Sensory Deprivation, Weightlessness and Anti-Gravity Mechanisms

The Problem of Fetal Adaptation to a Floating Existence

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SENSORY deprivation is important in relation to the effects of prolonged weightlessness. Publications from a number of laboratories attest to this fact.[5,6] These studies deal with several aspects of the subject. The hope is to discover the psychophysiological parameters of weightlessness so that the physiological limitations of man in space may be anticipated.

In aerospace medicine, attention focuses on the effects of the loss of gravitational pull on the body. The more fundamental question involved is the basic physiology of anti-gravity mechanisms upon the body. From this viewpoint, the entire spectrum of the consequences of weightlessness may be seen. Then evidence affirming the broad concept of sensory deprivation in general, and anti-gravity deprivation in particular, may be looked for. The principle is to go from the general to the specific rather than from specifics to generalities.

In their book, *Kybernetics of Natural Systems*,[14] D. and K. Stanley-Jones establish a case for the concept that physiological systems which are in a state of dynamic equilibrium, as are all living things, are under the control of built-in mechanisms which hold them under control. This is true of homeostasis and postural mechanisms. "The central nervous system is dependent for its functioning upon the ceaseless influx of neural permeability waves created by the activity of the sense organs."[14] This, then, is the source of neural dynamic energy.

In the case of the nervous system, mammals require that the spinal cord be connected with higher centers in order to exert a proper integration of muscle tone, for the spinal animal has flaccid muscles. The mid-brain contains the principal central components which, under the stimulus of neural input from the periphery, can cause the opposite of flaccidity, viz., rigidity. By neural integration of higher centers the system acquires its normal tone with the potential for voluntary or complex voluntary or complex involuntary reflex movements. The key to the system is sensory-input from stretch receptors in all the striated muscles, the otoliths, and some visual sensory input.

Fishes differ from mammals. They lack the continuing sensory input from stretch receptors since they are supported by water against the pull of gravity. However, they are equipped with lateral line organs which serve a comparable purpose in a different manner. Embryologically these organs are derived from the same ectodermal tissue as are the otolith organs of the inner ear, which are concerned with postural or antigravity orientation in vertebrates. However, in fishes, the system differs from that of mammals, for in them a spinal animal is not flaccid; rather, it exhibits continuing and energetic movements. There is a runaway to a maximum of activity because the modulating influence of the lateral line refection (feed back) system working through the centers of the brain is lost. The key to control is continuing sensory-input from specialized receptors lying in the lateral line modulating the reverberating neural circuits that keep the spinal fish active.

In some invertebrates, similar feed-backs con-

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Supported by USPHS Grand RG 4728.

trol the primitive neural system. Stanley-Jones points out that in the medusa, Aurelia, there is a simple nerve net which has specialized receptors at eight points about the periphery of the umbrella-shaped animal. In each of these points is a small otolith-like structure which has the capacity to stimulate the nerve fibers with which they are associated. Movements of, or in, the water agitate these receptors from time to time. If these organs are removed one by one, a medusa will retain its upright and normal posture. However, after the last one is removed, the medusa collapses in a helpless heap. The sensory input normally keeps the simple nerve net in a state of continual excitation which permits the entire body to respond to other environmental stimuli where food or escape from danger are concerned. Again, the key to the problem is adequate sensory input keeping the neural net activated.

The concept is expressed by the following quotation:[8]

> "Consideration of the comparative physiology of amphioxus, dogfish, amphibian and human support the view that the rhinencephalon has always non-olfactory, inhibitory (to augmentor, antigravity reverberatory circuits) properties. It is suggested that the purpose of the human rhinencephalon is to act as an inhibitory mechanism by housing in its bulk an immense nerve of neural energy in the form of circulating permeability-waves, instantly available for release in an emergency counter, in the proper currency of the nervous system, the reverberating circuits that maintain the postural tones of the muscles."

Stanley-Jones makes an excellent case for regarding the role of this sensory input from muscle spindles to be that of supplying the continual neural excitation ("neural-dynamic") of the nervous system, including the brain, so that it can respond readily to the usual tactile, auditory, taste, visceral and other stimuli. This bank of "neural dynamics must be replenished from time to time to maintain the nervous system in a reactive state."

There are two broad types of sense organs in the body: (1) those that exhibit rapid adaptation to a continuing stimulus and have a very brief after-discharge, and (2) those that adapt only very slowly to a continuing stimulus and which have very long after-discharge characteristics. The antigravity receptors, the otoliths, and lateral lines of fishes are of the second type. With these, there is assured a substantial and continuing input of nerve impulses into the nervous system in order to maintain the necessary reverberating neural activity of the brain. It is this, Stanley-Jones maintains, that provides the neuro-dynamic base upon which normal functioning of an organism depends.

Most of the work on weightlessness that has been done in aerospace medicine is concerned with the effects of weightlessness, achieved through water immersion, on physical fitness, muscular strength, cardiovascular changes, metabolic and renal functions, psychomotor ability, respiratory activity and the like. A decline of cardiovascular homeostasis has been most extensively studied and some impairment of function shown.[6]

It would be more instructive to approach the problem in another way. This would be to ascertain in individuals which have never had sensory input—or at least anti-gravity sensory input—the characteristics of the circulation, and then to determine how soon a degree of homeostatic competence is achieved once anti-gravity sensory input is begun. This cannot be done easily in humans, but it has been done in fetal lambs, floating *in utero,* and in fetal lambs at cesaerian section but with the placental circulation maintained. Embryologists until now have failed to consider the effect which a flotation-type of existence has on physiological activity, as opposed to physiological capability of the organism, as it develops. In developmental biology it is axiomatic to say that morphological differentiation of an organ or system precedes functional capability. This is equally true of a single organ system or of two or more interdependent systems such as homeostatic regulatory mechanisms. Less obvious is the fact, however, that full function of one or more completely developed secondary systems may not take place because a *primary* organ system essential to the *secondary* one is not yet called into action by the exigencies of the environment. It is this sort of system-system interaction that concerns us here.

An extensive literature exists in the field of fetal physiology. This is notably summarized by Windle[16] and by Barcroft[1] in their respective books on the subject. Nevertheless, it was not until 1954 when Dr. Paul, Dr. Huggett and I managed to record fetal blood pressure and heart rate of fetuses *in utero*,[10] with the membranes intact, that the circulatory characteristics could be studied in a nearly normal environment. In such preparations, fetal responses to different stressful situations can be compared with those observed when the fetus is delivered by cesaerian section and the placental circulation maintained, as in conventional investigations of fetal physiology or with newborn lambs.

Certain of the functional capabilities of the parasympathetic and sympathetic nervous systems have been explored largely with the fetus *in situ*. The points of study were the responses of the fetal circulation to (a) change of intrauterine pressure;[11] (b) graded degrees of hypoxia and nitrogen administration to, or asphyxia of, the ewe;[12] (c) disturbances of the maternal circulation;[2] (d) occlusion of the umbilical cord;[8] (e) vagotomy;[9] (f) stellate ganglionectomy of the fetus[9] and finally, (g) excision of the fetal adrenal glands.[9]

The resting fetal heart rate decreases when intrauterine pressure increases by a weight placed upon the uterus and decreases when the weight is removed. These are transient episodes evoked by a brief and dynamic stimulus. The bradycardia is vagal in origin since it is abolished by atropine. There is, therefore, a competent vagal mechanism which is brought into temporary action by this change in the environment.

A lamb *in utero* and its mother respond differently to the same asphyxial stimulus. When nitrogen is given to a ewe, her heart rate and blood pressure rise. The fetus shows a bradycardia and no change in blood pressure. When atropine is given to the fetus during bradycardia the heart rate becomes rapid. The bradycardia is vagally induced. Again we see that the autonomic system of the lamb responds to this stress by parasympathetic output and the fetal response is unlike that of the adult.

Less stressful stimuli have an effect also. When a pregnant ewe is subjected to progressively stronger hypoxia, the fetal heart rate decreases, or it shows a 2:1 heart block, which is vagal in origin. Similarly, if there are acute disturbances of the maternal circulation involving transient congestion of the maternal portion of the placenta, evanescent decreases in fetal heart rate occur. This is the result of induced vagotonia.

From these and other experiments, we conclude that the parasympathetic system of the fetal lamb *in utero* is functionally competent but it lacks a stimulus to maintain parasympathetic tone.

Most of the observations were made with the ewes lightly anesthetized with diallylethylabarbituric acid. It might be argued that this anesthetic abolishes existing vagal tone. This is unlikely, however, since vagotonia is the easiest response in the lamb to exhibit under this anesthesia and experiments made with the ewe operated under local anesthesia (Procaine) alone yield identical fetal responses to stress and the resting characteristics of the fetal circulation are the same.

Barcroft described progressive vagotonia as a fetal lamb becomes larger. However, the *in utero* rates observed by him were recorded by auscultation and by palpation which involved some pressure upon and handling of the uterus which, as we have shown, induces vagotonia. From Barcroft's experiments on lambs at cesaerian section, it appears that the acute response to the stress of handling induces vagotonia, since he operated and observed very rapidly. He says:

"Let me emphasize again, that if the phenomena which have just been described (fetal vagotonia) are to be observed they must be observed at once on the delivery of the fetus—a delivery which must be carried through with no strain on the uterine and umbilical blood vessels and no exposure of the cord or foetus—It may seem wasteful to do an experiment on a sheep which only takes ten minutes and produces but a single lesion, but it is less wasteful than for him to misinform himself on three or four matters."[1]

system is silent except in the face of transient and dynamic stresses.

Study of the development of cardiovascular responses in lambs soon after birth is crucial to the hypothesis suggested above. A few observations have been made in lambs from 4 to 12 days of age, averaging about 8 days. Responses to the following stresses have been studied: (a) carotid artery occlusion (6 lambs); (b) bilateral vagotomy (8 lambs); (c) severe hypoxia (9 lambs). The results are summarized in Tables I, II and III.

TABLE I. COMPARISON OF THE EFFECT OF CAROTID ARTERY OCCLUSION IN FETUSES, LAMBS AND EWES

	Blood Pressure*			Heart Rate*		
	+	0	−	+	0	−
Non-pregnant ewe (10)	100%	0	0	50%	20%	30%
Lambs (6)	100%	0	0	33%	0	67%
Fetuses (5) (last 3rd preg.)	20%	60%	20%	0	20%	80%

*Per cent of animals showing increase (+), no change (0) or decrease(−).

Concerning sympathetic activity in the fetus, evidence is meager but equally clear. When normal resting fetal heart rates in lambs are compared with resting heart rates after bilateral excision of the stellate and other thoracic sympathetic ganglia, no change occurs in resting fetal heart rate. This is true whether the vagi are intact or sectioned or both carotid sinus areas are excluded from the circulation. One must conclude that there is no appreciable resting sympathetic tone in the fetus so far as heart rate is concerned.

One type of evidence has been obtained which resulted in sympathetic system activity in the fetus. With the heart completely denervated, severe hypoxia was produced by temporary occlusion of the umbilical cord. The heart rate showed a slow but profound decrease due to myocardial depression. On release of the cord, an extremely fast and prolonged tachycardia was seen. The fetus struggled, exhibited strong expiratory effort and passed meconium. The experiment was repeated after excision of both fetal adrenal glands. Now, after anoxia, the heart rate returned to normal without tachycardia. *In extremis*, therefore, there was mass stimulation of the sympathetic system.

One must conclude that the sympathetic system of the lamb fetus, like the parasympathetic system, is functionally competent but inactive in a resting fetus. One asks, therefore, why a developed and competent autonomic

Table I shows that carotid artery occlusion in lambs yields a rise in blood pressure as in the adult; the heart rate response is more or less intermediate between the adult and the fetus.

Table II shows that vagotomy in adult ewes and lambs causes a fall in blood pressure and a decrease in heart rate while blood pressure in fetuses is unchanged, although the decrease in heart rate occurs. The effect of vagotomy in the lamb parallels more closely the change in the adult than it does the fetus.

There is great variability of response in the effects of severe hypoxia in all three groups. Table III shows that the blood pressure of the fetus was, with one exception, unaffected by acute hypoxia. The responses in lambs and adults are rather similar. The heart rates are variable, but once again the lambs and ewes resemble each other to the extent that some of each showed cardiac acceleration which was not seen in the fetus.

These data suggest that newborn lambs resemble adults more than fetuses in their responses to the three stresses employed. More refined experiments are needed to establish this point, but the evidence seems clear that circulatory homeostasis begins soon after birth in the sheep.

TABLE II. COMPARISON OF THE EFFECTS OF VAGOTOMY IN FETUSES, LAMBS, AND EWES

	Blood Pressure (mm Hg)		Heart Rate (b.p.m.)	
	Before	After	Before	After
Non-pregnant ewes (12)	101.5±8.9/81.8±8.2	87.3±8.5/64±6.6	110.4±8.5	99.5±6.5
Lambs (6) (mean blood pressure)	85.0	70.5	234	194
Fetuses (5) (mean blood pressure)	37.9±4.4	37.8±2.4	166.7±13.7	158.8±14.0

Recent experiments on men given bed rest[15] or immersed in water for a day to a week[6] show that cardiovascular homeostasis depends upon proprioceptive input to the central nervous system. Following immersion, there is a progressive decline in blood pressure, an increase in heart rate, and a loss of the diurnal variation in heart rate. The heart rate response to the mild stress of a tilt table is much exaggerated. An elevation of diastolic and a decrease of systolic blood pressure occurred, signifying diminishing cardiac output. With more severe stress of exercise on a treadmill, the deficiency of homeostasis is more evident as the response is more exaggerated. In short, prolonged reduction of proprioceptive input by weightlessness leads to loss of effective homeostatic regulation in man.

TABLE III. COMPARISON OF EFFECTS OF HYPOXIA IN FETUSES, LAMBS, AND EWES

	Blood Pressure*			Heart Rate*		
	+	0	−	+	0	−
Ewes (15)	33.4%	46.6%	13.4%	46%	46.6%	13.4%
Lambs (9)	55.5%	33.4%	10.1%	33.4%	20.2%	44.5%
Fetuses (7) (last trimester)	0	86.7%	13.4%	0	42.8%	57.2%

*Per cent of animals showing increase (+), no change (0) or decrease (−).

The concept that homeostatic regulatory mechanisms depend upon sensory input to the nervous system is nicely set forth in the recent book by Stanley-Jones entitled "The Kybernetics of Natural Systems"[14] mentioned above, in which the roles of positive and negative feed-backs in a wide range of biological systems are reviewed. Feed-backs stabilize physiological mechanisms resulting in homeostasis; consequently they prevent a runaway to a maximum (e.g., excessive sympathetic activity as in the immersed or deconditioned man[6]). Gravity evokes positive refection to skeletal muscle in order to maintain tonus and negative refection of the autonomic system (vagal tone) in order to hold the cardiovascular system at a functional, stabilized level. It is this which the fetus lacks and the immersed man has lost. Speaking of weightless adults deprived of all sensory input, Stanley-Jones says:

"The physical status of adults in these circumstances resembles nothing so much as a return to the foetal condition of isothermal floating in the amniotic fluid of the womb; it is not surprising therefore that the body regression to prenatal conditions should cause a similar regression on the mental plane." With respect to the latter reference, the reader should consult an editorial on the subject.[13]

The fetus *in utero*, like the immersed man in the experiment of Graveline, is a free-floating organism. As in that experiment, the fetus is in a sort of zero-gravity situation so far as weight is concerned. It is not called upon to use its proprioceptive reflexes in order to offset the effect of gravity for the purpose of maintaining posture. The fetus is not normally subject to unequal forces. It does possess, from time early in development, the capacity for well-characterized patterns of behavioral (dynamic as opposed to postural) responses as Coghill[3] and Hooker[7] have shown, although Windle[16] is of a different opinion regarding their nature.

After delivery in those species that are mature at birth, antigravity input to the central nervous system is established rapidly. It appears, therefore, that such sensory input to the central nervous system is an essential factor in contributing to sustained parasympathetic system output, so far as cardiovascular homeostasis is concerned. This problem is part of the larger one of sensory deprivation in general upon the body.

How effective homeostasis will be after birth must vary with the degree of morphological maturity at birth. Opossums, hamsters, mice, rats, rabbits, kittens, puppies, piglets, human babies and many other species will lack the capacity for homeostasis at a stabilized functional level at birth because they do not respond to gravity. Others, such as guinea pigs, foals, lambs, calves, kids, and many other species will possess to a marked degree the capacity for effective homeostasis since they can stand, walk (or run) and regulate body temperature fairly well when they are born. Most notably, they possess a capacity for proprioceptive input to the central nervous system when they are delivered from a condition of weightlessness during development.

It is a captivating thought that the uterus is the original space capsule of mankind, and that all men have been, so to speak, in weightless orbit before they were born.

WEIGHTLESS AND KYBERNETIC PRINCIPLES

We may now consider the weightless lamb fetus with the weightless man. Each is an organism which is deficient in certain regulatory mechanisms. The fetus is relatively lacking in both parasympathetic and sympathetic controls in the resting state. The circulation functions as does a heart-lung preparation, being under chemical control. The output side of the parasympathetic system (negative refection) may be evoked with ease by a gentle, transient stimulus; that of the sympathetic system (positive refection) with stronger stimulation. A man immersed for a week loses efficient parasympathetic control, since his resting heart rate increases and with mild or severe stress his sympathetic activity (positive refection) is much exaggerated, just as it is in neurasthenia and in the deconditioned state.

Viewed against the principles of stabilizing and runaway refection as described by Stanley-Jones,[14] the above situations come into perspective. Stabilizing refection of the heart rate depends upon negative feed-back. The input of refective neural energy is governed by the output of energy to maintain posture.

"Any system in dynamic equilibrium which is steady in the sense of stationary, or oscillating about a fixed point at midway, is regarded as stable. It owes its stability to the pattern of its monitor feed-backs. . . . If therefore oscillation is taken to be a form of stability, or as evidence of stability (rather than instability) it is permissible to generalize that stability (including oscillation) invariably demands negative feed-back. . . . When monitored by a stabilizing system, however, and subject to controlled release, positive feed-back enables the output to rise briefly to heights far above the normal optimal or safety limit, but often at the expense of prodigious expenditure of fuel."[14]

The antigravity mechanisms provide negative (parasympathetic) feed-back to maintain the normal dynamic cardiovascular state to prevent a positive (sympathetic) feed-back required by exertion from running away to a maximum while the body maintains skeletal muscle tonus. In the immersed man experiments lasting from six hours to seven days, the negative feed-back gradually disappears while the capacity for positive feed-back upon exertion persists. In the lamb fetus, positive feed-back does not normally exist unless the efferent aspects of it is induced by severe hypoxia *in extremis*. Negative feed-back does not exist because there is no input to the nervous system from muscle spindles or otoliths. However, vagal activity, the efferent component of the system, is called into action by less moderate hypoxia or gentle stimuli. The anti-gravity component involving sustained output of energy of a low order to the cardiovascular system is absent. Consequently the efferent component of the feed-back monitoring system is brought into play only transiently since the neural dynamic, as Stanley-Jones calls it, of the central nervous system is minor from short-lasting episodes of sensory input to the central nervous system.

Another evidence of the dependence of energy output on sensory input in the lamb fetus may be mentioned in conclusion. I refer to the response to chemoreceptor stimulation. It is well known that fetuses and the apneic new-born do not respond to chemoreceptor excitation, despite the fact that chemoreceptor organs are excited and bombarding the brain over the ninth nerve with what are normally excitatory (positive refectory) stimuli. If, however, a fetus is given artificial respiration, chemoreceptor stimulation now excites inspiratory effort. The response is abolished by vagotomy. Similarly when a fetus is made to swallow by pulling the tongue, this is followed by a strong expiratory effort. Chemoreceptor activity now excites exaggerated expiratory effort (Reynolds and Mackie, in press). Chemoreceptors, it should be noted, exhibit almost no after-discharge. In this, we witness a phenomenon similar to that of the antigravity mechanism: an external or environmental force provides neural input to the central nervous system rendering it sensitive to the positive refection of chemoreceptor stimulation. The difference is that antigravity mechanisms (muscle spindles) and their associated neuronal connections excite the stabilizing action of negative feed-back to the heart; chemoreceptor mechanism excites positive refection by reflex excitation of the muscles of respiration with the purpose of improving pulmonary ventilation for a few moments.

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