21.4 | 68 | 80 | 90 | 90 | 100 | 100 | 100 | 110 | 110 | 120 | 120 | 125 | 130 | 135 | 140 |
| 80 | 24.4 | 78 | 90 | 100 | 110 | 110 | 110 | 120 | 120 | 130 | 130 | 140 | 140 | 145 | 150 | 160 |
| 90 | 27.4 | 88 | 100 | 110 | 120 | 120 | 130 | 130 | 140 | 140 | 150 | 150 | 155 | 165 | 170 | 180 |
| 100 | 30.5 | 98 | 110 | 130 | 130 | 140 | 140 | 150 | 150 | 160 | 160 | 170 | 175 | 180 | 190 | 200 |
| 110 | 33.5 | 107 | 120 | 140 | 140 | 150 | 150 | 160 | 170 | 170 | 180 | 190 | 190 | 200 | 210 | 215 |
| 120 | 36.5 | 117 | 130 | 150 | 160 | 160 | 170 | 170 | 180 | 190 | 200 | 200 | 210 | 220 | 225 | 235 |
| 130 | 39.6 | 127 | 140 | 160 | 170 | 170 | 180 | 190 | 200 | 200 | 210 | 220 | 225 | 235 | 245 | 255 |
| Stops, ft | | | | | | | | | | | | | | | | |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 10.3 | 10 | 8.2 | 8.0 | 7.6 | 7.3 | 7.1 | 6.8 | 6.5 | 6.2 | 6.0 | 5.8 | 5.5 | 5.3 | 5.1 |
| | 20 | 20.6 | 20 | 16.5 | 16.0 | 15.3 | 14.7 | 14.1 | 13.6 | 13.1 | 12.6 | 12.1 | 11.6 | 11.1 | 10.7 | 10.2 |
| | 30 | 30.8 | 30 | 24.7 | 24 | 22.9 | 22 | 21.2 | 20.4 | 19.6 | 18.8 | 18.1 | 17.4 | 16.7 | 16 | 15.3 |

*1000 ft = 304.8 m

**TABLE 2**
EQUIVALENT OCEAN DEPTHS FOR DIVES AT ALTITUDE (METERS)

| Altitudes, × 1000 ft* | | 0 | 1 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Depth | | Equivalent Ocean Depths in msw | | | | | | | | | | | | | | |
| ffw | mfw | | | | | | | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 3.05 | 3.05 | 3.3 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 |
| 20 | 6.1 | 6.1 | 7.6 | 7.6 | 9.1 | 9.1 | 9.1 | 9.1 | 10.7 | 10.7 | 10.7 | 10.7 | 10.7 | 12.2 | 12.2 | 12.2 |
| 30 | 9.15 | 8.8 | 9.1 | 12.2 | 12.2 | 12.2 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 | 16.8 | 16.8 | 18.3 | 18.3 |
| 40 | 12.2 | 11.8 | 12.2 | 15.3 | 18.3 | 18.3 | 18.3 | 18.3 | 21.4 | 21.4 | 21.4 | 21.4 | 21.4 | 22.8 | 22.8 | 24.4 |
| 50 | 13.2 | 14.9 | 15.3 | 21.4 | 21.4 | 21.4 | 21.4 | 24.4 | 24.4 | 24.4 | 24.4 | 27.4 | 27.4 | 27.4 | 29.0 | 30.5 |
| 60 | 18.3 | 17.9 | 18.3 | 24.4 | 24.4 | 24.4 | 27.4 | 27.4 | 27.4 | 30.5 | 30.5 | 30.5 | 32.0 | 33.5 | 35.0 | 36.5 |
| 70 | 21.4 | 20.7 | 24.4 | 27.4 | 27.4 | 30.5 | 30.5 | 30.5 | 33.5 | 33.5 | 36.6 | 36.6 | 38.2 | 39.6 | 41.2 | 42.6 |
| 80 | 24.4 | 23.7 | 27.4 | 30.5 | 33.5 | 33.5 | 33.5 | 36.6 | 36.6 | 39.6 | 39.6 | 42.6 | 42.6 | 44.2 | 45.8 | 48.8 |
| 90 | 27.4 | 26.8 | 30.5 | 33.5 | 36.6 | 36.6 | 39.6 | 39.6 | 42.6 | 42.6 | 45.8 | 45.8 | 47.2 | 40.2 | 51.8 | 56.8 |
| 100 | 30.5 | 29.8 | 33.5 | 39.6 | 39.6 | 42.6 | 42.6 | 45.8 | 45.8 | 48.8 | 48.8 | 51.8 | 53.4 | 54.8 | 58.0 | 61.0 |
| 110 | 33.5 | 32.6 | 36.6 | 42.6 | 42.6 | 45.8 | 45.8 | 48.8 | 51.8 | 51.8 | 54.9 | 58.0 | 58.0 | 61.0 | 62.0 | 65.5 |
| 120 | 36.5 | 35.6 | 39.6 | 45.8 | 48.8 | 48.8 | 51.8 | 51.8 | 54.9 | 58.0 | 61.0 | 61.0 | 64.0 | 67.0 | 68.6 | 71.6 |
| 130 | 39.6 | 38.7 | 42.6 | 48.8 | 51.8 | 51.8 | 54.9 | 58.0 | 61.0 | 61.0 | 64.0 | 67.0 | 68.6 | 71.7 | 74.6 | 77.8 |
| Stops, meters | | | | | | | | | | | | | | | | |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 3 | 3.2 | 3.0 | 2.5 | 2.4 | 2.3 | 2.2 | 2.2 | 2.0 | 2.0 | 1.8 | 1.8 | 1.8 | 1.6 | 1.6 | 1.5 |
| | 6 | 6.3 | 6.0 | 5.0 | 4.8 | 4.6 | 4.5 | 4.3 | 4.2 | 4.0 | 3.8 | 3.7 | 3.5 | 3.4 | 3.3 | 3.1 |
| | 9 | 9.4 | 9.0 | 7.5 | 7.2 | 7.0 | 6.7 | 6.5 | 6.2 | 6.0 | 5.7 | 5.5 | 5.3 | 5.0 | 4.8 | 4.7 |

*1000 m = 3280 ft

TABLE 3
ASCENT RATES AND PRESSURE GRADIENTS AT ALTITUDE

| Altitude | | Actual Ascent Rate | | Depth at Which Pressure Doubles | |
|---|---|---|---|---|---|
| Feet | Meters | ftw/min | mfw/min | ftw | mfw |
| 0 | 0 | 61.6 | 18.7 | 33.9 | 10.3 |
| 1,000 | 305 | 59.4 | 18.1 | 32.8 | 9.9 |
| 6,000 | 1,829 | 49.4 | 15.0 | 27.2 | 8.3 |
| 7,000 | 2,134 | 47.5 | 14.5 | 26.2 | 7.9 |
| 8,000 | 2,438 | 45.8 | 13.9 | 25.3 | 7.7 |
| 9,000 | 2,743 | 44.0 | 13.4 | 24.3 | 7.4 |
| 10,000 | 3,048 | 42.4 | 12.9 | 23.4 | 7.3 |
| 11,000 | 3,353 | 40.7 | 12.4 | 22.5 | 6.8 |
| 13,000 | 3,962 | 37.7 | 11.5 | 20.8 | 6.3 |
| 14,000 | 4,267 | 36.2 | 11.0 | 20.0 | 6.0 |
| 15,000 | 4,572 | 34.8 | 10.6 | 19.2 | 5.8 |
| 16,000 | 4,877 | 33.4 | 10.1 | 18.4 | 5.6 |
| 17,000 | 5,182 | 32.1 | 9.8 | 17.8 | 5.4 |
| 18,000 | 5,486 | 30.8 | 9.4 | 17 | 5.2 |

getting into the water, and again before the descent. Each diver dived only once on a given day and always in pairs.

### Hypothermia

Hypothermia due to low surface temperature and immersion hypothermia can occur during diving at altitude. Surface temperatures ranging from 16°–19°C to 1°–4°C and water temperatures of 3°–5°C were known to occur in Pangong Tso. Sharp falls in temperature with depth were attributed to the melting snow that fed the lake. After trials of different suits in Lake Pykara (2134 m) the underwater swim suit (UWSS) "dry suit" with woolen inner garments was selected for dives at high altitude (13). Adaptation to cold can occur with frequent immersion (14). Therefore, to ensure adaptation to cold, surface swimming for 20–30 min (bare body or with 6-mm neoprene wet suit) was carried out during the acclimatization to altitude, and this preceded days of actual diving. This adaptation was considered adequate because no decompression dives were planned, requiring the divers to be in the water for a minimum time. In many ways, preparation for diving at this remote lake was similar to that required for diving in Antarctica (15).

To combat hypothermia we decided to use the same method we had been using for years at Pykara, where water temperatures are in the range of 4° to 10°C. Two stretchers with 6–8 blankets and 8–10 hot packs each were kept in readiness. Hypothermic divers with their diving suits were placed within the blankets, and the hot packs placed within the layer of blankets, avoiding direct contact with the diver, so that gradual warming took place. Special stress was laid on warming the head, axilla, and groin with minimum manipulation of the diver. Warm fluids in sips were given slowly to help core temperatures return to normal. Subsequently, acidosis, hypoglycemia, hypovolemia, and electrolyte balance can be managed. Hypothermia of 31°C has been managed with this arrangement.

### Survival in remote areas with sparse food and shelter

Loss of bodyweight at high altitude has been attributed to hypo-hydration, loss of body fat, and/or a loss in lean tissue (16). Nausea and mental depression are also known (5), which may lead to reduced appetite and loss of weight. To survive in these areas sufficient quantities of appetizing and wholesome food were carried. We had to manage in locally available shelters, but sufficient woollen clothing and sleeping bags, etc., were available.

### Equipment

Equipment used during this series of dives included:
- BASCCA diving set made in England by Aquarius Submarine Products Limited.
- Oxyger 57 underwater breathing apparatus manufactured by Spirotechnique, France.
- 6-mm Neoprene wet diving suit.
- UWSS with hood manufactured by Avon Rubber Company Limited, England.
- One-man portable recompression chamber, manufactured by Siebe Gorman and Co. Ltd., England, January 1971.
- Supportive diving equipment such as Gemini crafts, compressors, life lines, sinkers, etc.
- Medical resuscitation equipment.
- Woollen clothing and sleeping bags.

## OBSERVATIONS

### Acclimatization

Table 4 is a summary of disorders observed during the entire series of dives. No difficulty was felt in acclimatization at Pykara (2134 m), Srinagar (2073 m), and Manasbal (2134 m). Shortness of breath on strenuous exercise felt on the first day at Pykara was adapted to in a few days. At Leh (3353 m), all members felt breathlessness on mild exertion on Day 1, all except 2 had adapted by Day 3 and they too settled down in a week. No treatment was given and there was no evidence of any pulmonary abnormality.

During the entire stay at high altitude, feelings of reduced physical efficiency and poor appetite were universal. However, loss of appetite was significant in 4 members at Leh and 7 at Pangong Tso.

Headache responding to aspirin was significant in 6 at Leh and in 1 at Pangong Tso. Altered sleep rhythm manifesting as insufficient period of sleep, waking up breathless and restless, and unrefreshing sleep was noticed at Leh. Two members at Pangong Tso also felt sleep abnormality. Diazepam (5 mg) at bed time for 2–3 days helped revert the sleep pattern to normal. Irritability and lack of concentration in

TABLE 4
MANIFESTATION OF DISORDER

| Cause | No. of Cases | | | |
|---|---|---|---|---|
| | 7,000 ft (2,134 m) | 11,000 ft (3,353 m) | 14,200 ft (4,328 m) | |
| No. of days | ~10 | 8 | 6 | Manifestation |
| Altitude related[a] | | | | |
| Cerebral | — | 6 | 1 | headache |
| Pulmonary | — | 2 | — | breathlessness |
| Gastrointestinal | — | 4 | 7 | anorexia, vomiting |
| Psychosomatic | — | 3 | 2 | altered sleep rhythm |
| Behavioral | — | — | 2 | lack of concentration |
| Physical efficiency | — | 11 | 11 | reduced efficiency |
| Diving illness[b] | | | | |
| Decompression sickness | | | | |
| Type I | 1 | 2 | 1 | skin rash/arthralgia |
| Type II | — | — | — | |
| Hypoxia | — | — | 1 | loss of conciousness |
| Hypothermia | | | | |
| On surface | — | — | 2 | |
| On immersion | — | — | 1 | |
| Equipment malfunction | — | — | 4 | ? demand valve |
| Undiagnosed | — | — | 1 | |

[a]Number of subjects, 11; [b]no. of subjects, 8.

tasks were evident in 2 members at Pangong Tso. Rest, diazepam, and a thiazide diuretic on 1 day was sufficient to restore normalcy in 2 days time.

**Diving illness**

Table 5 is a summary of details of diving carried out.

Skin rash on the forearm was reported by 1 diver 6 h after a 30 ffw (9.15 mfw) actual depth dive at Leh. Intermittent oxygen on surface for 45 min, antihistamines, and topical steroid ointment were administered. The rash disappeared in about 3 days. General malaise and arthralgia were reported by 1 diver each at Leh and Pangong Tso after dives to 30 and 40 ffw (9.15 and 12.2 mfw) and in the morning after and the same evening, respectively. Clinically, no abnormality was detected. Analgesics and rest were sufficient to restore normalcy.

Diver SS soon after commencing a 60-ffw (18.3 mfw) dive at Pangong Tso rushed up from a depth of about 10–15 ffw (3–4.5 mfw) in distress. On removal of the set he was cyanosed and lost consciousness while being pulled into the Gemini. Body temperature was 36°C, there was no evidence of any barotrauma, and oxygen inhalation for a few minutes revived consciousness. He complained of "inability to breathe" and buoyancy mismatch on descent, thus he decided to return to surface. While ascending he suddenly blacked out and could not recall the happenings on regaining

**TABLE 5**
PARTICULARS OF WET DIVES AT ALTITUDE

| | Actual Depth | | Eqvt. Air Depth | | No. of Dives | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Altitude | ffw | mfw | fsw | msw | Air | Oxygen | Bottom Time, min | Decompression Time, min | Total Time In Water | Rate of Ascent |
| 7000 ft (2134 m) | 60 | 18.3 | 80 | 24.4 | 8 | — | 5 | 3 | 8 min | 48 ft/min |
| Pykara | 80 | 24.4 | 110 | 33.5 | 8 | — | 8 | 4 | 12 min | 14.5 m/min |
| | 100 | 30.5 | 130 | 39.6 | 8 | — | 7 | 4 | 11 min | |
| | 16.5 | 5 | 26 | 8 | — | 8 | 30 | 1 | 31 min | |
| 7,000 ft (2134 m) | 40 | 12.2 | 50 | 15.3 | 16 | | 5 | 2 | 7 min | 48 ft/min |
| Manasbal | 16.5 | 5 | 26 | 8 | — | 6 | 30 | 1 | 31 min | 14.5 m/min |
| 11,000 ft (3353 m) | 30 | 9.15 | 50 | 15.3 | 12 | | 8 | 2 | 10 min | 40 ft/min |
| Leh | 16.5 | 5 | 26 | 8 | — | 4 | 30 | 1 | 31 min | 12 m/min |
| 14,200 ft (4328 m) | 40 | 12.2 | 70 | 21.4 | 8 | | 5 | 2.5 | 7.5 min | |
| Pangong Tso | 60 | 18.3 | 105 | 32 | 6 | | 6 | 3 | 9 min | 35 ft/min |
| | 70 | 21.4 | 125 | 38.2 | 6 | | 6 | 3.5 | 9.5 min | 10.5 m/min |
| | 80 | 24.4 | 140 | 42.6 | 6 | | 7.5 | 4 | 11.5 min | |
| | 13 | 4 | 26 | 8 | — | 4 | 2 | 1 | 3 min | |
| | | | | Total | 78 | 22 | | | | |

consciousness. Recompression was not indicated and he was given intermittent oxygen inhalation, advised to rest, and kept under observation for 24 h. Hypoxia due to equipment malfunction was a possibility. Examination of the set, however, revealed the cylinders to be charged and the demand valve functional.

Diving on 100% oxygen was carried out at Pykara, Manasbal, and Leh successfully for 30 min. At Pangong Tso pairs of divers on two occasions abandoned diving within a few minutes. On both occasions the divers felt a combination of difficulties in correcting buoyancy, maintaining depth, and hyperventilation and headache.

### Hypothermias

Surface and water temperatures experienced during the dive are given in Table 6.

All 3 cases of hypothermia occurred at Pangong Tso, 2 during work-up swimming on surface for acclimatizing and 1 during diving. During surface swimming JSB showed inattention to verbal commands. On being pulled into the boat, he was pale and shivering and appeared confused. Core temperature was 35°C. While surface swimming, HS suddenly reduced speed, appeared in distress, and did not respond to commands. On being pulled into the boat he appeared pale and exhausted, incoherent in speech, and uncoordinated. Core temperature was 34°C. The third case occurred after the dive to 80 ffw (24.4 mfw) actual depth when the diver spent 11.5 min in the water. On removal of the set he appeared uncoordinated, was shivering severely, and extremities were pale and cyanosed. Core temperature was 35°C. Rewarming was done by the method described earlier, and the divers recovered rapidly and resumed normal work after 8–12 h.

### Equipment

Malfunction of demand valves was experienced at Leh (3353 m) and at Pangong Tso (4328 m). On at least four occasions at Pangong Tso inadequate flow was detected in time, and in the diver who had suffered from hypoxia, malfunction of equipment was thought to be the likely cause.

TABLE 6
TEMPERATURE AT VARIOUS ALTITUDES

| | Surface Temperatures, °C | | Water Temperatures, °C |
|---|---|---|---|
| | Maximum | Minimum | |
| Pykara (7,000 ft, 2,134 m) | 18–20 | 6–8 | 4–10 |
| Manasbal (7,000 ft, 2,134 m) | 25–30 | 6–10 | 12–14 |
| Leh (11,000 ft, 3,353 m) | 18–24 | 5–7 | 7–9 |
| Pangong Tso (14,200 ft, 4,328 m) | 16–19 | 1–4 | 2–5 |

## DISCUSSION

Possibly the earliest decompression tables for altitude were developed by Dr. Jon Pegg in 1965 for use in Lake Tahoe, but were never published. The Cross tables are widely referenced corrections for altitude and were presented by E. R. Cross, although apparently developed by H. J. Smith, Jr. Bell and Borgwardt examined the theoretical basis of the Cross tables and presented the Cross correction to the U.S. Navy decompression tables (17–19). Tables developed for a maximum height of 3200 m (10,500 ft) were tested in Switzerland and published in 1976 (3). The University of California at Davis conducts research and diver training at 6200 ft (1890 m) in Lake Tahoe. In Mexico City at 7500 ft (2286 m), diving tunneling operations have been carried out (17). In India, diving training is routinely carried out at 7000 ft (2134 m) in Lake Pykara in the Nilgiris.

The most extreme example of high altitude diving is Jacques Cousteau's underwater survey of Lake Titicaca in Bolivia in 1968 at altitudes of 12,500 ft (3810 m) (17). Diving at 14,200 ft (4238 m) in Lake Pangong Tso is the dive at the highest altitude according to the literature.

Decompression tables for diving at altitude are of two types: those that are specifically calculated for altitude diving and those that use sea level tables after applying a correction for altitude. Schedules computed by Bühlmann et al. (20), by Boni et al. (11), and by Bühlmann (3) are specific calculations for altitude diving. They can also be computed on the model suggested by Schreiner and Kelly (21). However, these tables are of limited value because they have not been adequately tested (17), and are only calculated for dives up to altitudes of 3200 m (10,500 ft).

The other practice is to use the tables for sea level after applying correction for altitude on the basis of available tables such as the Cross, Cross correction, and those presented by Smith (7, 17–19). Providing corrections are made for depth and ascent rates, a dive at altitude can be transformed to one at sea level for which theoretical tissue responses are mathematically similar to the altitude dive. This transformation fails if stops are required because the stop criteria do not obey the same rule of transformation (17). The theoretical basis of these corrections has been controversial, with various rules of thumb recommended by which corrections can be made (8, 12, 17). However, it has been recommended that even for no-decompression dives at altitude, a decompression stop is necessary for at least 3 min at 3 and 2 mfw (9.8 and 7.6 ffw) for the 0–700 (0–2296 ft) and 700–3200 m (2296–10,500 ft) tables, respectively (11). Attempts to compute an ideal table for diving at altitude have been carried out by many workers such as Hall (22), Hennesy (23), Moass et al. (24), and Smith (7). These authors have also described methods to calculate tables for different altitudes.

Effects of altitude are due to the reduced oxygen partial pressures in the atmosphere. Physiologic changes during acclimatization are in many ways different from changes due to diving in cold waters. Hemoconcentration at altitude is mainly due to secondary polycythemia, whereas during diving it is due to diuresis and decrease in plasma volume. Erythropoiesis is stimulated at altitude due to reduced pressure of oxygen, whereas during diving it is depressed due to high partial pressure of oxygen (12, 17). Despite acclimatization, work capacity is greatly reduced with altitude. However, no reduction in work capacity of well-trained men has been demonstrated up to 9000 ft (2743 m) (25). Acclimatization to hypoxia has been recommended for work at altitudes above 8000 ft (2438 m) (1, 26). In our experience, effects of altitude were felt only after ascent by air to 11,000 ft (3353 m). Acute mountain sickness, chronic mountain sickness, high altitude cerebral edema, cerebral thrombosis, and high altitude pulmonary edema are well-documented complications of stays at high altitudes (1, 3, 6, 26–28). Acclimatization for 12 h is also recommended before diving, even for divers ascending to low altitudes. This is to allow the nitrogen content of the tissues to reach equilibrium with the reduced ambient pressure. Alternatively, the correction for repetitive dive group must be applied (7, 29). Our planned acclimatization period adequately covered this and we made no corrections for these.

The clinical picture of immersion hypothermia after diving in cold water is well recognized (12). Various wet and dry diving suits have been tested to find an ideal insulation for divers (13). This is based on the knowledge that performance of divers is known to deteriorate in cold water (10, 29). Cold has also been attributed as a contributing factor in decompression sickness (10).

The effect of low ambient pressure on equipment can cause a possible malfunction of the hydrostatic compensation valves. Cold is also known to affect the properties of metals (12). Freezing of water vapor in valves of diving equipment or recompression chambers can cause malfunction. Freezing from increased flow is also produced with hyperventilation and panic (12). Malfunction was experienced both at Leh and at Pangong Tso. Objectively it may be difficult to define the fault. In the diver who had hypoxic hypoxia, malfunction of equipment was a likely diagnosis; examination of the set however revealed that the cylinders were charged and the valve functional. Freezing of water vapor with hyperventilation and malfunction of the hydrostatic compensation valves could have occurred. It is advised that demand valves not be purged in very cold temperatures. Practically, it is sound teaching and reassuring to the diver to confirm that valves are functional before diving. However, purging at high altitudes can cause malfunction. It is recommended that until special equipment tested for altitudes is available, equipment be tested in a hypoxic chamber with simulated heights and temperatures to realistically determine the limitations of the equipment.

Control of buoyancy with rebreathing apparatus near the surface can be difficult due to rapid changes in breathing bag volume with depth. This problem is exacerbated at altitude due to decreased pressure, especially since adequate ventilation may be difficult when a breathing bag has too much or too little gas in it. Strenuous work while the diver is trying to descend when incorrectly buoyant would lead to hyperventilation contributing to headaches. It is also hypothesized that after adaptation to low partial pressures of oxygen on the surface, a changeover to 100% oxygen under pressure during diving may cause oxygen toxicity at much shallower depths. These could be some of the causes for inability to carry out oxygen diving at 14,200 ft (4328 m).

Reports of actual diving at altitudes above 9000 ft (2743 m) are few. Limited availability of diving sites above these altitudes and inadequate incentives to dive at these sites may be among the causes. In the event of requirements for strategic or commercial gains, frequent diving would be carried out with valuable experience gained. Sport and adventure diving at these altitudes will remain restricted.

We were carrying out adventure dives at altitudes where no documented dives had been done before. Hence a conservative approach was adopted. The British tables are safe, and until safer tables are reported, these are recommended for use after calculating equivalent air depths.

Diving in extreme altitudes in remote areas has the fascination of adventure in addition to the thrill of diving in unknown waters. Diagnosis of problems can be perplexing, and it may be difficult to attribute a particular sign or symptom to altitude, to cold, to diving, or to equipment malfunction. In diving at Pangong Tso, the challenge was not only to dive at 14,200 ft (4328 m) but to travel 4500 km (2800 miles) in remote areas of the Himalayas and to plan in advance to meet the challenges that the terrain imposes on men and equipment.

## CONCLUSION

Diving at high altitudes (above 9000 ft, 2734 m) is experimental, and sufficient documented dives have not been done to recommend procedures to be followed. Physiologic adaptation to altitudes and effect of cold on men and equipment, in addition to changes in diving procedures, are significant. Equivalent air depths for no-decompression dives when applied to the Royal Navy air tables were found to be safe procedures during this series of dives.

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