Cardiovascular responses to diving and their relation to lung and blood oxygen stores in vertebrates

WARREN BURGGREN
Department of Zoology, University of Massachusetts, Amherst, MA, U.S.A. 01003-0027

Received January 16, 1987

BURGGREN, W. 1988. Cardiovascular responses to diving and their relation to lung and blood oxygen stores in vertebrates. Can. J. Zool. **66**: 20–28.

Air-breathing vertebrates generally respond to apnea during diving by adjusting cardiovascular performance (e.g., bradycardia, selective increases in peripheral resistance, reduction and redistribution of cardiac output). In mammals, and to a lesser extent in birds, the major O_2 stores at the beginning of a dive reside within blood and tissues rather than in lung gas. Consequently, there is limited respiratory benefit during apnea in either maintaining or transiently restoring extensive lung perfusion to predive levels, and so cardiac output (and thus lung perfusion) remains low during the dive. In contrast, in most amphibians and reptiles the major O_2 stores at the beginning of a dive reside within lung gas rather than in blood and tissues. Recent experiments on frogs and turtles reveal that pulmonary blood flow during diving can transiently increase to or above predive levels when it becomes necessary during the dive to transfer O_2 from lung gas to arterial blood. In this regard, cardiovascular responses to diving in lower vertebrates are qualitatively different from those of higher vertebrates.

BURGGREN, W. 1988. Cardiovascular responses to diving and their relation to lung and blood oxygen stores in vertebrates. Can. J. Zool. **66** : 20–28.

Les vertébrés à respiration aérienne réagissent généralement à l'apnée durant la plongée par des ajustements de leur rendement cardio-vasculaire (p.e., bradycardie, augmentations sélectives de la résistance périphérique, réduction et redistribution du rendement cardiaque). Chez les mammifères, et, dans une mesure moindre, chez les oiseaux, c'est dans le sang et dans les tissus et non dans les gaz plumonaires que résident les réserves majeures d'O_2 au début de la plongée. Il y a donc peu d'avantages respiratoires durant l'apnée à maintenir ou à restaurer temporairement au niveau initial l'irrigation du poumon; c'est pourquoi le débit cardiaque (et conséquemment l'irrigation pulmonaire) reste faible pendant la plongée. Contrairement aux vertébrés supérieurs, la plupart des amphibiens et des reptiles ont leurs réserves principales d'O_2 dans les gaz du poumon plutôt que dans le sang et les tissus. Des expériences récentes sur les grenouilles et les tortues ont démontré que, lorsqu'il devient nécessaire durant la plongée de transférer de l'oxygène des poumons vers le sang artériel, le flux de sang pulmonaire peut chez ces animaux, pour de courtes périodes, atteindre ou même dépasser les niveaux observés avant la plongée. En ce sens, les réactions cardio-vasculaires des vertébrés inférieurs durant la plongée diffèrent qualitativement de celles des vertébrés supérieurs.
[Traduit par la revue]

Introduction

The ability of air-breathing vertebrates to exploit the aquatic environment through diving has been investigated for hundreds of years (see Elsner and Gooden (1983) for references). Although numerous species from all vertebrate classes have now been examined, diving birds and mammals are often considered representative of all vertebrate divers. This paper compares and contrasts perfusion patterns of gas exchange organs during diving in phyletically lower and higher diving vertebrates. Diving responses of amphibians and reptiles are shown to differ from those of birds and mammals in several important ways, primarily relating to basic differences in sites of O_2 storage.

Cardiovascular responses to diving in mammals and birds

A great deal of interest, both historical and current, has centered on the physiological responses to diving in marine mammals and aquatic birds (for recent reviews see Kooyman *et al.* 1981; Butler and Jones 1982; Butler 1982; Elsner and Gooden 1983; other papers in this issue). Because birds and mammals have relatively high metabolic rates compared with other vertebrates, the hypoxia and hypercapnia associated with diving present demanding physiological challenges with respect to maintaining an adequate O_2 supply for highly aerobic tissues (e.g., heart, brain, adrenal gland, pregnant uterus).

The identification and measurement of the physiological adjustments that accompany diving in birds and mammals has been underway more or less continuously since the pioneering work of Irving (1939) and Scholander (1940). A recurring, if not central, theme in diving involves regional hypometabolism, what Elsner and Gooden (1983) have termed a "strategic retreat." Severe reduction during diving of blood flow to organs with temporarily interruptible functions (e.g., skin, gut, kidneys, some skeletal muscle) reduces aerobic metabolism in these tissues. The O_2 stores (primarily in the blood, at least in mammals; see below) at the beginning of the dive can thus be partially conserved and selectively distributed to those tissues that either are less tolerant of hypoxia (e.g., central nervous tissue) or must continue to function at predive metabolic levels (e.g., some locomotory muscles).

Reduction of blood flow to anoxia-tolerant tissues, combined with continued perfusion of selected highly aerobic tissues, is achieved during diving by a complex suite of physiological adjustments in mammals and birds. The most commonly observed diving response (probably as much because of the relative ease of its measurement compared with other cardiovascular changes as because of its true commonality relative to other responses) is a reduction in heart rate, diving bradycardia. Although some studies suggest that cardiac stroke volume either remains unchanged or declines only slightly with the onset of diving in mammals and birds (see Butler 1982; Elsner and Gooden 1983), the marked fall in heart rate results in a severe reduction in cardiac output. Concomitantly, there is a peripheral vasoconstriction resulting in a sharp increase in peripheral resistance in the tissue beds of those organs capable of anaerobic metabolism. The net effect of these cardiovascular adjustments is a reduction of cardiac output and a radical rearrangement of blood flow patterns to favor maintained perfusion of organs that are primarily dependent on aerobic metabolism.

Printed in Canada / Imprimé au Canada

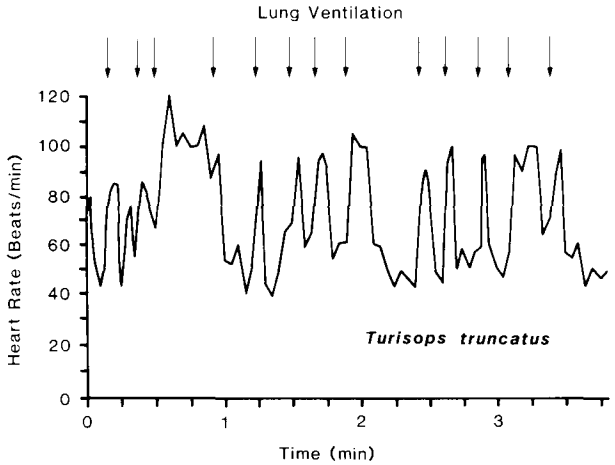

FIG. 1. Heart rate in a free-swimming dolphin (*Tursiops truncatus*) during intermittent breathing and diving. Periods of lung ventilation are indicated by the vertical arrows above the trace. (Redrawn with permission from Elsner and Gooden 1983, © 1983 Cambridge University Press.)

Much of our knowledge of the cardiovascular adjustments that accompany diving in birds and mammals came initially from restrained animals in laboratory situations. Diving responses of animals under these conditions frequently are relatively stereotypic and reproducible (e.g., Jones *et al.* 1982). Recent studies have suggested that, in fact, there may be considerable variability in cardiovascular adjustment during voluntary diving in free-ranging birds and mammals. For example, freely diving seals only rarely extend dives to a duration that requires a switch to anaerobic metabolic pathways in nonessential organs (e.g., Kooyman *et al.* 1980; Kooyman 1988). Comparison of voluntary with forced dives indicates that, while the classic cardiovascular responses usually persist during voluntary diving, the magnitudes of these adjustments frequently tend to be lower when compared with those evident during involuntary apnea (for references see Butler 1982; Elsner and Gooden 1983). In fact, both old and recent observations indicate that the stalwart of the diving response, bradycardia, may be quite muted or not occur at all during brief, voluntary, completely aerobic dives in mammals (e.g., Scholander 1940; Smith and Tobey 1983) and in birds (Butler and Woakes 1979; Kanwisher *et al.* 1981; Butler 1982; Fedak *et al.* 1988). On the other hand, dolphins trained to dive voluntarily actually showed more intense bradycardia (Elsner *et al.* 1966). As Elsner and Gooden (1983) comment, "some major component of the diving response is determined by the intention, conditioning or psychological perspective of the animal being studied."

It is important to emphasize that, while quantitative variation in cardiovascular responses to diving in mammals and birds is common, especially when forced and voluntary diving are compared, qualitative variations in the diving response are not. Thus, although the *magnitude* of the various cardiovascular responses to diving in birds and mammals is widely variable depending upon the length of dive, whether diving is forced or voluntary, etc., the suite of circulatory adjustments *once made* usually persists for the duration of the dive (see reviews cited in the next section). As but one example, the severity of the bradycardia during voluntary diving in the dolphin *Tursiops truncatus* varies from dive to dive when apneic periods of similar length are considered (Fig. 1). In some instances there may even be an anticipatory alleviation of some or all of the bradycardia immediately before surfacing. Nonetheless, heart rate (and presumably cardiac output) during almost all of the dive remains at values considerably lower than those typical during ventilation.

Cardiovascular responses to diving in birds vary considerably when comparisons are made both within and between species, but generally resemble those seen in mammals. Restrained birds experiencing forced dives typically show a severe bradycardia and a reduction and redistribution of cardiac output (see Butler and Jones 1982; Butler 1982, 1988). Telemetered information from voluntary dives in free-ranging ducks indicates that the "bradycardia" may actually represent a reduction of heart rate to predive levels following an anticipatory tachycardia immediately before the dive. Also, heart rate may return to resting predive levels immediately before the birds surface in anticipation of the resumption of breathing. In any event, as in mammals, once the particular diving response in a bird develops, it persists until close to the end of the dive.

Diving responses and oxygen storage sites in mammals and birds

If it is assumed that the cardiovascular responses of mammals and birds during diving contribute to the effective conservation and utilization of O_2 stores during apnea, then (teleologically) it seems appropriate that these responses be maintained for all or most of the duration of the dive. Critical to the interpretation of vertebrate diving responses is consideration of the sites of the O_2 stores and their accessibility. The major storage site for O_2 during diving in mammals is in the blood itself (Fig. 2). Many diving mammals exhale immediately before diving and the O_2 remaining stored as gas in the nonventilated lungs is usually considered to be so small as to be ignored in O_2 storage calculations (Elsner and Gooden 1983). In any event, in mammals diving to significant depths, pulmonary gas is driven by chest compression into the noncollapsible, nonrespiratory airways (Scholander 1940; Falke *et al.* 1985). Thus, any O_2 stored in lung gas during deep diving is unavailable for transfer to pulmonary venous blood during these dives. Diving mammals (and to a lesser extent diving birds) tend to have an unusually large venous blood volume which, by providing a site for vascular O_2 storage, is thought to constitute one of the major evolutionary adaptations to diving (for review see Harrison 1972; Elsner and Gooden 1983). Thus, the major site of O_2 storage in higher vertebrates is hemoglobin, with some smaller contribution by myoglobin in muscle (Fig. 2).

There is uncertainty as to where the major O_2 storage site is located in birds. At the beginning of a dive birds carry gas not only in their lungs, but also in the large air sacs that are an integral part of their respiratory system. If the O_2 in the entire respiratory system is considered, then diving ducks have O_2 stores approximately equally distributed between gas and blood (Fig. 2). To what extent the O_2 stores of the air sacs as distinct from those of the parabronchial lung are actually available is not yet clear. Both Keijer and Butler (1982) and Hudson and Jones (1986) include air sac gas in calculations of O_2 stores, and suggest that mechanical action on the sacs produced both by the beating heart and by body movements during locomotion results in convection of the gas through the lungs during diving. Yet, approximately 25% of the original O_2 store in the air sacs remains unused when ducks succumb to

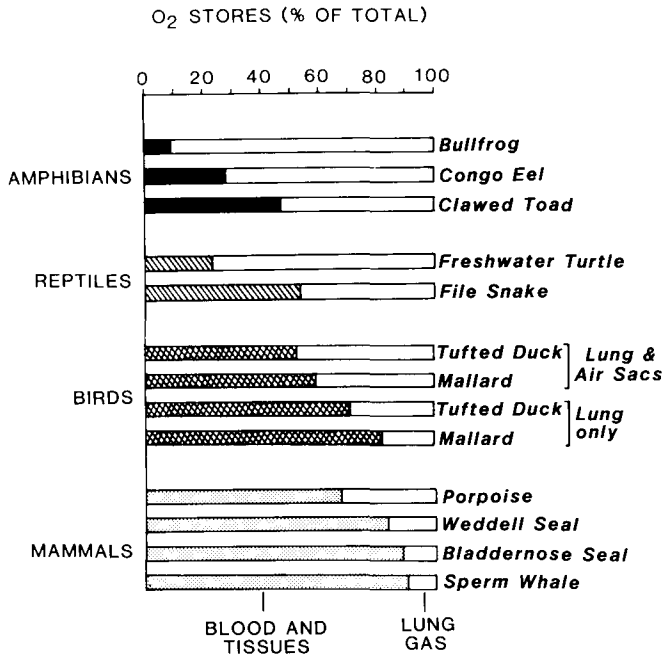

FIG. 2. Distribution of O_2 stores available at the beginning of a dive in specific amphibians, reptiles, birds, and mammals. These data have been calculated from blood and lung volumes and from O_2 partial pressures and O_2 dissociation curves or from contents of arterial and venous blood and pulmonary gas. Rarely are all of these data available from a single study, and so observations from different studies on the same species have been combined in most instances. Consequently, the values presented are only approximate and are intended for general purposes of comparison. Note that in the case of birds two estimates for O_2 stores are given, one including and one excluding the O_2 contained within the air sacs. Some proportion of the gas within the air sacs is available for gas exchange during diving (see text).

asphyxia. Figure 2 presents data for O_2 storage in birds that both include and exlude O_2 stored in the air sacs. In actuality the physiological O_2 stores likely fall between these two extremes. Regardless of the exact nature of the contribution of the air sacs to the total O_2 stores, at least half of the available O_2 at the beginning of a dive resides in the blood and tissues.

In both mammals and birds, then, the primary O_2 reserves during diving are immediately accessible to the tissues, with O_2 delivery being dictated by the O_2 partial pressure of the perfused tissues and the rate of blood flow through them. If, at some critical point in the dive, mammals or birds had to "tap" into O_2 stored remotely in the lungs, then their main recourse would be to increase lung perfusion. Because the systemic and pulmonary circulation are in series, systemic perfusion would have to be elevated to an identical extent. This might be viewed as a counterproductive response if all systemic tissues were already being perfused at rates optimal for diving conditions.

Sites of oxygen stores in lower vertebrates

One of the major features that distinguishes intermittently breathing amphibians and reptiles from diving birds and mammals is the nature and extent of the O_2 stores available during apnea (Fig. 2). The O_2 stored at the beginning of a dive resides primarily in the lungs in amphibians and reptiles. Relative to higher vertebrates, the absolute amount of O_2 stored in blood is typically much smaller in diving lower vertebrates, such as freshwater turtles or bullfrogs. Blood O_2 capacities in these animals are typically only 5–10 vol. % (Burggren *et al.* 1977; Burggren and Wood 1981; Pinder and Burggren 1983), compared with 25–35 vol. % in diving mammals (see Elsner and Gooden 1983). Moreover, with the exception of sea snakes and file snakes, blood volumes of reptiles and amphibians range from 5 to 9% of total body volume (Thorson 1968; Smits and Kozubowski 1985), a range of values not remarkably different from those found in nondiving mammals but far lower than those in many diving mammals (Lenfant *et al.* 1969).

The proportionately large pulmonary O_2 storage in amphibians and reptiles is attributable not only to relatively small blood O_2 stores, but also to a much larger weight-specific lung volume in amphibians and reptiles compared with birds and mammals (Tenney and Tenney 1970; Burggren 1988). Many lower vertebrates use their lungs for buoyancy regulation, in addition to gas exchange, and this appears to have acted (in part) as a selection pressure for large lungs. Few amphibian or reptilian species exhale before diving and, with the possible exception of marine turtles and sea snakes, almost all amphibians and reptiles dive to a maximum depth of only a few metres, obviating significant lung collapse. Thus, there is a large O_2 store in the inflated lungs potentially available to the highly aerobic tissues during diving.

Again in contrast to diving birds and mammals (in which the O_2 stores are readily available to perfused tissues by virtue of residing in the circulating blood itself), most of the O_2 stored at the beginning of apnea in intermittently breathing amphibians and reptiles can be made available to the most aerobic tissues *only* if a transfer of O_2 from lung gas to blood can be facilitated during the dive. Such transfer during apnea requires that some perfusion of the lungs with appropriately deoxygenated blood occur during the apneic period. Therefore, unlike in the diving responses in diving birds and mammals, there is good reason to anticipate that cardiovascular performance in amphibians and reptiles might be adjusted frequently and more variably during the dive to exploit pulmonary O_2 stores. What might these adjustments be?

Cardiovascular responses to diving in amphibians and reptiles

Anatomical and physiological considerations

The repertoire of cardiovascular responses of amphibians and reptiles during diving (bradycardia, reduced cardiac output, redistribution of cardiac output) includes the same types of responses as those available to birds and mammals. Yet, the diving responses of lower vertebrates differ from those of higher vertebrates because there is (*i*) a marked departure from higher vertebrates in the pattern of distribution and magnitude of O_2 stores through the body, (*ii*) a considerably greater flexibility of the amphibian and reptilian circulations with respect to coping with intermittent breathing and periods of apnea, and (*iii*) the potential for nonpulmonary gas exchange during diving.

The major distinguishing feature of amphibian and reptilian circulations of relevance to the present discussion is that the pulmonary and systemic arterial circuits are located in parallel, rather than in series as in higher vertebrates with completely divided cardiac ventricles. This crucial feature results from the fact that there is either a single ventricle (amphibians) or a

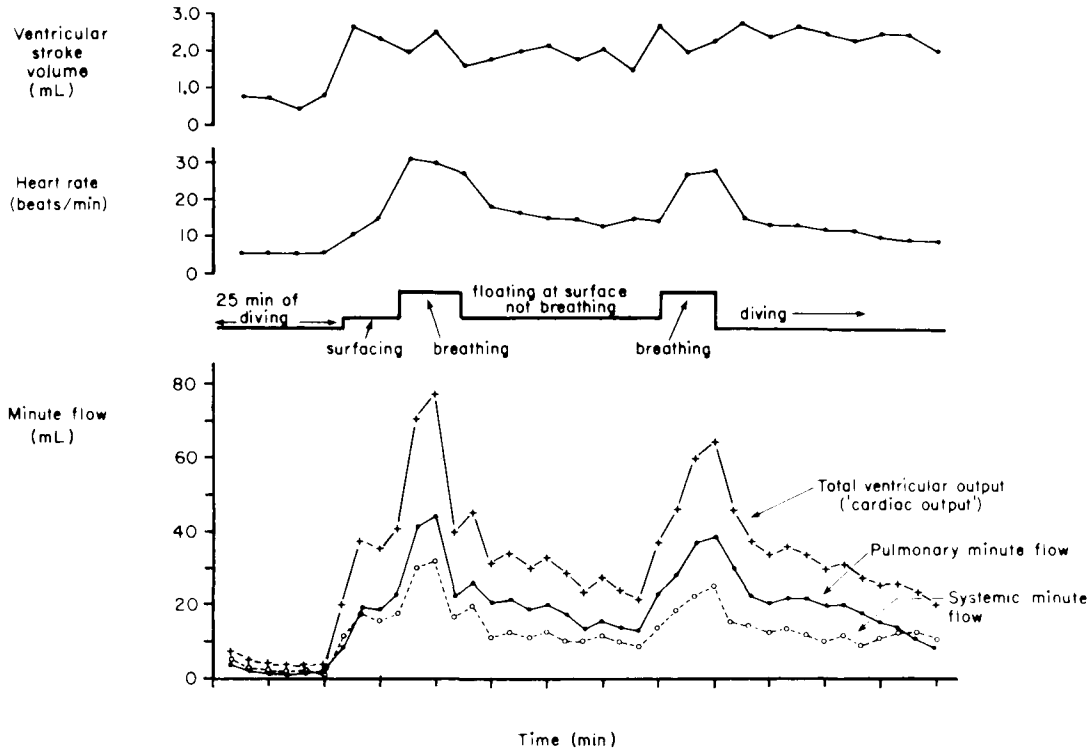

FIG. 3. Adjustments in cardiovascular performance during intermittent breathing and voluntary diving in an unrestrained freshwater turtle, *Pseudemys (Chrysemys) scripta*, at 20°C. (Redrawn from Burggren and Shelton 1979.)

complexly structured but incompletely partitioned ventricle (reptiles). Both configurations are now generally regarded as beneficial in intermittent breathers, rather than as anatomical imperfections in comparison with birds and mammals (for reviews see Shelton 1976, 1985; Johansen and Burggren 1980; Burggren 1985, 1987).

Because the pulmonary and systemic circuits are arranged in parallel in amphibians and reptiles, the rate of pulmonary perfusion can be regulated independently of the rate of systemic perfusion (see reviews cited above). A pulmonary bypass (intracardiac right-to-left shunt) can result in a much lower pulmonary perfusion relative to systemic perfusion, while a left-to-right shunt can result in a much higher pulmonary perfusion relative to systemic perfusion. The size and duration of these net intracardiac shunts generally are associated with the ventilatory state in both amphibians and reptiles. Thus, during brief periods of active lung ventilation, cardiac output may be distributed approximately evenly to lungs and body tissues (or perhaps even primarily to the lungs). With the onset of apnea (either a dive in aquatic species or simply prolonged breath holding in terrestrial species), pulmonary resistance often rises and a small right-to-left shunt frequently develops and may intensify as apnea continues. When combined with an overall reduction in cardiac output due to both bradycardia and a fall in stroke volume, the net effect during a long apneic period can be a reduction in systemic and especially pulmonary blood flow to a small fraction of the maximum evident during active lung ventilation. Figure 3 illustrates an extreme case of cardiac output adjustment and redistribution during intermittent breathing and diving in the freshwater turtle *Pseudemys (Chrysemys) scripta*.

Short-term diving and use of oxygen stores

A substantial, maintained redistribution of cardiac output away from the pulmonary circuit, if typical of diving in amphibians and reptiles, would seem to imply that the large O_2 store in the lungs is not exploited during apnea. In fact, the pulmonary gas stores can be exploited during diving, but the extent of their use may vary considerably depending upon the following considerations.

All of the energetic reasons that make it advantageous for diving birds and mammals to remain within their aerobic "envelope" during diving apply similarly to amphibians and reptiles. Although lower vertebrates are generally much more tolerant of asphyxia than are birds and mammals (for references see Ultsch and Jackson 1982), a far smaller rate of generation of ATP occurs if the animal must depend upon anaerobic pathways during diving. Consequently, although amphibians and reptiles can and will voluntarily dive for astonishingly long periods of time, most species nonetheless usually show relatively brief periods of apnea, minutes rather than hours (Burggren 1975; Shelton and Boutilier 1982). Combining typically short apneic episodes with an intrinsically very low metabolic rate, most voluntary dives in undisturbed amphibians and reptiles appear to draw relatively lightly from the total available O_2 stores, with the ensuing periods of active lung ventilation serving to replenish or "top off" these stores.

What is the pattern of utilization of O_2 stores during these short dives in amphibians and reptiles? It is quite clear that, in fact, during dives of short duration most amphibians and reptiles simultaneously draw from both pulmonary and blood O_2 stores at a relatively low rate (Burggren and Shelton 1979; Shelton and Boutilier 1982; Boutilier and Shelton 1986). Although heart rate and cardiac output fall and pulmonary perfusion declines almost immediately upon the cessation of lung ventilation during even short dives, blood flow to the lungs rarely stops during apnea (although the potential for this exists). Thus, as O_2 diffuses from lung gas to blood perfusing

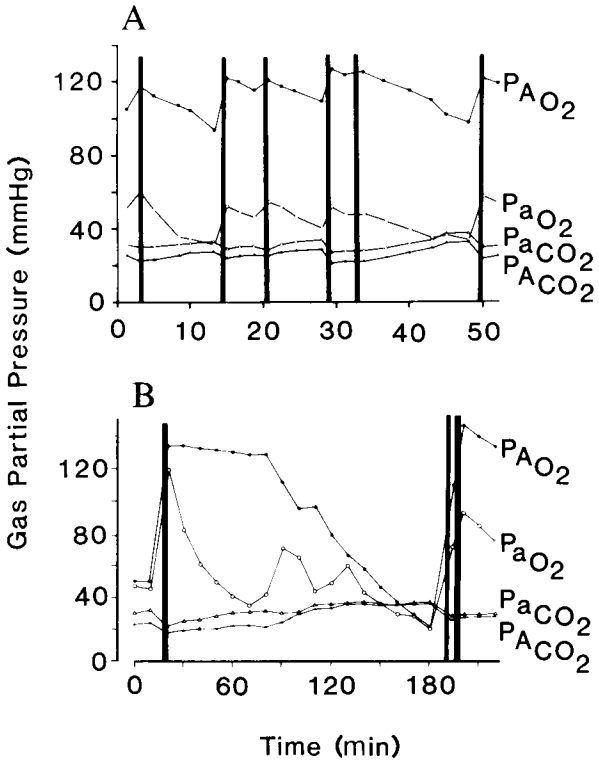

FIG. 4. Changes in arterial and alveolar O_2 and CO_2 partial pressures during voluntary dives in the freshwater turtle, *Pseudemys (Chrysemys) scripta*, at 20°C. Shaded vertical bars represent periods of lung ventilation. Representative patterns of O_2 depletion from lung gas and arterial blood (A) during relatively brief periods of diving (0.97-kg turtle) and (B) during a longer period of apnea (1.2-kg turtle). The pattern of O_2 depletion depicted in Fig. 4B was commonly observed during very long voluntary dives. (Redrawn from Burggren and Shelton 1979.)

the lungs during brief dives, there tends to be a continual slow decline in lung O_2 that parallels the fall in blood O_2 (Fig. 4A).

The cardiovascular responses seen during these typically short periods of breathing in amphibians and reptiles appear to be similar to those in diving mammals and birds. There is an increased pulmonary resistance, decreased heart rate, decreased stroke volume, right-to-left shunt, and decreased lung perfusion, all of these phenomena persisting throughout the brief dive. When the animal resumes breathing at the termination of the dive, these responses are reversed until the beginning of the next period of apnea.

Long-term dives and oxygen metering from the lung

Observations of the physiological adjustments accompanying longer dives in some amphibians and reptiles appear to suggest a quite different situation, in which cardiovascular responses during a single dive can range between the extremes typically seen during short dives and during lung ventilation.

Some of the first circumstantial evidence of the great variability in cardiovascular performance during diving came from simultaneous measurements of blood and lung gases during short and long diving periods in the freshwater turtle *Pseudemys scripta* (Burggren and Shelton 1979). During relatively short periods of diving in this species, the P_{O_2} of arterial blood and pulmonary gas fell approximately in unison (Fig. 4A), and there was a significant right-to-left shunt and reduced cardiac output (White and Ross 1966; Shelton and Burggren 1976; Burggren and Shelton 1979).

During relatively long dives, however, a considerably different pattern emerged (Fig. 4B). Immediately upon the initiation of diving and in complete contrast to the situation in shorter dives, blood O_2 stores began to be drawn upon heavily, and arterial P_{O_2} fell at a rate much higher than during short dives of less than 30 min duration. These rates of O_2 depletion appeared to be completely unconnected with variations in activity. Concomitant with this progressive decrease in arterial O_2 was an almost total preservation of lung O_2 levels. Pulmonary gas P_{O_2} during approximately the first 30 min of these long dives fell extremely slowly, if at all. These data suggest that a profound and immediate reduction in pulmonary flow in the face of continued systemic flow must be occurring at the outset of long-term diving in *Pseudemys scripta*. Although this reduction in lung perfusion could have been achieved by a general reduction in total cardiac output, the rapid depletion of systemic arterial O_2 suggests that significant perfusion of the systemic circulation was continuing. Presumably, then, the marked reduction in pulmonary perfusion leading to preservation of pulmonary O_2 stores early in the dive was achieved by the development of a pronounced right-to-left intracardiac shunt.

Eventually during one of these longer dives in *Pseudemys scripta*, however, an abrupt change occurred in the pattern of O_2 depletion. The P_{O_2} of the lung gas began to decline at a rate considerably greater than that during short dives, in which some pulmonary perfusion persisted throughout. Simultaneously, systemic arterial P_{O_2} actually increased during this phase of the dive by as much as 40 mmHg (1 mmHg = 133.3 Pa). After a brief period of O_2 transferral from pulmonary to arterial blood, the pattern of O_2 depletion evident at the beginning of the dive often briefly returned, indicating the reestablishment of a large right-to-left shunt. This pattern of intermittent perfusion of the lung could persist through several "cycles" before diving was terminated.

Observations on anuran amphibians also suggest that the potential exists for the "classic" diving responses to be partially or fully reversed during apnea to draw from the lung stores, as in chelonian reptiles. Recent observations on voluntarily diving *Xenopus laevis* (R. Boutilier, P. Butler, and B. Evans, unpublished data) show that an experimentally induced reduction in lung O_2 stores (produced by N_2 gas purging of the lungs via implanted pulmonary catheters) produced a complex pattern of O_2 decline in the lungs (Fig. 5). Not surprisingly, at the outset of N_2 purging following the beginning of a dive, the P_{O_2} of lung gas began to decline at a much higher rate than during undisturbed dives. After a few minutes, however, there was a brief increase in pulmonary O_2 levels in spite of continued N_2 flow through the lungs. The investigators interpreted this to represent a transiently reversed diffusion of O_2 along a partial pressure gradient from pulmonary arterial blood to the lung gas.

Now, if pulmonary perfusion remained at steady, low levels during this apneic period, one might anticipate that pulmonary O_2 levels during N_2 purging would first decline rapidly as the O_2 store in the lung was washed out. Then, as lung gas P_{O_2} approached the P_{O_2} of pulmonary arterial blood under conditions of constant low lung perfusion, the high rate of decline of pulmonary perfusion would be tempered by diffusion of O_2 from blood to lung gas, causing lung gas P_{O_2} to continue to decline but at a subsequently lower rate. Indeed, the observed changes at the beginning and towards the end of dives with N_2 purging of the lungs are consistent with a pattern of continu-

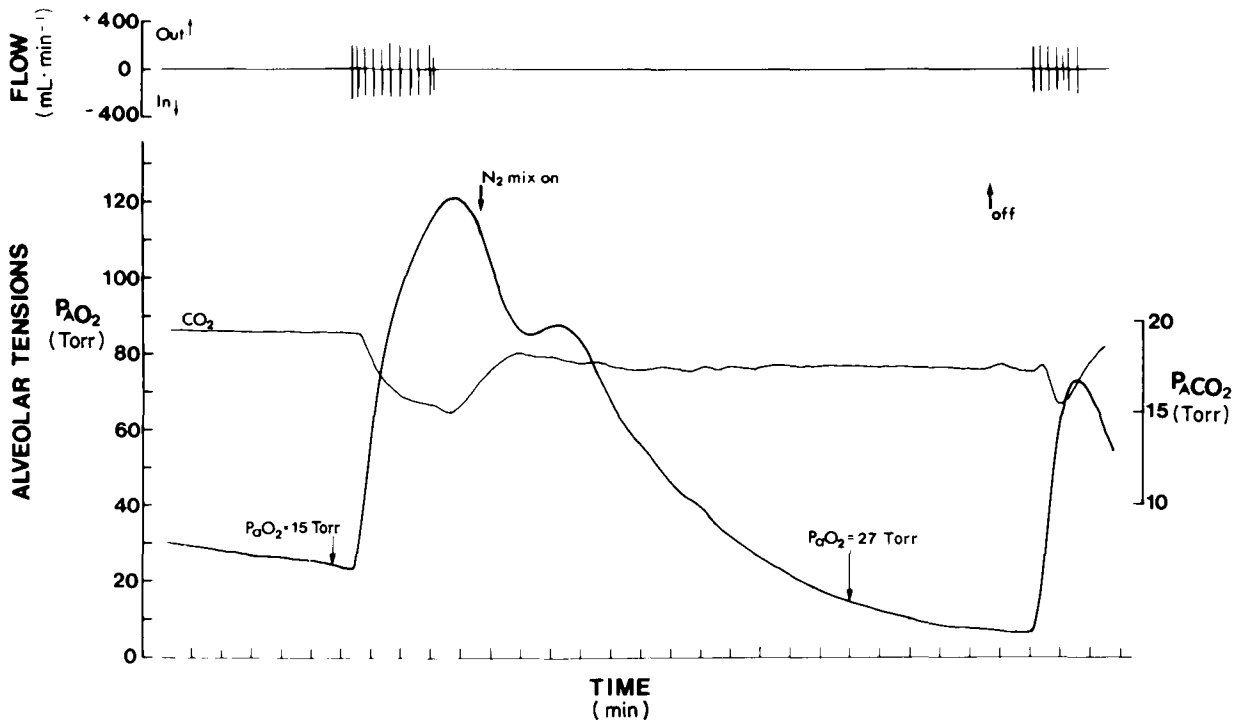

FIG. 5. Changes in aleveolar O_2 and CO_2 partial pressures during intermittent ventilation (top trace) in a voluntarily diving clawed toad (*Xenopus laevis*). Lung partial pressures were monitored via a pulmonary extracorporeal loop. At the first downward pointing arrow, an isovolumetric purge of the lungs with N_2 gas was begun via implanted lung catheters. Note the initial rapid fall in lung P_{O_2}, followed by a transient rise before the eventual continued decline as nitrogen purging continued. 1 Torr = 133.3 Pa. (R. Boutilier, P. Butler, and B. Evans, unpublished data.)

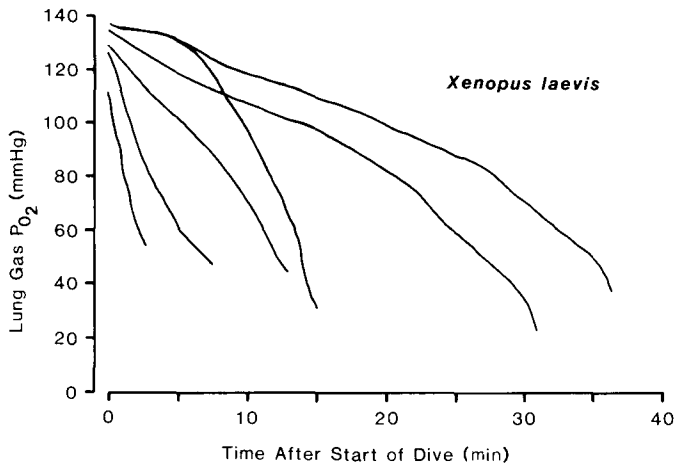

FIG. 6. The range of patterns of O_2 depletion from the lungs of the clawed toad, *Xenopus laevis*, during voluntary diving. Not only does the rate of decline differ from dive to dive, but the rate of lung O_2 depletion can also change sharply during the course of a single dive. (Redrawn with permission from Boutilier and Shelton 1986, © 1986, The Company of Biologists Ltd.)

ous, low pulmonary perfusion. However, the abrupt, temporary increase in lung P_{O_2} shortly after purging begins is highly suggestive of a sudden, transient increase in the rate of pulmonary perfusion, perhaps reflexively triggered by falling lung or blood O_2 levels.

Circumstantial evidence for perfusion-related changes in utilization of pulmonary O_2 stores in amphibians is also evident in the patterns of O_2 depletion from the lungs of *Xenopus laevis* during voluntary, undisturbed diving (Fig. 6). While the pulmonary O_2 store appeared to be steadily depleted in some dives, during others there were highly variable and abrupt changes reminiscent of those occurring in *Pseudemys scripta* during long dives. Thus, at least the potential for significantly increasing pulmonary perfusion during apnea appears to exist in anuran amphibians, as it does in chelonian reptiles.

Direct evidence (i.e., actual measurement of pulmonary blood flow) for flow-related metering of lung O_2 during diving is very limited for both amphibians and reptiles. However, recent experiments have generated direct evidence of the variable nature of pulmonary perfusion during diving in the Australian side-necked turtle, *Chelodina longicollis* (W. Burggren, A. Smits, and B. Evans, unpublished data). Lung gas and femoral arterial blood O_2 partial pressures were measured simultaneously via extracorporeal catheter loops, while pulmonary blood flow was measured either with an electromagnetic flow transducer or by impedance techniques. In some dives, *Chelodina* allowed blood P_{O_2} to run down before replenishing from lung O_2 stores, a pattern similar to that exhibited in most dives by *Pseudemys scripta*. However, in the majority of dives (both short dives of less than 10 min and long dives over 30 min) arterial blood P_{O_2} was maintained at a value representing approximately 80–95% O_2 saturation throughout the apneic period (Fig. 7). In fact, nearly 40% of 87 dives monitored in seven turtles showed a transient increase in $P_{a_{O_2}}$ of 4 mmHg or greater at some point during the dive. In most cases, these increases in arterial P_{O_2} immediately followed a marked but transient increase in pulmonary perfusion. These data suggest that the relative constancy of arterial oxygenation was achieved by periodic increases in pulmonary perfusion to affect pulsatile transfer of O_2 from lung gas to pulmonary venous blood. In effect, pulmonary flow was being regulated to meter O_2 from the lung.

Clearly, amphibians and reptiles are able to exploit the large

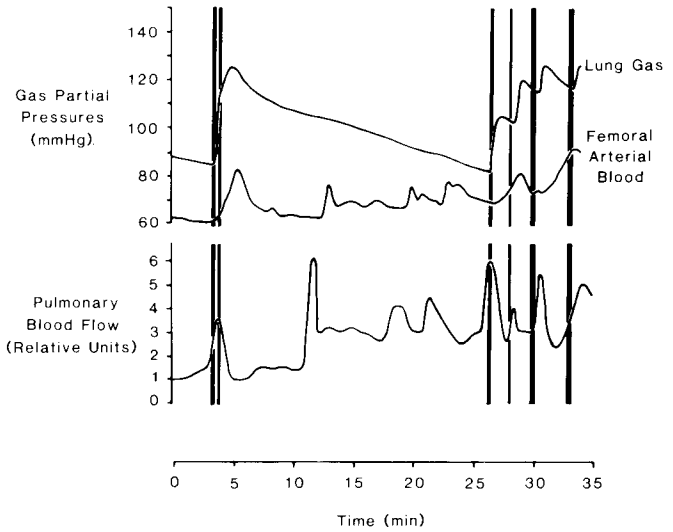

FIG. 7. Adjustments in pulmonary gas and femoral arterial blood P_{O_2} and in pulmonary blood flow (measured by an impedance technique) during alternating periods of lung ventilation (solid vertical bars) in a 0.60-kg Australian side-necked turtle, *Chelodina longicollis*. Increases in arterial blood O_2 during the middle of the dive correlate with periods of high pulmonary blood flow. (W. Burggren, A. Smits, and B. Evans, unpublished data.)

O_2 stores of the lungs during apnea. Unfortunately, we know little of the dynamics of gas exchange in the non-steady-state situation presented by diving, and in particular how the various sites of O_2 storage are depleted and restored during intermittent ventilation (for discussion see Shelton 1985; Boutilier and Shelton 1986; Shelton and Croghan 1988). Why do amphibians and reptiles show such large animal-to-animal or dive-to-dive variability in patterns of O_2 utilization from the large pulmonary O_2 stores available during apnea? Constancy of arterial oxygenation, as frequently observed in *Chelodina* during diving, provides for homeostasis with regard to tissue O_2 transport and unloading in the face of an intermittent breathing pattern. On the other hand, allowing arteriovenous blood O_2 stores to be depleted first by severely restricting pulmonary perfusion (e.g., some long dives in *Pseudemys scripta*) presumably results in a large diffusion gradient between lung gas and pulmonary capillary blood, which would facilitate replenishment of blood O_2 during the brief periods of restored pulmonary flow during apnea. A pattern of intermittent lung perfusion and O_2 utilization during apnea would also limit the period of time during apnea when the lungs would actually have to be perfused. This would not only conserve cardiac energy (though there is some doubt as to the amount of conservation that is achieved by reduced perfusion; see Burggren 1987) but would also minimize the very large amount of plasma filtration (by mammalian standards) that occurs during perfusion of the lungs of amphibians and reptiles (Burggren 1982; Smits *et al.* 1986; Smits 1988). Certainly, future investigations designed to understand the physiological rationale behind these different metering patterns are highly warranted.

Cardiovascular adjustment associated with nonpulmonary gas exchange in amphibians

A third example of partially or fully reversible adjustment in cardiovascular performance during diving comes from experiments on the bullfrog *Rana catesbeiana* (A. Pinder, unpublished data). Cutaneous gas exchange in amphibians (and probably many other skin-breathing aquatic animals) is now known to be influenced by movement of the surrounding water. Water currents disrupt the stagnant boundary layers adjacent to the skin, aiding diffusion of gases between water and blood by steepening diffusion gradients (Feder and Burggren 1985; Burggren and Feder 1986; Pinder and Burggren 1986). Measurement of blood flow in involuntarily submerged bullfrogs has shown that a marked redistribution of cardiac output towards the skin occurs when the surrounding water is stirred. When stirring is stopped (and the conditions for cutaneous gas exchange presumably become less favorable than when the surrounding water is stirred), then bulk perfusion of the skin declines sharply (Fig. 8). These marked changes in cutaneous perfusion are accompanied by substantial adjustments in the exchange of O_2 and CO_2 across the skin. Although pulmonary perfusion has yet to be measured under these conditions, there is evidence for a reciprocity of pulmonary and cutaneous perfusion in the pulmocutaneous circuit of amphibians (for references see West and Burggren 1984). It would thus seem likely that there are also coordinated increases in lung perfusion associated with decreases in skin perfusion when conditions for cutaneous gas exchange deteriorate.

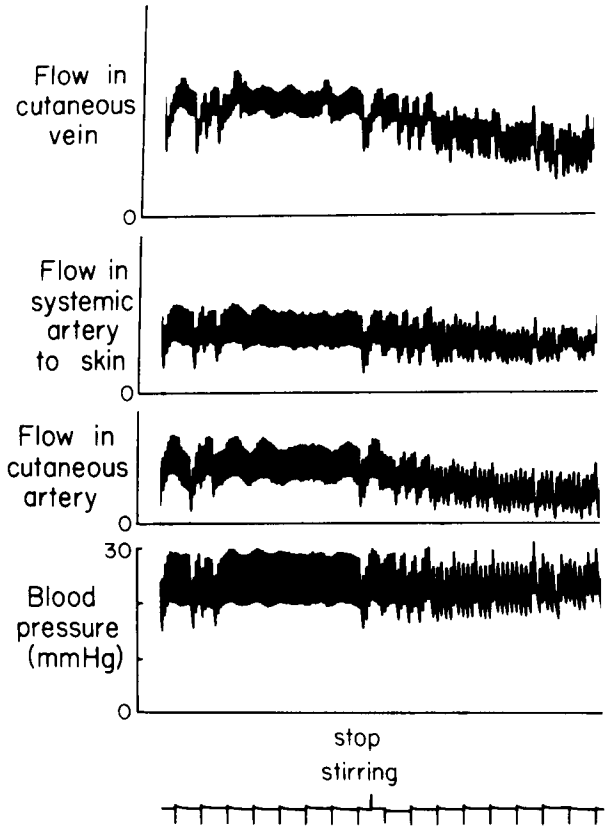

FIG. 8. Change in cutaneous blood flow associated with stirring of the ambient water in a submerged, curarized bullfrog (*Rana catesbeiana*) at 10°C. Blood flows were measured with uncalibrated Doppler flow probes. (A. Pinder, unpublished data.)

Conclusions: diving responses are influenced by oxygen storage sites

Many of the cardiovascular responses to diving exhibited by birds and mammals and by amphibians and reptiles are quite

similar, involving reduced heart rate and cardiac output and selective redistribution of cardiac output within the systemic circulation. In lower vertebrates, however, the major O_2 stores are located in lung gas rather than in blood or tissues. Thus, when amphibians and reptiles either (*i*) dive for longer periods, necessitating replenishment of blood O_2 stores from the proportionately large O_2 stores in the lungs, or (*ii*) experience changing conditions for cutaneous gas exchange in the case of amphibians, then O_2 transfer from lung gas to arterial blood during apnea may be elevated by a temporary redistribution of the cardiac output to the gas exchange organ(s). Physiological responses to diving in amphibians and reptiles thus are best regarded as very widely adjustable across a very broad spectrum of cardiovascular performance, rather than representing a stereotyped response to apnea.

Acknowledgments

Drs. R. G. Boutilier and A. W. Pinder kindly provided unpublished material, while Drs. N. H. West and A. W. Smits made valuable suggestions during the development of the manuscript. The author was supported by National Science Foundation (U.S.A.) grant No. PCM-8609404.

BOUTILIER, R. G., and SHELTON, G. 1986. Gas exchange, storage and transport in voluntarily diving *Xenopus laevis*. J. Exp. Biol. **126**: 133–156.

BURGGREN, W. W. 1975. A quantitative analysis of ventilation tachycardia and its control in two chelonians *Pseudemys scripta* and *Testudo graeca*. J. Exp. Biol. **63**: 367–380.

——— 1982. Pulmonary plasma filtration in the turtle: a wet vertebrate lung? Science (Washington, D.C.), **215**: 77–78.

——— 1985. Hemodynamics and regulation of central cardiovascular shunts in reptiles. *In* Alfred Benzon Symposium 21. Cardiovascular shunts: phylogenetic, ontogenetic and clinical aspects. *Edited by* K. Johansen and W. W. Burggren. Munksgaard International Publishers, Ltd., Copenhagen. pp. 121–136.

——— 1987. Form and function in the reptillian circulation. Am. Zool. **28**(1): 5–19.

——— 1988. The structure and function of amphibian lungs. *In* Lung biology in health and disease—comparative physiology. *Edited by* S. C. Wood. Marcel Dekker, New York. In press.

BURGGREN, W. W., and FEDER, M. E. 1986. Effect of experimental ventilation of the skin on cutaneous gas exchange in the bullfrog. J. Exp. Biol. **121**: 445–450.

BURGGREN, W. W., and SHELTON, G. 1979. Gas exchange and transport during intermittent breathing in chelonian reptiles. J. Exp. Biol. **82**: 75–92.

BURGGREN, W. W., and WOOD, S. C. 1981. Respiration and acid–base balance in the tiger salamander, *Ambystoma tigrinum*: influence of temperature acclimation and metamorphosis. J. Comp. Physiol. B, **144**: 241–246.

BURGGREN, W. W., HAHN, C. E. W., and FOËX, P. 1977. Properties of blood oxygen transport in the turtle *Pseudemys scripta* and the tortoise *Testudo graeca*: effects of temperature, CO_2 and pH. Respir. Physiol. **31**: 39–50.

BUTLER, P. J. 1982. Respiratory and cardiovascular control during diving in birds and mammals. *In* Control and co-ordination of respiration and circulation. *Edited by* P. J. Butler. J. Exp. Biol. **100**: 195–221.

——— 1988. The exercise response and the "classical" diving response during natural submersion in birds and mammals. Can. J. Zool. **66**. This issue.

BUTLER, P. J., and JONES, D. R. 1982. The comparative physiology of diving in vertebrates. Adv. Comp. Physiol. Biochem. **8**: 179–364.

BUTLER, P. J., and WOAKES, A. J. 1979. Changes in heart rate and respiratory frequency during natural behavior of ducks, with particular reference to diving. J. Exp. Biol. **79**: 283–300.

ELSNER, R., and GOODEN, B. 1983. Diving and asphyxia: a comparative study of animals and man. Physiol. Soc. Monogr. No. 40. Cambridge University Press, Cambridge.

ELSNER, R., KENNEY, D. W., and BURGESS, K. 1966. Diving bradycardia in the trained dolphin. Nature (London), **212**: 407–408.

FALKE, K. J., HILL, R. D., QVIST, J., SCHNEIDER, R. C., GUPPY, M., LIGGINS, G. C., HOCHACHKA, P. W., ELLIOTT, R. E., and ZAPOL, W. M. 1985. Seal lungs collapse during free diving: evidence from arterial nitrogen tensions. Science (Washington, D.C.), **229**: 556–558.

FEDAK, M. A., PULLEN, M. R., and KANWISHER, J. 1988. Circulatory responses of seals to periodic breathing: heart rate and breathing during exercise and diving in the laboratory and open sea. Can. J. Zool. **66**. This issue.

FEDER, M. E., and BURGGREN, W. W. 1985. Cutaneous gas exchange in vertebrates: design, patterns, control and implications. Biol. Rev. Cambridge Philos. Soc. **60**: 1–45.

HARRISON, R. J. (*Editor*). 1972. Functional anatomy of marine mammals. Academic Press, London.

HUDSON, D. M., and JONES, D. R. 1986. The influence of body mass on the endurance to restrained submergence in the Pekin duck. J. Exp. Biol. **120**: 351–368.

IRVING, L. 1939. Respiration in diving mammals. Physiol. Rev. **19**: 112–134.

JOHANSEN, K., and BURGGREN, W. W. 1980. Cardiovascular function in lower vertebrates. *In* Hearts and heart-like organs. *Edited by* G. Bourne. Academic Press, New York.

JONES, D. R., WEST, N. H., BAMFORD, O. S., DRUMMOND, P. C., and LORD, R. A. 1982. The effect of the stress of forcible submergence on the diving response in muskrats (*Ondatra zibethica*). Can. J. Zool. **60**: 187–193.

KANWISHER, J. W., GABRIELSEN, G., and KANWISHER, N. 1981. Free and forced dives in birds. Science (Washington, D.C.), **211**: 717–719.

KEIJER, E., and BUTLER, P. J. 1982. Volumes of the respiratory and circulatory systems in tufted and mallard ducks. J. Exp. Biol. **101**: 213–220.

KOOYMAN, G. L. 1988. Pressure and the diver. Can. J. Zool. **66**. This issue.

KOOYMAN, G. L., WAHRENBROCK, E. A., CASTELLINI, M. A., DAVIS, R. W., and SINNETT, E. E. 1980. Aerobic and anaerobic metabolism during voluntary diving in Weddell seals: evidence of preferred pathways from blood chemistry and behavior. J. Comp. Physiol. B, **138**: 335–346.

KOOYMAN, G. L., CASTELLINI, M. A., and DAVIS, R. W. 1981. Physiology of diving in marine mammals. Annu. Rev. Physiol. **43**: 335–346.

LENFANT, C. K., ELSNER, R., KOOYMAN, G. L., and DRABEK, C. M. 1969. Tolerance to sustained hypoxia in the Weddell seal *Leptonychotes weddelli*. *In* Antarctic ecology. *Edited by* M. W. Holdgate. Academic Press, New York.

PINDER, A. W., and BURGGREN, W. W. 1983. Respiration during chronic hypoxia and hyperoxia in larval and adult bullfrogs (*Rana catesbeiana*). I. Changes in respiratory properties of whole blood. J. Exp. Biol. **105**: 205–213.

——— 1986. Ventilation and partitioning of oxygen uptake in the frog *Rana pipiens*: effects of hypoxia and activity. J. Exp. Biol. **126**: 453–468.

SCHOLANDER, P. F. 1940. Experimental investigations on the respiratory function in diving mammals and birds. Hvalradets Skr. **22**: 1–131.

SHELTON, G. 1976. Gas exchange, pulmonary blood supply, and the partially divided amphibian heart. *In* Perspectives in experimental biology. I. Zoology. *Edited by* P. Spencer-Davies. Pergamon Press, Oxford. pp. 247–259.

——— 1985. Functional and evolutionary significance of cardiovascular shunts in the Amphibia. *In* Alfred Benzon Symposium 21. Cardiovascular shunts: phylogenetic, ontogenetic and clinical

aspects. *Edited by* K. Johansen and W. W. Burggren. Munksgaard International Publishers, Ltd., Copenhagen. pp. 100–116.

SHELTON, G., and BOUTILIER, R. G. 1982. Apnoea in amphibians and reptiles. *In* Control and co-ordination of respiration and circulation. *Edited by* P. J. Butler. J. Exp. Biol. **100**: 245–273.

SHELTON, G., and BURGGREN, W. W. 1976. Cardiovascular dynamics of the Chelonia during apnoea and lung ventilation. J. Exp. Biol. **64**: 323–343.

SHELTON, G., and CROGHAN, P. 1988. Gas exchange and its control in non-steady-state systems: the consequences of evolution from water to air breathing in the vertebrates. Can. J. Zool. **66**. This issue.

SMITH, E. N., and TOBEY, E. W. 1983. Heart-rate response to forced and voluntary diving in swamp rabbits, *Sylvilagus aquaticus*. Physiol. Zool. **56**: 632–638.

SMITS, A. W. 1988. Lung fluid balance. *In* Lung biology in health and disease—comparative physiology. *Edited by* S. C. Wood. Marcel Dekker, New York. In press.

SMITS, A. W., and KOZUBOWSKI, M. M. 1985. Partitioning of body fluids and cardiovascular responses to circulatory hypovolaemia in the turtle, *Pseudemys scrita elegans*. J. Exp. Biol. **116**: 227–250.

SMITS, A. W., WEST, N. H., and BURGGREN, W. W. 1986. Pulmonary fluid balance following pulmocutaneous baroreceptor denervation in the toad. J. Appl. Physiol. **61**(1): 331–337.

TENNEY, S. M., and TENNEY, J. B. 1970. Quantitative morphology of cold-blooded lungs: Amphibia and Reptilia. Respir. Physiol. **9**: 197–215.

THORSON, T. B. 1968. Body fluid partitioning in Reptilia. Copeia, 1968: 592–602.

ULTSCH, G. R., and JACKSON, D. C. 1982. Long-term submergence at 3°C of the turtle, *Chrysemys picta bellii*, in normoxic and severely hypoxic water. I. Survival, gas exchange and acid–base status. J. Exp. Biol. **96**: 11–28.

WEST, N. H., and BURGGREN, W. W. 1984. Factors influencing pulmonary and cutaneous arterial blood flow in the toad, *Bufo marinus*. Am. J. Physiol. **247**: R884–R894.

WHITE, F. N., and ROSS, G. 1966. Circulatory changes during experimental diving in the turtle. Am. J. Physiol. **211**: 15–18.