Brain, Lung, and Heart Functions During Diving and Recovery

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Summary. Cooperative metabolic functions of central organs stabilize fluctuations in glucose and lactate in the blood and tissues through diving and recovery cycles.

Diving in marine mammals, particularly under experimental conditions, is accompanied by apnea, bradycardia, and peripheral vasoconstriction (*1–3*). Apnea cuts off the animal from the medium (air) it normally breathes, bradycardia leads to a drop in cardiac output, and peripheral vasoconstriction allows for the maintenance of arterial blood pressure and the regulated redistribution of blood. Although these changes had been observed earlier, they were first assembled into a coherent theory by Scholander (*4*) in 1940. Scholander (*1, 4*) appreciated the strategic positioning and physiological roles of the central organs and anticipated that the major purpose of bradycardia and peripheral vasoconstriction was to conserve blood oxygen stores for them. Nevertheless, neither the metabolic roles nor metabolic requirements of the brain, heart, and lung during diving have ever been clarified, and therefore my colleagues and I turned our attention to this problem, monitoring the metabolic status of these three central organs in the Antarctic Weddell seal during cycles of diving and recovery (*5, 6*).

The Weddell seal is an outstanding example of a pinniped diver, capable of breath-hold excursions to great depth (up to 600 meters) and great duration (more than an hour). Its physiological responses to simulated diving (*6*) are qualitatively similar to those of numerous marine mammals and birds (*1–3, 7*). Although the onset of bradycardia is rapid (*8*), the percentage drop in heart rate from about 55 to 15 beats per minute is not at all unusual. Cardiac output falls from about 40 to 6 liters per minute, but a mean blood pressure of about 120 torr is maintained through simulated diving, indicating the activation of extensive peripheral vasoconstriction (*6*). To complicate the issue further, these circulatory adjustments in effect cause a partial compartmentalization of central blood (about 8 liters) and peripheral blood (the remaining 52 liters) because of different circulation times.

Neither the stability of these two blood compartments nor the kinetics of exchange between them has been analyzed. However, indications are that the exchange is fast enough to dampen within 100 seconds a tracer pulsing between left and right sides of the central blood volume, but is not fast enough to fully equilibrate metabolite pools in the two blood volumes (*5*). Quantitative measurements on the selective distribution of blood flow (*6*) indicate that only the tissues of the central nervous system are supplied with an unchanging blood flow through diving and recovery sequences. One organ, the adrenal gland, is subject to only a modest decline in perfusion. All other organs and tissues sustain markedly reduced blood flow, down to one-tenth to one-twentieth that of normal. Even coronary blood flow decreases to about one-sixth of the resting values, coincident with a reduced work load on the heart. Similarly, pulmonary arterial blood flow drops by the same factor in step with a decrease in cardiac output (*6*).

The metabolic organization of the three central organs during diving and whether it changes, if at all, through diving and recovery is not known. It is possible to argue, from a simplistic view, that the purpose of the above physiological adjustments is to protect the central organs from the consequences of breath-hold diving; if this is so and the system is working well, no change in metabolic activities of the brain, heart, and lung may be seen; no change may be needed. This would, however, indicate that the metabolism of the central organs in no way contributes to the transition (i) between rest and diving states and (ii) between diving and recovery states. In ascertaining what is likely, it is useful to outline metabolic conditions in the blood through the cycles of diving and recovery.

Carbon and Energy Sources During Diving

Although the role of endogenous glycogen in different tissues during diving has not been quantified, it seems certain that blood glucose reserves are a critical source of carbon and energy for the seal during diving. This is indicated not only by the extensive depletion of blood glucose during diving (*5*) but also by the observation of only minor simultaneous changes in the free amino acid in the blood (*9*). A decrease in glucose concentration is consistently seen during short- and long-term dives in samples of whole blood taken either from the pulmonary artery or the aorta (*5*).

During the first 5 to 10 minutes of recovery, when cardiac output is high and the total blood volume (60 liters) is well mixed (*6*), blood glucose levels continue to decrease; but within the next 5 to 10 minutes, they begin to return to normal, then often overshoot the normal concentrations; that is, those prior to diving. Since fatty acids are not likely to take on enhanced importance during the progressively hypoxic conditions developing in diving, these data suggest that blood glucose reserves are a major, if not the only, source of carbon for metabolism during diving. This in itself is not surprising. The unexpected finding is that a large part of the depleted blood glucose is represented by accumulated lactate. During diving, blood lactate concentrations increase in arterial blood, usually from less than 1 μmole/ml just before diving to more than 3 μmole/ml at the end of the diving periods (*5*). Pyruvate levels are not altered much during diving, but in recovery a large transfer from tissues to blood of both pyruvate and lactate is always observed. Interestingly, there is a large difference in the kinetics of pyruvate and lactate appearance in the blood, with the pyruvate peak always lagging behind the lactate peak (*5*). As a result, during diving and

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Table 1. Whole blood glucose and lactate concentration gradients across the brain in micromoles per milliliter [data from (5) with modification].

Samples (No.)	Condition	Lactate production (μmole/ml)	Glucose uptake (μmole/ml)	ATP produced (μmole/min · g)
20	Predive mean	0.14	0.28	4.7
12	Diving mean	0.16	0.40	8.3

into early states of recovery, lactate levels may rise before pyruvate levels change, causing large fluctuations in ratios of blood lactate to pyruvate during the diving and recovery cycles.

These findings imply, somewhat surprisingly, that anaerobic glycolysis is activated somewhere in the organism well before the oxygen reserves are depleted. However, the findings are entirely expected in the sense that the blood glucose and lactate profiles are the outcome of a regulated partitioning of oxygenated blood between those tissues that need oxygen and those that tolerate hypoxia. In this view the blood glucose and lactate profiles are biochemical representations of the diving response.

Effect of Diving on Brain Metabolism

In most species of mammals the brain is considered to be obligatorily dependent on blood glucose, and therefore it is not surprising that glucose is also a good substrate for the seal brain. Glucose uptake by the seal brain can be estimated by simultaneous sampling of arterial (A) blood in the aorta and epidural venous (V) blood close to the occiput. Measurements of such AV glucose gradients indicate that glucose uptake by the brain during simulated diving (0.4 μmole per gram per minute) is somewhat (120 percent) higher than during resting states (Table 1). Only a small fraction (about one-eleventh) of the total brain hexokinase activity would be needed to sustain this rate of glucose metabolism. Lactate release accounts for about 20 to 25 percent of the cerebral glucose uptake during both diving and rest.

In principle, these gradients could be generated by changes in cerebral blood flow or by changes in uptake and release of the two metabolites. However, parallel microsphere studies (*6*) indicate that cerebral blood flow remains essentially unchanged during early diving, and thus this factor cannot account for changes in glucose and lactate profiles. More significantly, the blood flow and metabolite data, taken together, indicate that brain metabolism in diving is not oxygen-limited. If it were, glucose uptake would have to increase by up to 18-fold because of the inefficiency of anaerobic glycolysis; similarly, the fraction of glucose appearing as lactate would rise. The estimated increase of the rate of glucose uptake of only 120 percent, with no change in the fraction fermented to lactate, indicates that this organ's dependence on anaerobic glycolysis does not rise much during simulated diving of up to 30-minute duration, despite the arterial oxygen pressure (PaO_2) (down to 25 mm-Hg), which is distinctly hypoxic to nondiving mammals (*10*).

Since the mean blood flow to the seal brain is known, we can estimate from the glucose and lactate gradients the metabolic rates—in terms of micromoles of adenosine triphosphate (ATP) per gram of tissue per minute—that can be sustained with glucose as the carbon and energy source. The calculated metabolic rates (Table 1) sustainable by glucose catabolism are about 50 to 70 percent of brain metabolism in man (*10*). The reported estimates of cerebral metabolic rates in the Weddell seal, however, do not take into consideration the flow of glucose carbon into nonoxidative pathways, and this may explain the apparent differences between the diving and control states (Table 1). At least tentatively, therefore, no significance is attached to the differences noted.

A simple set of calculations shows whether or not these metabolic rates are high enough to cause significant depletion of blood glucose reserves during diving. If an average AV glucose gradient across the brain of 0.4 μmole/ml, and an average blood flow of 700 ml per kilogram per minute are accepted (*5, 6*), then a 500-g brain can take up glucose at a rate of 0.14 mmole/min, or about 3 mmole during a 20-minute dive. On the assumption that the 8-liter volume undergoes a slow exchange with the total blood volume during diving (*5*), this rate of uptake causes a change in glucose concentration in the blood of about 0.4 μmole/ml during a 20-minute dive. But when the total blood volume is well mixed, this rate of glucose uptake decreases the blood glucose by less than 0.05 μmole/ml. Essentially complete mixing occurs very early in the recovery process since cardiac output usually overshoots prediving control levels, reaching volumes as high as 60 liters per minute during the first minute of recovery (*11*). Similar calculations demonstrate that brain anaerobic glycolysis can cause only a modest increase in blood lactate concentrations, and therefore it is fair to conclude that during routine diving periods (of about 20 minutes duration) brain metabolism on its own does not markedly alter total blood pools of glucose or lactate. In dives of maximal (70 minutes) duration, however, brain metabolism would utilize about 10 mmole of the 30-mmole glucose pool in central blood, provided that there is no change in the ratio of oxidative to anaerobic metabolism. If, as may be expected (*12*), anaerobic metabolism became increasingly important during such long-duration diving, the brain contribution to glucose depletion and lactate production in central blood could become even larger. That is why we attach particular significance to the observation that changes mediated by brain metabolism are to some extent counteracted by the effects of lung metabolism.

Effect of Diving on Lung Metabolism

Arterial venous concentration gradients across the seal lung can be obtained by comparing levels of metabolites in the pulmonary artery and the left ventricle or aorta. Such measurements in the Weddell seal first demonstrated that the lung during diving takes up lactate from the blood at a rate that generates an AV gradient in the blood of 0.1 μmole/ml (*13*). If all the lactate taken up were oxidized it would consume 90 mmole of oxygen per hour per 4 kg of lung tissue, a value not too far off that measured with isolated lung slices (*5*). Glucose can also be utilized by the seal lung, but does not appear to be an important substrate during diving; in fact, some measurements imply that the seal lung can release small quantities of glucose into the blood, a result consistent with the relative activities of glucose-6-phosphatase and hexokinase (*5*). Whether or not this is a general phenomenon is not clear since in later studies (*5*) de novo synthesis of glucose from lactate could not be demonstrated. Rather, the dominant fate of lactate in the lung appears to be oxidation. The best evidence for this conclusion derives from in vivo experiments monitoring metabolic derivatives of in-

jected ^{14}C-labeled lactate on a single circulatory pass through the lung. These experiments demonstrate that shortly after injection, when the labeled lactate and absolute lactate concentrations are still decreasing in the pulmonary circulation, $^{14}CO_2$ is already appearing in aortic blood; this carbon dioxide can only be derived from lung metabolism since the lung is the only tissue (other than blood) to have received ^{14}C-labeled lactate. Most of the $^{14}CO_2$ appears under these conditions on the left side of the heart, reaching a peak about 35 seconds after the lactate was injected; the smaller initial peak of $^{14}CO_2$ in the pulmonary arterial blood probably is formed via the coronary circulation. For this reason oscillations in blood $^{14}CO_2$ levels on the left and right sides of the heart initially are about 90° out of phase with each other. But these oscillations are dampened within about 100 seconds presumably because of exchange with peripheral blood. Nevertheless, during diving, the oxidation of ^{14}C-labeled lactate by the lung exceeds oxidation of injected ^{14}C-labeled lactate by any other organs, which is why $^{14}CO_2$ levels in the aorta are consistently higher than in the pulmonary artery (*5*).

Further evidence indicating that lactate is a good substrate for the lung comes from tissue slice experiments that show higher rates of ^{14}C-lactate oxidation than of ^{14}C-glucose oxidation. Increasing glucose concentration from 1 to 10 m*M* causes a threefold increase in the rate of oxidation, while increasing lactate concentration from 1 to 10 m*M* increases oxidation rate by nearly fivefold. Interactions between glucose and lactate metabolism in the seal lung are modest in contrast to that in the rat heart, where high lactate levels strongly inhibit the rate of oxidation of glucose (*14*). Although lactate oxidation exceeds glucose oxidation rates at all substrate concentrations, this is accentuated at high concentrations of lactate (*5*).

These data show that lactate can be used in preference to glucose as a substrate for the seal lung, a conclusion in good agreement with recent studies of the perfused rat lung (*15, 16*). Whether this preference prevails under all metabolic conditions is not known, but at least during diving it is safe to assume that with an AV concentration gradient of 0.1 μmole/ml, lactate uptake by 4 kg of lung tissue (*5, 13*) can reduce blood lactate accumulation at a rate of about 10 mmole during a 20-minute dive while sparing blood glucose for other organs. At the beginning of diving, the lactate in the central blood pool is about 3 mmole while at the end of a 20-minute dive it is usually about 18 mmole, assuming a central blood volume of 8 liters. This increase in the size of the lactate pool by 15 mmole during 20 minutes of diving clearly would be nearly twice as great were it not for the uptake of lactate by the lung, implying that the local effects of lactate uptake by the lung may be very significant. In such a role the lung may be assisted by the heart, which may also be effective in reducing lactate accumulation in central blood during diving.

Potential Contributions of the Heart

It is worth emphasizing that just the opposite situation was first envisaged for the heart (that is, lactate formation rather than utilization), which may in fact occur in emergency situations. Several arguments support this idea. In the first place, while the activities of hexokinase and other glycolytic enzymes are comparable to those in other species, heart lactate dehydrogenase activity and glycogen stores are the highest thus far measured in mammals (*5*). Moreover, glycogen is stored as α rosettes of large diameter rather than as the usual β particles (*17*), a storage pattern typically observed only in organs storing unusual amounts of glycogen (*18*). As in other mammals, heart lactate dehydrogenase is potentially bifunctional, favoring either lactate formation or lactate utilization depending on metabolic circumstances (*5*). All the above are consistent with a high potential for anaerobic glycogenolysis or glycolysis, but such potential may rarely be utilized because during diving both cardiac output and coronary blood flow decrease by about 85 percent. At the low coronary flow rates occurring during bradycardia, the concentration gradient across the heart would have to be more than 20 μmole/ml if the heart were to produce all the blood lactate formed during diving; this value represents a release rate 100 times greater than that of the brain, which my colleagues and I consider highly unlikely, and the same considerations apply for glucose depletion. Finally, a dependence on anaerobic glycolysis would necessitate a large increase in coronary flow per watt of cardiac work, but again this is not observed. From measurements of blood flow, cardiac output, and arterial pressure (*6*), Brill (*19*) has calculated that coronary flow per unit of cardiac work increases by only about 15 percent (from 75 to 87 ml/g · min · watt). Thus, heart work during diving in the seal remains supported, primarily and probably solely, by oxidative metabolism. Whereas oxidative metabolism in the mammalian heart may be fired by a variety of substances (glucose, lactate, fatty acids), lactate is preferentially utilized whenever concentrations rise above normal (*20*). This is precisely the situation developing through the diving period, and it may explain why the Weddell seal heart has very high levels of lactate dehydrogenase kinetically well suited for lactate oxidation.

Role of Peripheral Organs and Tissues in Glucose Metabolism

From the above considerations, it appears that only in emergency situations could the seal heart contribute to the lactate accumulating during diving; in routine diving lasting up to 30 minutes, it could not possibly account for all the lactate formed. The same considerations apply for glucose uptake. Since the brain and lung can also be eliminated from these roles, the overall glucose depletion and lactate accumulation observed must be largely due to metabolism of peripheral hypoperfused organs and tissues. Although their blood flow is greatly reduced during diving, it is not zero. Skeletal muscles and skin, for example, receive about 15 percent of cardiac output (*6*), but because they receive a greatly reduced blood supply, these organs must rely fairly exclusively on anaerobic glycolysis (*6*). This interpretation explains a number of observations that would otherwise be perplexing. First, it explains—indeed it predicts—a close stoichiometry between glucose depletion and lactate accumulation in whole blood (*5, 13*). Second, it also explains why glucose utilization and lactate production are so high: in part because markedly hypoperfused organs and tissues constitute the bulk of the animal, and in part because anaerobic glycolysis is inefficient and requires a large glucose consumption. Finally, the interpretation presented in this article also explains why glucose concentrations in the blood continue to fall during early recovery even after complete mixing of central and peripheral blood volumes: namely, because glucose is depleted in the total blood volume, not only in the slowly exchanging volume of central blood. If only the latter occurred, glucose would return to near-normal levels within the first minute of recovery as cardiac output rose and promoted full mixing of the blood.

Role of the Brain, Lung, and Heart in Recovery

Our first insight into the roles played by the central organs during recovery comes from the lactate dehydrogenase isozymes present, since each organ has the potential for lactate utilization; operationally, this is often represented by the ratio of pyruvate reductase activity to lactate oxidase activity, which is comparatively low in all three organs (*5*). Consistent with this isozyme distribution and in part because of it, the seal brain switches from lactate release to lactate uptake (*5*) whenever lactate peaks are high (over about 6 μmole/ml). If all the lactate consumed at such time were fully oxidized, it could generate 9 μmole of ATP per gram of tissue per minute, provided that brain blood flow were normal (*6*). This metabolic rate is equal to, or greater than, that sustainable by glucose metabolism and indicates that lactate metabolism under these conditions can readily supply all of the energy demands of the brain.

Although similar data are not yet available for the heart, qualitative patterns of lactate dehydrogenase isozymes for the brain and heart are almost identical, and overall activities are fivefold higher in the heart. Therefore, it is not unreasonable to suggest that, during recovery, blood lactate is used as a source of carbon and energy for the seal myocardium, as it is under conditions of rising blood lactate concentrations in other vertebrate species (*14, 20*). A similar metabolic capacity for lactate conversion is displayed by the lung (*5, 13, 15, 16*), particularly at the high concentrations of lactate found in the blood during the recovery process.

Thus, the central organs of the Weddell seal undergo fascinating adjustments in their metabolism during diving and recovery cycles. Their summed metabolism in a sense appears to be cooperative, and minimizes disruptions in blood glucose and lactate pools through diving-recovery sequences. During diving, only the brain relies on blood glucose as a carbon and energy source, whereas the heart and lung preferentially appear to utilize lactate, thus minimizing its accumulation and sparing glucose for other tissues. A slightly different strategy apparently extends into recovery, when all three organs accelerate the clearance of the postdiving lactate, in effect sparing glucose for subsequent diving. These metabolic interactions depend (i) on the cycling of substrate and anaerobic end product (glucose and lactate) between tissues varying in their oxidizing power and (ii) on how enzyme potentials are used; they do not, however, depend upon the development of any "new" or qualitatively different enzymatic machinery. In fact, only modest adjustments in a few enzyme levels, such as heart lactate dehydrogenase, seem to correlate with the observed metabolic activities (*5*). In this important way, the biochemical strategies utilized in extending hypoxia tolerance of the whole organism seem to differ fundamentally from those utilized by many lower animals (*18*).

Determinants of Diving Duration

Central to all previous discussions of diving duration in aquatic mammals is the idea that the central organs in general and the brain in particular somehow set the time limits to diving. This conception, which can be traced back at least to Scholander's work in 1940 (*4*), rests on the premise that two of these organs, the heart and brain, are the most oxygen-dependent in the vertebrate body. In that our data on the Weddell seal, an acknowledged champion of pinniped divers, do not in any way challenge the high oxygen dependence of brain, heart, or lung metabolism (*5*), it may appear somewhat surprising to conclude that these organs do not seem directly involved in determining diving duration (*21*). Yet that seems to be the case and it derives from two kinds of adjustments (scaling and metabolic).

One set of adaptations involves the scaling of the brain and the blood volume with respect to the total body weight. This can be illustrated by comparison to man, for whom there are complete data. Although the lung and heart are of similar relative size in the two species (Table 2), the seal brain is scaled downward and constitutes only 0.1 percent of the total body weight. On a relative scale, the human brain is 20 times larger and is about 2 percent of body weight. Not only is the seal brain physically small, its weight-specific metabolic rate is only two-thirds that of man; because both size and metabolism are relatively reduced, the whole-organ metabolic rate is only one-fourth that of the human brain. For these reasons, seal brain metabolism contributes only 0.6 percent to total whole-organism metabolism, while in man it is at least 25 times higher and contributes minimally 15 pecent to total basal metabolism (Table 2).

A similar comparison of brain metabolism in the Weddell seal and man can be made from data on glucose uptake since glucose is a preferred substrate for the brain in both species. This is a useful exercise since it demonstrates the role of scaling blood volume. Although normal glucose levels in whole blood in both species are similar (about 5 μmole/ml), the blood volume in the Weddell seal is scaled upward relative to body size: for a 7-fold increase in body weight, for example, blood volume increases about 11- to 12-fold. With no other adjustments, this leads to a total blood glucose pool in the seal some 11-fold greater than in man. But because the seal brain is scaled down in size and metabolic rate, the organ's glucose utilization rate is actually only one-third that of the human brain (Table 3). Calculations show that as a result of these adjustments, the Weddell seal brain consumes per 1.2 hours only 3.6 percent of the total blood glucose pool, compared to 90 percent utilization per 1.2 hours by the human brain (Table 3). The maximum diving time for the Weddell seal is 1.2 hours (*22*), which

Table 2. Size and metabolism of brain, heart, and lung in the Weddell seal compared to man. Metabolic data are for seal during experimental diving (*6*) and for man at rest (*23*).

Item	Seal (500 kg)	Man (70 kg)
Brain weight (kg)	0.5	1.4
Brain weight as percent of body weight	0.1	2
Brain metabolic rate as ATP (μmole/g · min)	6	9
Brain metabolic rate as oxygen consumed (mmole/1.2 hours)	36	151
Whole-organism basal metabolic rate (mmole/1.2 hours)	6000	960
Brain metabolic rate (percent of total)	0.6	15
Heart weight (kg)	1.4	0.3
Heart weight as percent of body weight	0.3	0.4
Heart metabolic rate during diving (mmole/1.2 hours)	144	96
Heart metabolic rate (percent of total)	2.4	10
Lung weight (kg)	4	0.5
Lung weight as percent of body weight	0.8	0.7
Lung metabolic rate (mmole/1.2 hours)	72	12.6
Lung metabolic rate as percent of total	1.2	1.3

*The heart metabolic rate was calculated from work (in watts) for a 1-kg left ventricle during diving bradycardia (*6*), assuming 10 percent efficiency (*24*). All other data from (*5, 6, 22, 23*).

could not be determined by the brain's depletion of blood glucose supplies.

Perhaps that is not surprising; but since the diving animal is in effect cut off from a supply of oxygen, the question arises whether "on board" oxygen stores become limiting because of uptake by the heart, lung, and brain. From previous studies (*22*), we know that the total blood oxygen stores in the Weddell seal equal about 1000 mmole. Direct measurements of substrate use and product release indicate that brain aerobic metabolism requires about 36 mmole of oxygen per 1.2 hours (*5*). Thus, in a maximum dive, the seal brain would use up only about 3 to 4 percent of its blood reserves of oxygen; in man over the same interval, the brain would use up 90 percent of the stored oxygen (Table 4).

Similarly, because of upward scaling of the blood volume, the seal heart utilizes during 1.2 hours of diving only about 14 percent of the available oxygen, while in man at rest the heart would use up about 57 percent of blood oxygen stores over the same time interval. These dramatic metabolic effects of scaling and adaptation do not extend to the lung (Tables 2 and 4). Nevertheless, brain, heart, and lung metabolic rates summed together utilize in 1.2 hours less than 25 percent of the total blood oxygen reserves (Table 4).

Two important implications arise. First, during maximum duration (1.2 hours) diving, the brain, heart, and lung rates of oxygen and glucose depletion cannot determine the time limits observed. And second, about 96 percent and 75 percent of the immediately available blood glucose and oxygen supplies, respectively, are "spared" for other organs and tissues during maximum duration diving.

Knowing the oxygen uptake rates of the central organs allows easy calculation of the metabolic rate of the rest of the body because the two values must add up to the metabolic rate of the whole organism; for a 500-kg Weddell seal, this value is about 3750 mmole of oxygen per hour. If in a dive of maximum duration (1.2 hours), the central organs use 250 mmole of oxygen, the remaining 750 mmole of stored oxygen could sustain aerobic operations for only 0.2 hour before all the oxygen stores in the blood were fully depleted. The only other source of oxygen available to the animal under these conditions is that bound to myoglobin, which in the Weddell seal is equal to about 500 mmole (*22*), enough to keep the animal going aerobically for another 6 minutes. That is, maximum diving duration with all systems supported by oxidative metabolism is 18 minutes, a value remarkably close to that estimated by Kooyman *et al.* (*22*) on the basis of entirely different evidence. This time estimate must, of course, be strongly influenced by the energy cost of swimming, because the larger the fraction of on-board oxygen used for muscle work, the shorter the dive or the greater the depression of metabolism in other hypoperfused tissues. In mammals, skeletal muscle accounts for about 30 percent of basal, whole-organism metabolism; thus, during a dive of 1.2 hours, the maximum scope for aerobic activity in the Weddell seal, that is, the maximum activation of muscle aerobic metabolism, clearly cannot be greater than about threefold.

Table 3. Brain utilization of blood glucose in the Weddell seal during experimental diving (*5*, *6*) compared to man at rest (*10*).

Item	Seal (60 liters of blood)	Man (5.6 liters of blood)
Total blood glucose pool size (mmole)	300	28
Brain uptake rate (mmole/1.2 hours)	10.8	25.2
Percent of total blood glucose used by brain per 1.2 hours	3.6	90

Table 4. Utilization of blood oxygen by brain, heart, and lung in the Weddell seal during diving (*4*, *6*, *25*) compared to man during basal metabolism (*9*, *26*).

Item	Seal (60 liters)	Man (5.6 liters)
Total blood oxygen stores (mmole)	1000	168
Brain utilization rate (mmole/1.2 hours)	36	151
Percent of blood oxygen stores used by brain per 1.2 hours	3.6	90
Heart utilization rate (mmole/1.2 hours)	144	96
Percent of blood oxygen stores used by heart per 1.2 hours	14	57
Lung utilization rate (mmole/1.2 hours)	72	12
Percent of blood oxygen stores used by lung per 1.2 hours	7.2	7.2
Percent of blood oxygen stores utilized by brain, heart, and lung per 1.2 hours	24.8	154.2

However, if all physiological responses to diving were "supereffective" and all blood oxygen stores were in fact conserved for only the heart, lung, and brain, the Weddell seal could dive for 4 hours on the available oxygen stores in the blood, provided that the blood supplies of glucose for fermentation by other tissues and organs were adequate. This last condition, however, cannot be met. In simulated dives, when the diving response is probably activated maximally (*22*), the blood glucose falls from 5 to about 4 μmole/ml during 0.25 hour of diving, while the total glucose stores drop from about 300 mmole to 240 mmole per 60 liters of blood. In 1.2 hours, the maximum diving time, this rate of glucose consumption would require 288 mmole or about 95 percent of the total blood glucose available. This calculation does not take into account tissue glucose and glycogen deposits; but, for recharging blood glucose supplies, liver glycogen is the only major reserve that is tapped. Although this process is strongly activated only during recovery from diving (*5*), it must also occur to some extent during diving since the Weddell seal cannot and does not go hypoglycemic during near-maximum diving (*5*, *22*). Nevertheless, the closeness of the correlation between maximum diving time and the rate at which the Weddell seal utilizes blood glucose in a mixed aerobic-anaerobic metabolism is uncanny. This correlation suggests that it is either blood glucose utilization rate alone or in combination with oxygen utilization rate that determines diving duration. In either event, these rates during diving in the Weddell seal are much more strongly influenced by peripheral organs than by the heart, lung, and brain. That is why metabolic events in the former, and not in the latter, determine diving duration.

This unexpected conclusion is in fact a reasonable arrangement without which the organism clearly would be incapable of the long duration dives that underpin its unique success. In maximum duration diving much of the available blood glucose must be utilized by hypoperfused parts of the body in a massive fermentation that is energetically inefficient because it requires large amounts of glucose and forms twice those amounts of lactate. That explains the need for a large glucose pool and hence the upward scaling of blood volume. In such circumstances, it is also advantageous for the brain to make each micromole of glucose consumed go as far as possible by using

an efficient oxidative metabolism, and at the same time keeping glucose requirements low. That explains why the brain and its metabolic rate are both scaled downward. And finally, since large amounts of lactate must be generated by this system, it is advantageous to maintain large potentials for lactate oxidation by tissues such as the heart and lung, which remain on central circulation routes during diving. Not only does this latter capability minimize lactate accumulation, but also it uses a substrate that would be otherwise wastefully piled up and indirectly thus contributes to maximizing glucose conservation.

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National Science Foundation Budgets: Fiscal Years 1981, 1982, and Beyond

Lewis M. Branscomb

In the National Science Foundation Act of 1950, the 81st Congress and the 33rd President of the United States assigned to the Foundation the following purposes (Public Law 81-507 as amended):

> To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense; and for other purposes.

The National Science Foundation's (NSF) budget request for fiscal year 1982 and the associated proposed rescissions for fiscal year 1981 present the National Science Board with both an immediate task and a longer term opportunity. The Board recognizes the emergency nature of the economic situation and the vigorous remedies the President seeks in the way of federal expenditure reductions in nonmilitary areas. The emergency precluded the normal process of discussion of program priorities in which the Board could participate meaningfully.

It is the National Science Board's statutory responsibility to assist the President by establishing policies and priorities, and by guiding the activities of the NSF to ensure that with the available resources the NSF fulfills the functions defined by the Congress and the goals established by the President in the most efficient and effective manner possible.

Managing the Short-Term Problems

In the short term the NSF must focus the available resources on the task of contributing as much as possible to the strength of American science and technology; the quality and sufficiency of scientists and engineers educated for careers in research, development, and engineering; and maintenance of the U.S. position as a leader in international scientific and technological endeavors.

In accord with this near-term goal, the budget for fiscal year 1981 puts high priority on science and engineering research performed in academic environments to optimize both educational and knowledge benefits from a single investment. The Board fully supports this short-term priority, which reflects the federal government's awareness that the nation's basic scientific and engineering capabilities, and the academic institutions that sustain them, cannot maintain primacy for the United States without strong federal commitments.

The National Science Board is, however, faced with two problems of serious concern for the immediate future of American science and engineering. First, unless additional resources can be found—in the NSF budget or from other sources—the alarming obsolescence of research equipment in our university laboratories will accelerate. The nation's principal academic research laboratories need new instrumentation and a method of sustaining refurbishment over a number of years. University research equipment produces the most demanding technical and innovative requirements. Thus, keeping university equipment at the cutting edge sparks both innovation and productivity improvements in American industry broadly. Obviously, the research equipment problem is with us,

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