15 The Significance of the Human Diving Reflex

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SUMMARY

Hardy (1977) and Morgan (1982) have both argued that the existence of a human 'diving reflex' provides strong evidence in favour of the Aquatic Ape Theory, but the reflex has received relatively little attention in the subsequent debate. This chapter describes the cardio-vascular component of this reflex, and discusses its importance in the AAT discussion.

THE DIVING REFLEX IN ANIMALS AND MAN

Diving mammals and birds have developed a series of mechanisms for oxygen conservation which permit prolonged diving. Among the most pronounced adjustments are a redistribution of the circulating blood (by selective vasoconstriction) and a lowering of the pulse rate (bradycardia). This 'diving reflex' leads to oxygen-saving by diverting blood-flow away from organs that can function anaerobically, while maintaining the flow to organs like the heart and brain which are more sensitive to asphyxia (Andersen, 1966), as well as to working muscle groups (Butler and Woakes, 1987). The consequent reduction in the work of the heart results in a further saving of oxygen (Lin, 1982). The response is initiated when the head of a diving mammal is submerged, and when the animal returns to the surface the changes are reversed and the lactic acid – produced by any anaerobic metabolism – is removed. These 'debit and credit' measures enable certain marine mammals, such as the Weddell seal, to withstand submersion for more than one hour (Kooyman et al., 1980).

Humans react in a similar way during breath-hold diving (Gooden, 1972). The reflex is strongest when the whole body is exposed to cold water (Lin, 1984), but it is still clearly operative when only the face is immersed and the breath is held (Furedy et al., 1983). Apnoea alone reduces the heart rate by about half as much as apnoea plus facial cooling (Hurwitz and Furedy, 1986). Cold stimulation of the face without wetting produces a similar bradycardia, indicating that facial cold receptors are involved in triggering the response (Kawakami, Natelson and Dubois, 1967). Probably these cold receptors are most densely distributed on the forehead (Schuitema and Holm, 1988). This would

explain the efficacy of the traditional way of treating fever or stress with an ice-bag on the forehead (Bergmark, 1985).

FACTORS INFLUENCING DIVING BRADYCARDIA IN HUMANS

A method often used in laboratory studies of the diving reflex in humans is breath-holding combined with face immersion. The resulting bradycardia is the measure used most often for quantifying the reflex. Many factors influence the magnitude of the bradycardia. Both water and ambient air temperatures are important (Moore *et al.*, 1972). The bradycardia is inversely proportional to water temperature within a range that is determined by the ambient air temperature (Schagatay and Holm, to be published).

Humans, like sea otters, dive after inspiration, but a maximal inspiration counteracts the development of diving bradycardia (Gooden, 1982; Ferrigno *et al.*, 1986). If the intrathoracic pressure gets too high it inhibits the return of venous blood to the heart, and the pulse rate increases to compensate for a smaller stroke volume. Skilled divers like the Ama of Korea and Japan and Indonesian skin-divers are known to dive after less than maximal inspiration (Hong and Rahn, 1967; Schatagay, unpublished observations). An important factor determining the magnitude of bradycardia is the duration of breath-holding, because the reflex has a gradual onset and during the initial 30–40 seconds the bradycardia is proportional to breath-holding time. After about 40 seconds the bradycardia is fully manifested at a level which is usually maintained throughout the dive (Figure 15.1). In many investigations only the first 30 seconds of submersion have been studied. Stress can attenuate or abolish the diving bradycardia (Gooden, 1982). Much of this effect can be avoided if inexperienced subjects perform one or two test dives before the experimental dive. If three to five breath-holds are performed at short intervals, the duration of breath-holding increases because of the so-called short-term training effect (Sterba and Lundgren, 1988). This effect is different from the effect of long-term training, and can be avoided by spacing dives apart with adequate periods of rest.

The individual ability to hold the breath can be improved by training (Hentsch and Ulmer, 1984). The increase in breath-holding time involves learning to make the appropriate preparations for diving — physiologically by slight hyperventilation, and psychologically by resisting the drive to breathe. These factors probably account for some of the differences between a group of trained Indonesian divers and an untrained control group of Swedish students (Figures 15.1 and 15.2). Factors such as the use of adequate lung inflation, stress avoidance and relaxation in the professional divers may also contribute to the differences
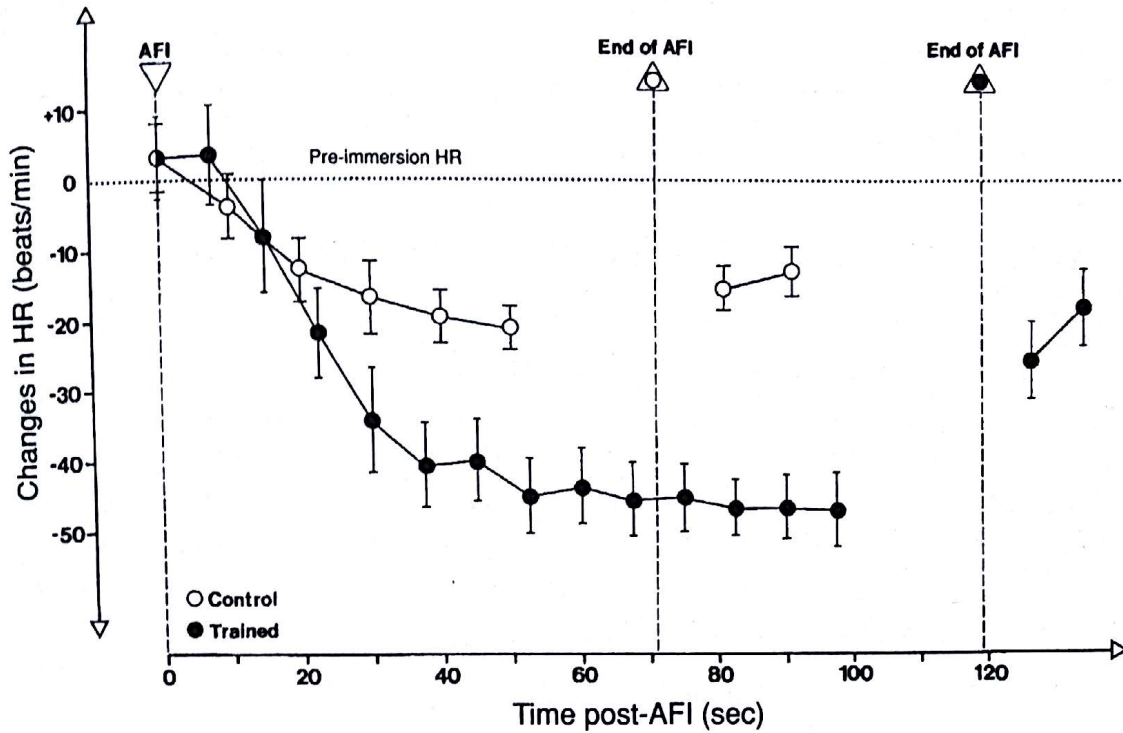
Figure 15.1 Changes in heart rate (HR) from pre-immersion values during apnoeic face immersion (AFI) in untrained Swedish control and trained Indonesian subjects.

The values are means ± SE for n=10 in each group. The arrows indicate onset of and mean end of AFI for the two groups. The tests were performed supine, at rest and in an ambient temperature of 31° ± 1C. Each subject breath-held at spontaneously chosen lung volume for as long as possible while immersing the face in water of 20° ± 1C.

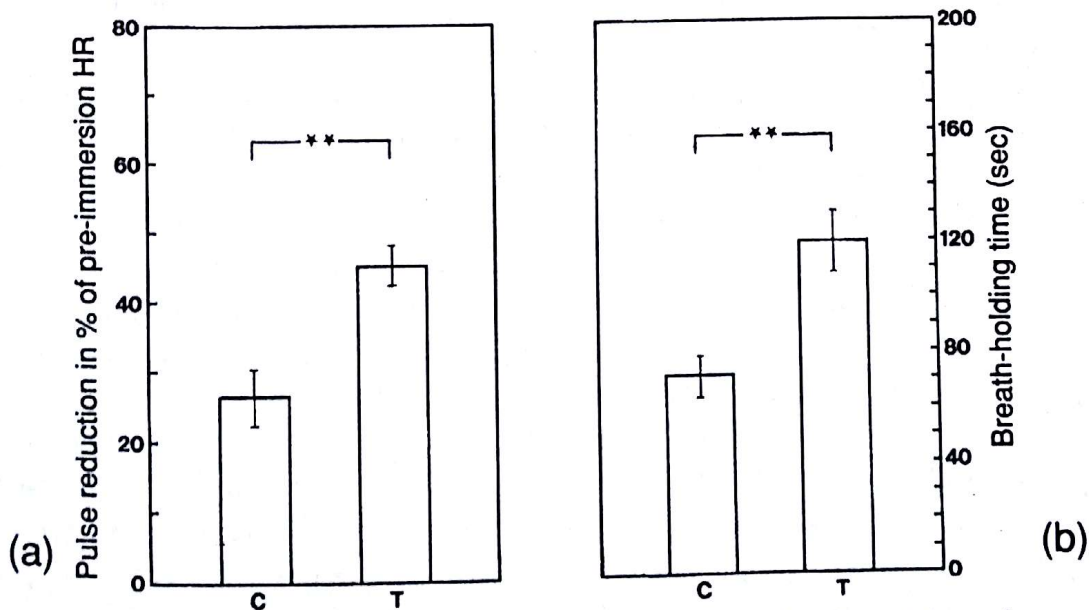
Figure 15.2 Comparison of mean (±SE) pulse reduction (a) and mean (±SE) breath-holding time (b) between untrained Swedish control (C) and trained Indonesian (T) subjects.

The pulse reduction values are obtained from the last 30 seconds of each AFI, and expressed as a percentage of the individual pre-immersion pulses.

both in diving time and bradycardia between the two groups. Other effects of lifelong training may also contribute to the pronounced bradycardia in the Indonesian divers. Ethnic differences between the two groups cannot be ruled out.

COMPARATIVE ASPECTS OF DIVING BRADYCARDIA

When terrestrial, semi-aquatic and aquatic species are compared, bradycardia on immersion correlates with their involvement in diving. The extent of the response in trained humans is intermediate between the response in terrestrial mammals and that found in diving mammals (Strauss, 1970). In deep-diving animals like the Weddell seal the heart rate may fall by up to 90 per cent (Strauss), while in semi-aquatic species like the beaver and musk-rat the bradycardia is 40–60 per cent of the pre-submersion value (Gilbert and Gofton, 1982).

In many early studies of aquatic animals bradycardia was induced by forced submersion, which has later been shown to display extreme responses which may seldom occur in the animals' normal range of activities (Butler and Jones, 1982; Kooyman, 1989). In the harbour seal the reduction in heart rate on forced submersion was 94 per cent of the pre-submersion rate, while on trained face immersion it was about 80 per cent. Studies of free-diving Weddell seals reveal that these animals depress the heart rate between 40 and 80 per cent, depending on the duration and type of diving (Kooyman).

The human diving reflex has been described as similar to the reflex found in marine mammals, but attenuated or modified (Gooden, 1982; Ferrigno *et al.*, 1986). However, the data used in such comparisons have generally been derived from subjects with little or no training in breath-hold diving. The heart rate reduction on face immersion in untrained human subjects generally varies between 10 and 40 per cent (Mathew, 1981), but some untrained subjects may reduce their pulse rate by 70–80 per cent or more (Arnold, 1985). The 45 per cent mean pulse rate reduction in the trained Indonesians (Figure 15.2 (a)) is in accordance with observations in Ama divers (Hong and Rahn, 1967), and is in the range of the responses found in semi-aquatic mammals.

A bradycardia also occurs in species that do not naturally dive (Lin, 1982). Dogs trained to immerse their snouts voluntarily in water exhibited a heart rate reduction of 43 per cent of the pre-immersion value (Lin *et al.*, 1983). These dogs had been selected for their ability to learn breath-holding. Other studies of terrestrial animals have often included either forced submersion or anaesthesia, and this makes comparisons with natural divers difficult. There appear to have been no studies of voluntary breath-holding, face immersion or diving in monkeys or apes. This is possibly because such behaviours are not easily

taught, due to the animals' fear of water or because of problems with voluntary control of breathing. A study of anaesthetised infant macacas reveals weak bradycardia when apnoea is induced by electrical nerve stimulation (Sutton, Taylor and Lindeman, 1978). Without data from fully aware, unrestrained primates it is difficult to assess the evolutionary origin of the human diving reflex.

In marine mammals the effect of the diving reflex in making prolonged diving possible seems clear, but in humans there is some doubt as to whether the reflex is efficient enough to cause a reduction in the rate of oxygen consumption (Butler and Woakes, 1987). When bradycardia and breath-holding time are compared between apnoea in air and apnoea with face immersion in untrained and trained divers, we find that in the trained group the increase in bradycardia between dry and wet apnoea corresponds to an increase in breath-holding time (Table 15.1). This suggests that the diving reflex may have an oxygen conservation function in trained divers, while other factors are more important in determining breath-hold duration in untrained subjects. Considering the engagement of the trained divers in working dives with long durations, the benefit of a measure for oxygen conservation is obvious, and dives exceeding two minutes produced with lungs filled to only 70–80 per cent may be difficult to explain without including an effective diving reflex.

Table 15.1 Comparison of bradycardia and breath-holding time between apnoea in air (A) and apnoeic face immersion (AFI) in untrained control and trained divers

time (sec)

	Control		Trained	
	A	AFI	A	AFI
Pulse reduction (% of pre-immersion)	10.5 ± 4	26.3 ± 4	25.0 ± 5	45.0 ± 3
Breath-holding	79.0 ± 15	71.0 ± 8	76.0 ± 5	119.3 ± 11

The values are means ± SE for n=10 in each group.

ALTERNATIVE EXPLANATIONS FOR THE PROMINENCE OF THE HUMAN DIVING REFLEX

One suggestion is that the reflex helps the baby to survive the unusually long delivery, but this does not explain the differences between divers and non-divers, the persistence of the reflex into adulthood, or its

temperature-dependence. A more favoured explanation is that the reflex has arisen as a protection against accidental drowning. The chances of reviving a drowned person increase if the accident has occurred in cold water. Notwithstanding the temperature-dependence of the diving reflex, this observation can be at least partially explained by the reduction in metabolism that occurs when the body is cooled. This explains why children survive near-drowning better than adults: they are cooled down faster because of their smaller body/surface ratio (Hayward *et al.*, 1984). Even the brain can recover from 30 minutes' oxygen starvation, provided it is cooled down quickly enough.

THE TEMPERATURE-DEPENDENCE OF THE DIVING REFLEX

The temperature-dependence of the diving reflex may at first seem difficult to relate to a tropical diver, especially since the reflex has often been shown to have its maximal effect at about 10°C. The warm surface water of a tropical sea normally has a chilling effect sufficient to cause a moderate diving bradycardia. This is because the stimulation of the cold-receptors is not only dependent on the water temperature, but also on the state of acclimatisation before the immersion to the ambient air temperature. The dependency on ambient air temperature also implies that a maximal diving bradycardia is more easily reached at warmer water temperature in a tropical environment than where the environmental temperature is low. Thus a water temperature of about 20°C may elicit maximal diving bradycardia in a tropical diver.

A temperature-dependent diving reflex may have been of adaptive value during an aquatic phase of hominid evolution. If engaged in shallow diving the diver does not spend much time descending and ascending, and a series of short dives with short surface intervals is productive. When diving deeper, the diver encounters colder water, and the deeper the dive, the more important it is for the reflex to function fully for maximisation of bottom time.

THE 'SEA PEOPLE'

The existence of ethnic groups leading a self-sufficient life dependent on marine food sources obtained largely by diving suggests that modern *Homo* possesses adaptations to diving, swimming and being in water for long periods. Adults in one such group in Indonesia spend a daily average of 6 hours in water, and the children 4–5 hours. The children swim before they can walk, and contribute to the family economy by diving from the age of six. Individuals spend up to 10 hours daily in the water (with a surface temperature higher than 29°C), and with short intervals

for bringing the catch home to primitive houseboats or huts on poles close to small islands.

Going into the water during the hottest part of the day serves as a good means of thermoregulation, and may have been one reason for early *Homo* to enter the water.

The diving skills of the Indonesian divers include breath-holding times of up to 4 minutes and diving depths of 30 m or more, although a typical dive seldom exceeds 2 minutes or 15 m (Schagatay, unpublished observations). Whatever the origin of these skills, these groups – who call themselves the 'sea-people' – demonstrate that a semi-aquatic way of life is within the range of present-day human physiological adaptation.

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