Effect of Water Immersion on Human Tolerance to Forward and Backward Acceleration

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THE physical basis of the protective effect of water immersion during acceleration has been recognized for many years. In essence, the immersed subject, rather than being exposed only to the inertial force caused by acceleration is suspended, as it were, between this force and an opposite and almost equal force due to buoyancy. Acceleration causes a proportional increase in the magnitude of both of these forces. Thus, even at large accelerations, there is little net force acting to displace the subject. For this reason, the immersed subject would not be expected to experience shifts of blood like those which cause blackout. Further, the immersed subject should require no restraint during acceleration and should retain the ability to move the entire body at all accelerations.

The heart and mediastinum however, are immersed in the air-filled lungs and never in water. For this reason water immersion does not alter the forces acting on the heart and mediastinum during acceleration, and any symptoms arising from these organs would be expected to be equally prominent during acceleration in or out of water.

The hydrostatic pressure at any given depth in the water is increased by a factor equal to the acceleration. Thus at a depth of 1 foot, hydrostatic pressure becomes 10 feet of water at an acceleration of 10 G. To breathe with this pressure acting on the chest, a means of supplying an equivalent positive respiratory pressure is required.

This report presents a series of preliminary experiments designed to evaluate the magnitude of protection and the technical problems associated with acceleration of subjects immersed in water. We are aware of no previous studies of the effect of total water immersion on human acceleration tolerance. Immersion of the legs and abdomen was used during World War II to prevent pooling of blood during headward acceleration.[5,6,8] The first operational anti-G suit used this principle. Margaria[7] has reported extensive studies of the effect of immersion of fish and small mammals on tolerance to abrupt and prolonged acceleration. These studies demonstrated a marked increase in tolerance during submersion.

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METHOD

A semi-anthropomorphic tank was designed to withstand the large pressures anticipated with minimal weight penalty. Plastic blocks were fitted around the subjects to displace water and thus further lighten the weight. Nonetheless, the total weight of the tank, water, and subject was about 700 pounds. Because this approaches the weight limit of the Aero Medical Laboratory centrifuge, accelerations in excess of 14 G were not attempted.

The tank was mounted in the free-swinging cab of the human centrifuge so that acceleration was directed from the bottom toward the top (the inertial forces acted in the opposite direction). Acceleration in three body positions were studied: forward acceleration, subject erect (supine); backward acceleration, subject erect (prone); and forward acceleration with the spine tilted forward 35° and the legs extended perpendicular to the direction of acceleration (Fig. 1).

Subjects in the first two positions, were 2 to 3 inches below the water level. During the studies in which the spine was tilted forward, the water level was varied between ear level and 2 to 3 inches over the eyes.

Air for respiration was supplied from a high pressure tank of compressed air through a skin diver's valve,* mounted in the water tank at chest level, and a face mask. The efficacy of several variations of this basic apparatus was investigated. The skin diver's valve was ratchet-mounted so that the subject, by turning a screw, could adjust the depth of the valve during acceleration. In this way the subject was able to control the magnitude of mask pressure. In some experiments, a standard skin diver's mask was used with a flutter valve expiration outlet arranged so that mask pressure must exceed water pressure at the level of the valve to allow expiration. Because subjects experienced expiratory dyspnea with this system, the valve was modified in such a way that the subject was able to control the airway pressure by hand at all times. This was effected by admitting air to the mask at a pressure higher than ever required. A valveless tube leading from the mask could be raised and lowered in the water by the subject. Thus pressure in the mask was essentially equal to hydrostatic pressure at the level of the end of the tube. By lowering the tube, mask pressure was increased while by raising the tube mask pressure was decreased. With practice, subjects were able to ventilate themselves passively by raising and lowering the tube (Fig. 1).

Mask pressure was measured continuously by a Statham strain gage during many of the experiments to determine the magnitude of pressure and to help subjects develop the optimal respiratory technique by study of the patterns of pressure changes.

The subjects were young males, experienced in riding the human centrifuge, who were allowed many runs to become accustomed to the apparatus. Tolerances were determined with acceleration patterns consisting of a slow onset of acceleration (0.2 G per second) to a preselected level of 6, 8, 10, 12, or 14 G. The subjects were in-

*Aqua-Lung, manufactured by U. S. Divers Corp., Los Angeles, California.

structed to stop the acceleration if there was blackout, extreme discomfort, or dyspnea. In the absence of a tolerance-limiting symptom, subjects same position when not immersed.[6,7] Our subjects experienced chest pain at somewhat lesser accelerations when immersed than when not immersed.

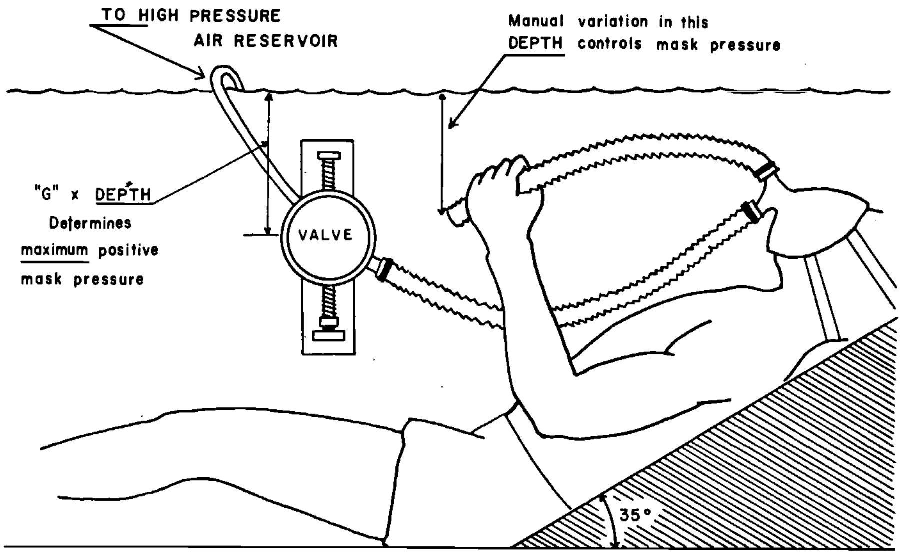

Fig. 1. Schema of breathing apparatus used in water-immersion acceleration experiments.

were encouraged to remain at peak acceleration for a period of time equivalent of that sufficient to produce a change of velocity of 50,000 mph at each G level (Fig. 2).

RESULTS

Tolerance to Forward and Backward Acceleration in the Erect Position.—Five subjects were studied during twenty-five accelerations in the forward position. Neither the magnitude nor the duration of tolerance to forward acceleration was in excess of values previously reported for non-immersed subjects (Table I).[5] Tolerance was usually limited by chest pain which was indistinguishable from that encountered during acceleration in the

Tolerance of the erect subject to backward acceleration was studied in five subjects in twenty-one experiments. Dyspnea and chest pain prevented three subjects from exceeding 8 G. One subject tolerated 10 G for fifty seconds but experienced severe residual chest pain for some twenty-four hours.

Tolerance to Forward Acceleration with the Spine Tilted in the Direction of Acceleration.—Six subjects were studied during more than 200 experiments in this position. It was determined in preliminary experiments that chest pain was minimized if the spine was tilted forward at an angle of 35° (Fig. 1).

The optimal respiratory device, as described above, is illustrated in Figure 1. Records of mask pressure revealed the expected increase with when the full face mask was used. Blackout was never observed with a mask which covered the nose and mouth, but not the eyes.

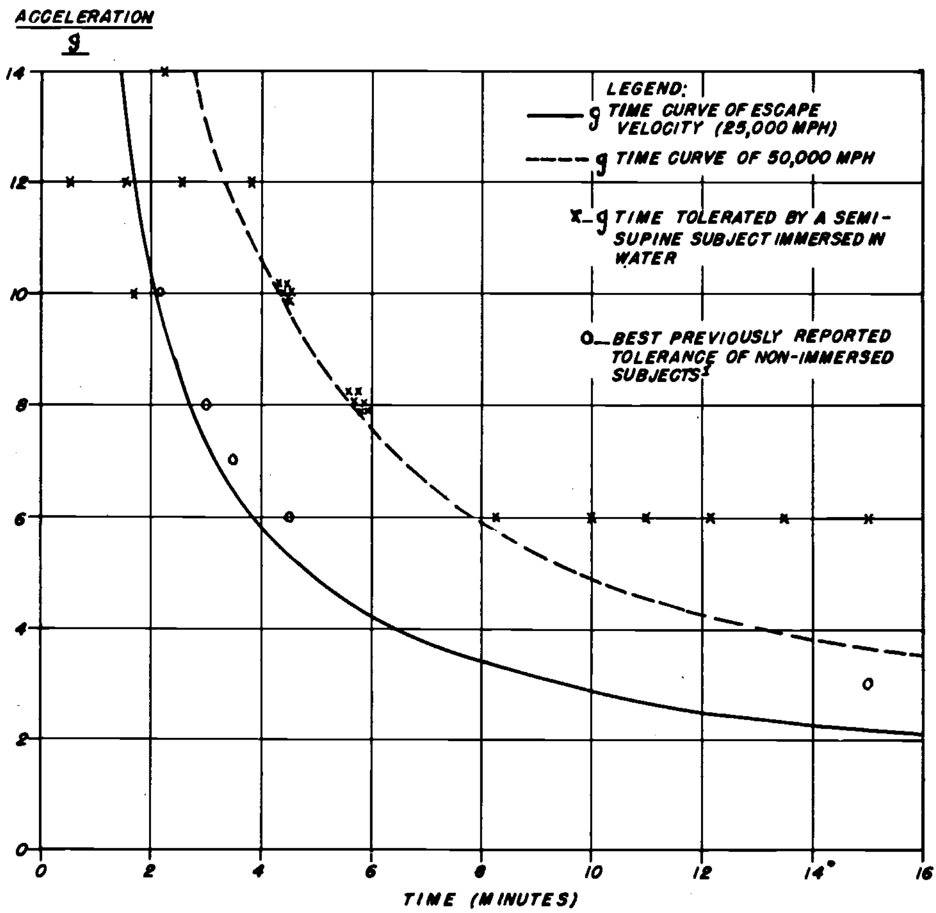

Fig. 2. Acceleration times tolerated by subject immersed in water.

acceleration and with inspiration (Fig. 3). Respiratory rate was highly variable. With this system, respiration could be almost entirely passive at from 6 to 8 G. At larger accelerations, respiration was increasingly difficult. With accelerations of 10 G, blackout was occasionally observed

TABLE I. TOLERANCE OF IMMERSED AND NON-IMMERSED SUBJECTS TO FORWARD ACCELERATION IN THE EXTENDED POSITIONS*

Subjects	G	Duration (seconds)
Immersed	5.0	25
Non-Immersed	5.3	13

*Mean values are given for 5 subjects.

Acceleration times indicated in Figure 2 were tolerated. The figures which lie to the right of the line representing 50,000 mph are not maximum tolerance times but rather represent the arbitrary end-points previously selected. (G-time equivalent to 50,000 mph change in velocity). In those experiments in which the subjects were unable to reach the preselected end-points, dyspnea and chest pain were essentially the only limiting factors. In contrast to studies of acceleration tolerance of non-immersed subjects, petechia were never observed.

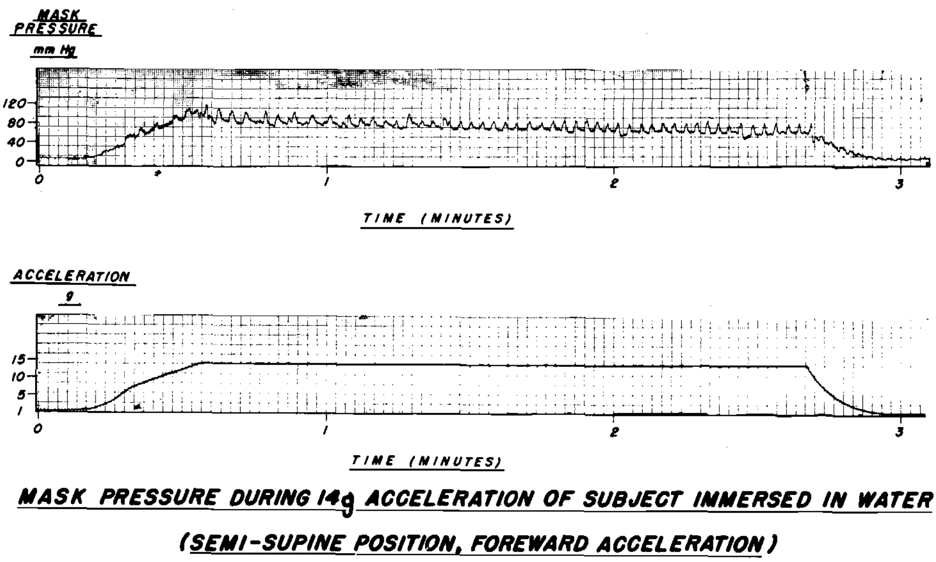

Fig. 3. Mask pressure of subject immersed in water during acceleration to 14 G (semi-supine position, forward acceleration).

General.—It was the consensus of these experienced centrifuge subjects that acceleration during immersion was generally more comfortable and less fatiguing than an equivalent acceleration when not immersed. Indeed, there are none of the usual sensations of acceleration such as pressure on the seat and facial distortion. As anticipated, there was freedom of movement of all parts of the body regardless of the magnitude of acceleration. It was the impression of all subjects and of the medical monitors that post-acceleration dizziness and malaise were rather less marked than with equivalent accelerations when not immersed.

DISCUSSION

It is not possible to ascribe the extraordinary acceleration tolerances observed in this study to the addition of the buoyant force of the water alone. At least two other factors may be of importance. Tolerance to forward acceleration of the non-immersed subject with the spine tilted forward is usually limited by either blackout or dyspnea.[5,6,7] Dorman and Lawton[4] have shown that an anti-G suit constituted effective protection against the blackout which occurs with forward acceleration in this position. As pointed out by Franks[6] and by Gauer,[5] immersion of the leg and abdomen constitutes effective protection against blackout by applying counter pressure over those parts of the body. It may be, therefore, that a part of the gain in tolerance reported here is due to the anti-G suit effective of the water. There are no reports of tolerance of subjects during acceleration protected by anti-G suit in the position used in this study. Lacking such true control observations, the precise value of water immersion cannot be stated.

The other factor which commonly limits tolerance of non-immersed subjects to forward acceleration is dyspnea. The cause of this dyspnea has not been established. However, intermittent positive pressure breathing might be expected to improve acceleration tolerance by assisting respiration. While no such study has been reported, it is pertinent that the respiratory system of the present study used a form of intermittent positive pressure. It is therefore also possible that a part of the gain in tolerance described herein is due to artificial support of ventilation during acceleration rather than to water immersion.

The relative importance of these three factors remains to be investigated. The data of the present study do indicate, however, that with a system incorporating all three, tolerance times in excess of twice any previously reported were demonstrated.[1]

The present study confirms the report of previous investigators that the chest pain associated with forward acceleration is decreased by forward tilt of the spine, but it does not contribute further information concerning the cause of this pain.

The dyspnea which limited tolerance during these experiments may have been caused by several factors. Prolonged positive pressure respiration might be a contributing factor. Further, it has been shown that the lungs become less elastic during forward acceleration.[2] This change would be expected to make breathing more difficult. In addition, because the thorax is tilted forward, there is a difference of about 1 foot in the depth of the top and bottom of the thorax. When the system is accelerated at 10 G, the effective difference in depth of the top and bottom of the thorax is 10 feet. Under these conditions, a mask pressure sufficient to expand the upper chest would leave the lower chest unexpanded because of the hydrostatic pressure there. A mask pressure sufficient to expand the lower chest would greatly overexpand the upper chest. Thus the forward tilt of the spine, necessary to avoid incapacitating chest pain, may be a cause of the dyspnea which becomes incapacitating at somewhat larger acceleration.

The cause of blackout at high G levels when the full face mask was used is not entirely clear. The fact that blackout was not observed with a mask which applied equivalent airway pressure, but did not apply pressure to the eyes, would suggest that pressure on the eye was a factor. However, the knowledge that skin divers do not blackout with even greater pressures on the eye indicate that occular pressure alone is not the cause. It seems likely that an inbalance between introthoracic pressure, hydrostatic pressure acting on the body, and mask pressure might be the cause.

While the increased mobility and decreased post-acceleration symptoms as well as the increased acceleration tolerance all indicate a potential gain from water immersion, the need for this gain has not been established. With adequate restraint and proper positioning, man can tolerate most of the linear acceleration expected to be encountered in routine atmospheric and space flight in the near future.[3]

The increase in acceleration tolerance demonstrated in these experiments however, is so large as to warrant further exploration. Of particular interest would be studies, using more refined respiratory apparatus, of acceleration of greater magnitude (such as abrupt deceleration as suggested by Margaria[7]) and in different directions.

SUMMARY

A preliminary investigation of the effect of water immersion on tolerance to forward and backward acceleration is reported. Respiration was maintained during acceleration by use of a system modified from that used by skin divers. Acceleration time tolerances at 6 to 14 G were greater than twice any previously reported. As expected, immersed subjects are able to move with freedom during acceleration in water. Post-acceleration symptoms seem to be less severe than following equivalent acceleration of non-immersed subjects.

ACKNOWLEDGMENT

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