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ISOLATION OF CIRCULATORY INFLUENCE IN HSG

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The respiratory and circulatory function in chickens exposed to high sustained Gz (HSGz), greater that 6 G for 15 seconds is reported. In mammals, such treatment induces ventilation perfusion inequalities and pulmonary shunts which limit tolerance. Chicken lungs undergo little distortion during acceleration exposure because of their inelastic, noncompliant nature.

Acceleration tolerance time (T_t, min) for cocks exposed to +6, +8, +10, and +12 G_z is hyperbolically related to the field strength (G): $T_t = \frac{240.15}{G} - 18.6$

This indicates that the product of exposure time and field intensity is constant over the range examined. Chickens, unlike mammals, have near normal Pa_{O_2} and Pa_{CO_2} during HSGz exposure. Forced ventilation of centrifuging chickens with oxygen increased pa_{O_2}, a response not found with mammals. Ventilation of one

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lung with air at 1 G produced near normal pa02 and PaCO2, but in HSG_z it gave low Pa02 as compared to spontaneously breathing mammals. Ventilation did not extend all tolerance times, indicating tha t circulatory imparirments are factors limitating acceleration tolerance. Expired PC02 during oxygen ventilation indicated that cardiac output decreased during HSG_z, even down down to zero for several seconds; after HSG_z, expired PC02 increased, indicating that oxygen debt and metabolismperfusion inequalities occurred during HSG_z.

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BACKGROUND

Exposure of man and other mammals to high sustained $+G_z$ fields impairs circulatory and respiratory function. The mammalian lung distorts significantly during acceleration exposure and results in the development of ventilation-perfusion inequalities and pulmonary shunts. The acceleration-induced decreased arterial oxygen tension and hemoglobin saturation reflect these changes in pulmonary function. The resulting progressive hypoxia may limit acceleration tolerance in man.

Birds have been considered as an appropriate human analog for the study of cardiovascular function during acceleration. Birds are bipedal and as such, are subject to similar circulatory problems that man experiences during HSG_z exposure. The anatomy and physiology of the avian respiratory system, however, is fundamentally different from that in mammals and allows for experimental separation of circulatory from ventilatory function during acceleration. The bird lung is relatively small and inelastic, and ventilation is not a function of its compliance. It is hypothesized that little relative distortion occurs in the avian lung during acceleration exposure. Barring a ventilatory impairment, acceleration tolerance in the bird would be primarily a function of circulatory impairment. It was the purpose of this study to determine if acceleration-induced $\dot{V}/\dot{Q}$ inequalities or pulmonary shunts generate arterial desaturation and if a ventilatory impairment, in part, limits acceleration tolerance in birds.

Ventilation and gaseous exchange occur in the same organ in the mammal -- the large compliant lung. In birds, however, gaseous exchange takes place in the lung, while ventilation is achieved through the bellows-like action of a large system of thin-walled air sacs. Figure 1 is redrawn from a picture of a latex cast of the avian respiratory system (20).

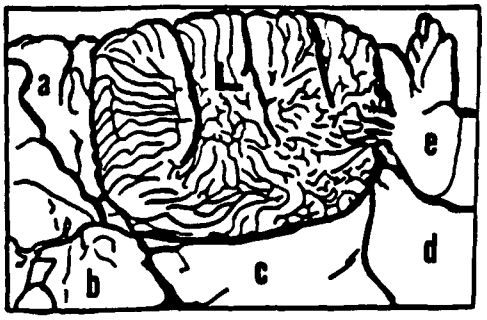

Figure 1. Drawing of a latex cast of the left lung and air sacs of the chicken (lateral view). L = lung; a = cervical; b = interclavicular; c = cranial thoracic; d = caudal thoracic, and e = abdominal air sacs.

The relatively nondistensible avian lung is located dorsally in the thorax. They are so firmly attached to the ribs that their dorsal surfaces are deeply incised (12,20,27). The lungs are constrained ventrally by the horizontal septum arising from the ventral crest of the vertebrae (20). As the lungs occupy a small dorsal ventral distance in the thoracic cavity, hydrostatic gradients within the lung are limited. The air sacs emanate from the lung and are divided into two functional groups, the cranial group consisting of the cervical, interclavicular and cranial thoracic and the caudal group consisting of the caudal thoracic and abdominal air sacs (12,21). The air sacs fill much of the continuous thoracic and abdominal cavities and penetrate the interior of many bones.

The gas exchange surfaces are located in the lung. The avian lung is basically a tubular structure consisting of three types of bronchi; the intrapulmonary bronchi, secondary bronchi and the parabronchi. The gas exchanging surfaces in the lung are the air capillaries which radiate-out from the parabronchial lumen and intermingle with blood capillaries (1,12). This structure provides a high ratio of exchange surface to lung volume. The blood-air barrier is thinner than that found in mammals (12). Gas exchange in the air sacs is negligible (33).

The lungs do not expand and contract during ventilation; rather, gas moves through the lung to and from the air sacs. Airflow through most of the lung is basically unidirectional. Gas flow is bidirectional in a small portion of the chicken lung called the neopulmo (12,41). During both inspiration and expiration, gas flows the same direction through the lung. This distribution of gases within the respiratory system provides for gas exchange during both phases.

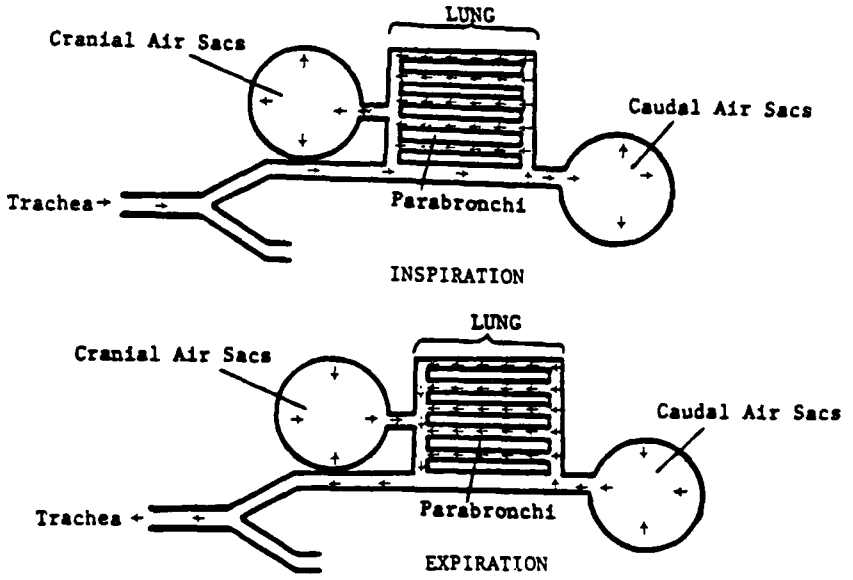

Figure 2. Gas flow patterns through avian lung and air sacs during inspiration and expiration (after Scheid, 41).

During inspiration, about half of the inspired gas volume flows from the primary bronchus to the secondary bronchus and into the gas exchange region of the parabronchus. The ramaining volume flows through the primary and secondary bronchi and into the caudal air sacs, without having undergone gas exchange in the paleopulmo parabronchi. Upon expiration, the exchanged gas in the parabronchus and cranial air sacs flows into the intrapulmonary bronchus, while the gas in the caudal air sacs flow into the paleopulmo parabronchus, exchanging gases with the blood (21,41).

Burger and Lorenz (13) described a method for unidirectional artificial ventilation in the bird. By passing a catheter into one of the caudal air sacs, a flow of gas (of any composition) can be delivered to the lung, in much the same flow pattern as occurs during normal expiration.

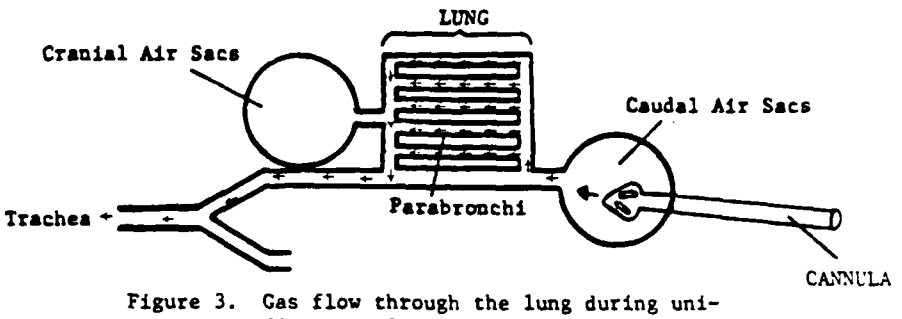

Figure 3. Gas flow through the lung during unidirectional artificial ventilation.

By this method, birds can be artificially ventilated during acceleration exposure, eliminating hypoxic hypoxia -- the reduced oxygen tension in the arterial blood induced by ventilatory impairments -- as a determinant of acceleration tolerance. Comparing acceleration tolerance times for nonventilated birds and ventilated birds, will indicate if a ventilatory impairment influences tolerance. The validity of this model, however, is based on the hypothesis that little or no pulmonary shunting or $\dot{V}/\dot{Q}$ abnormalities develop during acceleration in the avian lung. Blood gas levels will reflect these changes in pulmonary function if they do develop. By determining arterial saturation, it is possible to detect these changes if they occur. If arterial blood desaturates, it could be caused by:

(1) A ventilatory impairment;
(2) $\dot{V}/\dot{Q}$ inequality, or
(3) development of pulmonary shunts.

If the desaturation is due to a ventilatory impairment, artificial ventilation should bring the saturation levels back up to control levels. However, if ventilation with pure O_2 does not return arterial saturation to normal, pulmonary shunts are developed during acceleration.

The purpose of this research was to determine the relative degree of respiratory impairment in the bird during HSG_z. The following experimental questions are asked:

(1) Does acceleration induce arterial desaturation in the chicken?
(2) Does artificial ventilation block the acceleration-induced fall in arterial saturation if it exists?
(3) Is ventilation a limiting factor in acceleration tolerance in birds? and finally,
(4) Can the bird be used as a human analog for the study of peripheral circulatory function during HSG_z?

MATERIALS AND METHODS

Animals

All of the chickens used in these experiments were mature single comb White Leghorn cocks from the flock maintained at the Chronic Acceleration Research Unit. They were individually caged and were maintained at a constant light/dark cycle of 12L:12D. A commercially available ration was provided *ad libitum*. The chickens used were between 6 and 13 months old at the time of the experiments.

Centrifuge

The centrifuge used in these experiments is a hydraulically-driven apparatus designed by S. J. Sluka and originally built to reproduce launch and recovery acceleration fields for biosatellites. The centrifuge and the procedures used in acceleration studies with birds have been described in detail elsewhere (47).

Instrumentation

The centrifuge was equipped with a 24 channel commutator located at the center of rotation. This system of slip-rings provided electrical connections, both outgoing and incoming signals, from the end of the centrifuge arm to the control room. Four of the channels were utilized to record electrocardiogram signals (EKG), three channels were used to monitor cloacal temperature and three channels were used to control a blood sampling device.

Expired gases were continuously sampled and analyzed for CO_2 concentration. A Beckman Instrument carbon dioxide analyzer (Model LB-2) was connected in series to a nylon tubing (internal diameter of 1.5 mm) which attached at the center of rotation of the centrifuge to a rotating union (Deublin Company, Northbrook, Illinois, Model 1005-20). Nylon tubing from the rotating section of the rotating union passed down the length of the centrifuge arm and into the animal carriage. A short section of small diameter polyethylene tubing with a constricted end was attached to the nylon tubing, and secured in the left side of the nares of the chicken. The cannula tip determined the flow rate of the CO_2 sampling system. The tubing and analysis chamber of the CO_2 analyzer was evacuated to ½ atmosphere by a vacuum pump (Spectrum Medical Industries, Los Angeles, California, Vac/Trol Lab Vac Regulator with pump) placed in series with the CO_2 analyzer. The delay was approximately three seconds from the time of sample to the recorded signal. The CO_2 analyzer, vacuum pump suction and delay time were calibrated for each experiment.

A Beckman Instruments Type-R Dynograph was used to record data. Five channels of the dynograph recorded the following:

(1) Heart rate via a cardiotachometer coupler (No. 9857B) which triggered from the incoming EKG signals;
(2) EKG (AC/DC coupler No. 9806A);
(3) nasal temperature indicating respiratory frequency (AC/DC coupler No. 9806A);
(4) body temperature (AC/DC coupler No. 9806A);
(5) % CO_2 in the expired air (AC/DC coupler No. 9806A).

EKG signals were monitored using subdermal electrodes (safety pins) placed along the axis of the spine. One lead was placed at the base of the neck and the second lead at the base of the tail (location of the tail feathers). The ground lead was placed in the fleshy portion of the wing.

Nasal temperature was recorded via a Yellow Springs Instruments (YSI) No. LN-8157 thermister probe which was secured outside the right nares. Signals were transmitted to a YSI telethermometer No. 43TA and subsequently to the pen writer. Cloacal temperature was recorded via a YSI thermister (No. 401) which connected to another telethermometer and pen writer.

The blood sampling device used in these experiments was designed and built by Mr. Jamie Jaggars, USAF School of Aerospace Medicine, Brooks Air Force Base, Texas. Two syringes were mounted "back-to-back" on a board and connected at their plungers by a plexiglass disc. A pressure source (compressed air tank mounted on the centrifuge) delivered pressurized gas (8 psi) through a flow regulating valve to a miniature solenoid. The current was supplied through a switch in the control room and powered by the 12 volt airplane battery on the centrifuge. The output port of the solenoid was connected to a port located behind the driving plunger such that activation of the system drove the plunger of the sampling syringe. Blood samples were drawn from a carotid artery catheter and analyzed for P_aO_2 and P_aCO_2 with an Instrumentation Laboratory Blood Gas Analyzer (Models 113 and 123). The in-dwelling catheter (PE) was attached to a larger diameter cannula (PE 190, and interior diameter of 1.175 mm) approximately 20 cm in length, by short pieces of silastic tubing. Blood was drawn from the artery, filling the tubing, and into the syringe. The silastic tubing was clamped with hemostats, and the middle section of the tubing was removed to be analyzed. A replacement cannula, filled with heparinized saline was inserted and the remaining blood in the cannula and syringe were returned to the chicken. As the blood samples taken during acceleration could not be analyzed until the centrifuge had stopped, the blood analyses were done 3.75 minutes after the sampling. The high surface area-to-volume ratio of the cannula provided for rapid cooling of the sample. The temperature of the blood sample equilibrated quickly to that of ambient air. The blood was reheated to 41.5°C before P_aO_2 and P_aCO_2 were recorded.

A gas delivery system was mounted on the centrifuge so that birds could be unidirectionally ventilated during acceleration. A line of tygon tubing was placed along the arm of the centrifuge from the tank to the animal carriage. An aquarium valve was in series to control flow. The flow rate, measured before the bird was ventilated, was set at a flow of 500 ml per minute with a flow meter. A small walk-around bottle (USAF) installed at the center of rotation of the centrifuge was used when ventilating with oxygen. Oxygen was delivered at a constant pressure, controlled by the tank regulator (15 cm H_2O). When animals were to be ventilated with air, a compressed air tank (size E) and flow regulating valve was substituted for the oxygen tank. Pressure was controlled from this tank by installing a "T-tube" vent. Gas was delivered into a T-tube, one arm of which was submerged in water such that the pressure was equal to that from the oxygen tank. When pressure exceeded this level, gas escaped to the outside via the side arm.

Surgical Preparation

Ventilation Procedure: Unidirectional ventilation of birds, described by Burger and Lorenz (13), requires surgical implantation of a catheter into one of the caudal air sacs. Gas is introduced into the cannula so that it passes into the air sac and through the lung, where it exchanges gases, and leaves through the trachea. Burger and Lorenz (13) cannulated the caudal thoracic air sac. Their procedures did not require that the cannula remain patent for more than a few hours. Our experimental protocol required that surgical intervention be followed by a 24 hour recovery period prior to acceleration exposure. Attempts at maintaining a caudal thoracic air sac cannula for 24 hours were unsuccessful. Consequently, we moved to the large abdominal air sac to implant the catheter.

Birds were anesthetized intravenously (IV) with sodium pentobarbitol (Diamond Laboratories, 60 mg/ml) and maintained under anesthesia throughout the

surgery. An endotracheal tube (4.2 mm outside diameter) with an inflatable cuff was inserted into the trachea and secured. Birds were ventilated with oxygen delivered by a Phipps-Bird respiratory valve. Normally, the abdominal air sac is collapsed; in order to visualize this air sac, it must be inflated. Inflation of the abdominal air sac was achieved by increasing tidal volume and expiratory pressure.

A skin incision was made laterally and slightly dorsally to the cloaca. Muscle layers were separated using blunt dissection and the large abdominal fat pad was exposed. The air sac was located at the junction of the caudal aspect of the fat pad and the large intestine where it was carefully separated from the gut so that it bulged out of the cavity. The sac was clamped with a hemostat and punctured with a small scissors as shown by a high flow of oxygen escaping from the puncture site. A four-wing French type malecot catheter (General Hospital Supply, Los Alamitos, California) was introduced into the air sac. Gas must escape from the cannula during artificial ventilation, and after disconnecting the respiratory valve, gas delivered into the cannula must pass out through the trachea. Valving of gas flow by air sac membrane apparently occurred in several of the cannulated birds. Gas escaped from the cannula during normal respiration, but the introduced gas did not pass through the lung; instead, the gas was trapped in the abdominal cavity, increasing the volume of the cavity and pressure in it, leading to distress of the animal. These birds were not used for the ventilation trials.

Once proper placement of the catheter had been ascertained, muscle layers surrounding the cannula were sutured to provide a "tight-fit" around the catheter. The skin was then sutured closed. The catheter was doubled-back on itself, occluding the lumen, and the folded catheter was sutured to the skin. Birds were allowed a 24 hour recovery period before their first acceleration exposure.

Blood Sampling Procedure: In order to prevent clotting within the indwelling carotid artery cannula, the birds were cannulated just prior to acceleration exposure. Birds were restrained on their backs with their necks extended. Local anesthetic of 1% procaine in oil was injected subdermally in the neck near the thoracic margin and allowed to take effect. Feathers in the region were plucked, and the ventral aspect of the neck extending approximately 8 cm from the clavicle was exposed. A skin incision was made, and local anesthetic was injected intramuscularly. Muscle layers were separated via blunt dissection. The carotid arteries were located mid-ventrally and separated. The cranial aspect of the right carotid artery was ligated. The catheter was introduced through a small incision in the artery and advanced toward the heart. The catheter was filled with heparinized saline and flushed periodically. The skin incision was sutured and the birds were placed on the centrifuge.

Experimental Protocols

Three separate experimental protocols were employed. The first series was the nonventilated tolerance determination protocol (NVTD). The second set of experiments was the ventilated-nonventilated tolerance comparisons (VNVTC). The final series of experiments involved blood gas determination (BGD). They are described individually in the following discussion. The objectives of the experiments required that the birds be fully conscious, so no anesthetic was used during the centrifugation treatments.

NVTD, Non-ventilated tolerance determination: Sixteen birds, 13 months of age, with a mean body mass of 2.3 kg were divided into four equal groups. Each group was accelerated once a week over four consecutive weeks at +6, +8, +10 or +12 G_z (one $+G_z$ field per group). The duration of the acceleration period was determined individually for each acceleration experiment, as the time at which a bradycardia of 120-180 beats per minute (bpm) develops. Smith *et al.*, (45) noted a severe reduction in heart rate of birds during acceleration exposure. Prolongation of acceleration beyond this point results in animal death; however, if the acceleration field is reduced immediately, the animal recovers. The onset of the characteristic bradycardia is taken as a near-leathal limit of acceleration tolerance in birds. During this series of experiments, birds were accelerated until bradycardia developed or for 30 minutes, whichever came first.

Heart rate was monitored through the use of EKG signals and a cardiotachometer coupler. The method proved reliable; during these experiments, only one animal died during acceleration exposure.

VNVTC, ventilated nonventilated tolerance comparisons: Twelve birds ranging in age from 5 to 7 months with a mean body mass of 1.6 kg were divided into three groups. All three groups were surgically implanted with an air sac catheter on the day preceeding their initial acceleration exposure, as described earlier. Seven birds in Group I were exposed to +6 G_z on two successive days, three of which were ventilated with oxygen the first day and not ventilated the second. The other four were nonventilated the first day and ventilated with oxygen the second day. Seven birds in Group II were exposed to +8 G_z on two successive days, as in Group I. Five birds in Group III were exposed to +10 G_z, similarly (three ventilated on day 1 and two ventilated on day 2).

Birds in this experiment were accelerated for a duration determined by the onset of bradycardia or for 20 minutes. The experimental limitation of 20 minutes was taken from the protocol of Smith *et al.*, (45) in which they accelerated chickens to their end-points. They determined that two-thirds of the birds would be included in the zero to 20 minute period. The tolerance times were recorded and subsequently compared (between ventilated and nonventilated conditions). Heart rate, EKG, nasal temperature, body temperature and % CO_2 in the expired air were recorded two minutes prior to acceleration, during acceleration exposure and two minutes following acceleration.

BGD, blood gas determination: Thirteen birds, 9 to 10 months old, with a mean body mass of 1.7 kg ($\pm$ 0.2 standard deviation) were surgically implanted as described earlier with an abdominal air sac cathether 24 hours prior to acceleration exposure. These birds were then implanted with a carotid artery catheter on the following day, just prior to acceleration exposure. The birds were exposed to acceleration fields of +6, +8, and +10 G_z for one minute without artificial ventilation and ventilated with oxygen or with air. Three blood samples were taken, prior to acceleration exposure, one minute into acceleration (immediately before acceleration was stopped) and 10 minutes after acceleration exposure and were analyzed for P_aO_2 and P_aCO_2.

In each case, the birds had more than 10 minutes of recovery time between acceleration trials. Preacceleration blood gas levels during ventilation were taken at least two minutes after ventilation was initiated. Preacceleration blood gas levels without ventilation, taken after a ventilatory series, were sampled at least two minutes after ventilation had been terminated. Following O_2 ventilation, P_aO_2 returns to normal within two minutes.

Heart rate, EKG, nasal temperature, body temperature and CO_2 in the expired air were continuously monitored throughout these experiments.

Correction Factors

Blood gas samples were taken with a polyethylene catheter which is permeable to oxygen. Oxygen ventilated birds have a high P_aO_2 such that there is a sizable oxygen gradient from the blood to the air. Correction factors were determined using chicken blood equilibrated with known oxygen concentrations and placed in the sample cannula for the specified length of time (3.75 minutes). The following equation was used to correct the oxygen-ventilated blood gas values:

$$\Delta P_aO_2 = -0.42\ (P_aO_2 - 150)$$

Blood gas values below 100 mm Hg were not significantly affected by oxygen diffusion across the catheter. The gradient across the cannula was much less, and the buffering characteristics of the oxygen dissociation curve of hemoglobin limited P_{O_2} changes by exchange with air.

Chicken red blood cells are nucleated and have a relatively high metabolic rate. Red blood cell metabolism should be determined and P_aO_2 values corrected for the metabolic utilization of O_2. In these experiments, blood samples were collected in a cannula with a high-surface-to-volume ratio and stored away from the bird's body for approximately four minutes. Blood cools rapidly in the cannula, decreasing metabolic rate. Besch (6) measured the metabolic rates of red blood cells of chickens and different temperatures. At 40°C, he found a rate of 126.81 $\pm$ 6.54 mm^3 O_2/ml cells/hour. Scheid and Kawashiro (42) reported a metabolic rate of 0.041 $\pm$ 0.002 [mmoles·(L blood)$^{-1}$·min^{-1} $\pm$ standard error] for duck blood at 41°C. The calculated change in O_2 content (mmoles) for blood samples stored at 21°C for 3.75 minutes in these experiments would be 0.038 mmoles/L, a negligible amount in our calculations. Therefore, no corrections were made for metabolic rate changes in the blood gas results.

RESULTS

Nonventilated Birds

Acceleration Tolerance Time: The mean acceleration tolerance time declines exponentially with increasing field strength, and this relationship is summarized in Table 1.

TABLE 1. TOLERANCE TIMES (mean ± standard error).

Field Strength $+G_z$	Animals (n)	Mean Tolerance (min)
6	16	21.73 ± 2.8
8	14	11.36 ± 2.4
10	16	4.87 ± 2.0
12	16	1.63 ± 0.3

Three separate regression lines were calculated between log tolerance times and field strength:

(1) Using 62 animals (all birds in all trials);
(2) using the average tolerance time for each of the 16 animals; and,
(3) using the average tolerance time at each $+G_z$ level (4 animals).

In all cases, the regression lines were statistically significant.

The significant exponential relationship between field strength and tolerance time indicates that a simple additive function is not involved (Figure 4). One would expect a linear relationship if that were the case. As the field strength increases, it has a progressively greater effect on tolerance time.

The similarity between exponential and hyperbolic relationships over limited ranges suggested that the data be analyzed as a hyperbolic function as well. The variances in means were not homogeneous such that a transformation was utilized to obtain the slope and intercept for the relationship (32).

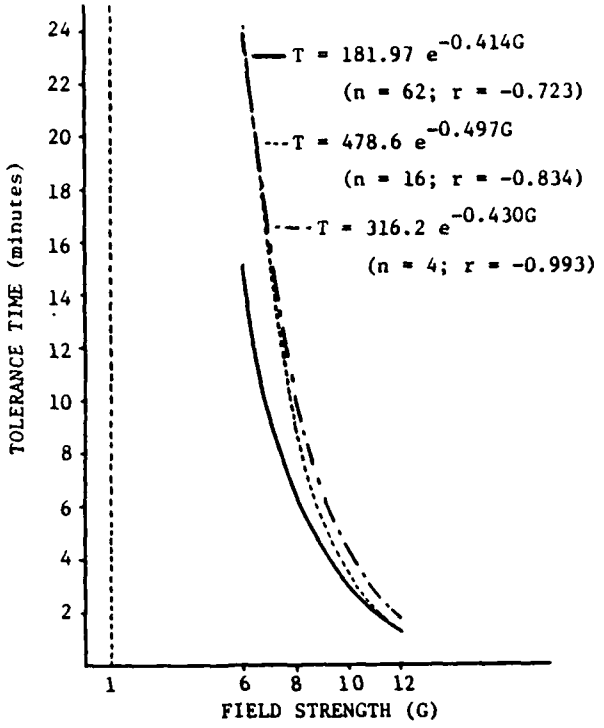

Figure 4. Exponential regression of acceleration tolerance time on field strength.

Data presented were calculated from all acceleration trials (n = 62); mean acceleration tolerance time for each bird (n = 16); and from mean acceleration tolerance at each $+G_z$.

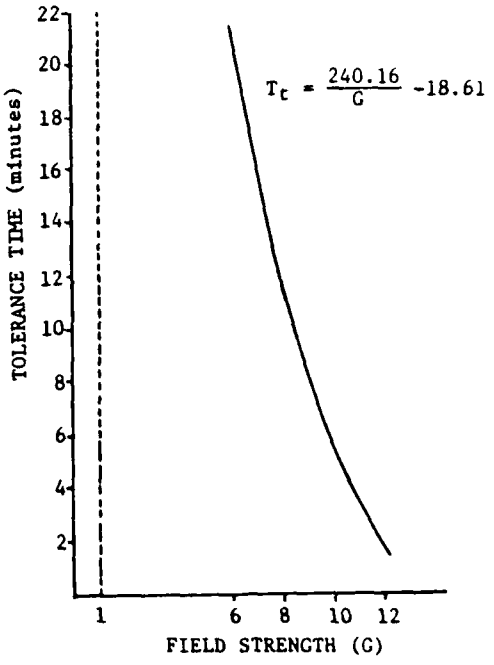

Figure 5. Hyperbolic regression of acceleration tolerance time on field strength.

Data presented were calculated from the mean acceleration tolerance for each bird (n = 16).

The significant hyperbolic relationship between field strength (G) and tolerance time (T_t, Figure 5) indicates that the product of time and intensity determines the effect, *i.e.*, the bradycardia:

$$G\,(T_t + 18.61) = 240.16$$

$$T_t = \frac{240.15}{G} - 18.61$$

These equations have been calculated between the limits of +6 and +12 G_z. Extrapolation of the values outside these limits is not necessarily valid. For example, the equation predicts that zero G can be tolerated for an infinite time, but 1 G can only be maintained for 221.6 minutes without bradycardia. Conversely +13 G_z is the predicted maximum G tolerated for a minimum time period.

Smith *et al.*, (45) discussed factors affecting tolerance limitations in Rhode Island Red chickens -- a large breed. They found that tolerance time is inversely related to age and body mass. In our experiment, animals were of similar body mass and all were hatchmates. The regressions determined for Rhode Island Red chickens would predict tolerance times of 5.9 and 9.4 minutes, based on age and body mass, respectively. These are much less than experimentally determined value of 21.4 minutes obtained for the smaller Leghorn chickens. Animal type has a marked effect on acceleration tolerance, and this must be considered when examining tolerance limitations to HSG_z.

Blood Gas

Arterial Oxygen Concentration (P_aO_2) and Hemoglobin Saturation (S_aO_2): The P_aO_2 and S_aO_2 values obtained at 1 G are slightly higher than the values from the literature. Besch *et al.*, (7) reported a P_aO_2 level in adult unanesthetized, single-comb White Leghorn cocks of 89.8 mm Hg. Kawashiro and Scheid (30) reported a value of 82 mm Hg as well as summarizing the values obtained in the literature for P_aO_2:

	P_aO_2
Chiodi and Terman, 1965	99
Frankel, 1965	88
Butler, 1967	99
Frankel and Franscella, 1968	92
Piiper *et al.*, 1970	87

With increasing field strength, there is a decline in P_aO_2, and this is summarized in Table 2. The linear regression of P_aO_2 on field strength is presented in Figure 6. Although P_aO_2 in chickens declines with increasing $+G_z$, the reduction in oxygen tension is much less than that reported for humans -- Figure 6 (8,16,34). The latter data, obtained by Michaelson (34), is summarized in Table 3, and Table 4 summarizes the blood gas data reported by Besch *et al.*, (8). The data of Michaelson and of Besch agree; arterial oxygen tension in humans falls significantly with increasing field strength. However, P_aO_2 values measured in chickens remain relatively high in similar fields. The mean P_aO_2 in chickens at +10 G_z for one minute is 91.1 mm Hg as compared to 75 mm Hg for man at +3 G_z.

TABLE 2. Mean P_aO_2, P_aCO_2 and calculated arterial pH values during 1 G, +6 G_z, +8 G_z and +10 G_z (mm Hg ± standard error).

	1 G	+6 G_z	+8 G_z	+10 G_z
(n)	(34)	(11)	(10)	(13)
P_aO_2	108.7 ±1.9	97.1 ±6.9	93.6 ±7.4	91.1 ±5.7
P_aCO_2	38.3 ±0.9	40.9 ±1.3	42.0 ±2.2	41.2 ±1.5
pH	7.44±0.007	7.42±0.009	7.42±0.013	7.42±0.008

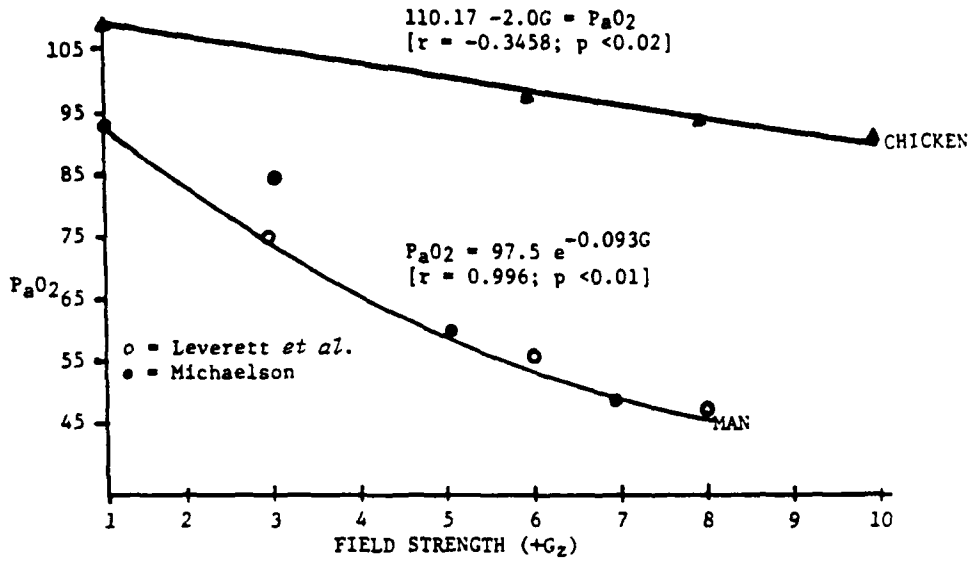

Figure 6. Linear regression of arterial oxygen tension (P_aO_2) on field strength for the chicken and P_aO_2 data from Michaelson (40) and Leverett *et al.* (31), for man.

TABLE 3. Mean values ± standard deviation of 9 men breathing air and exposed to 45 seconds of various levels of +Gz (reported by Burton *et al.*, 16).

	1 G	+3 G_z	+5 G_z	+7 G_z
P_aO_2	91.6 ±7.9	84.7 ±14.8	60.2 ±9.9	50.1 ±7.3
P_aCO_2	35.0 ±4.1	32.0 ± 4.0	32.1 ±3.0	33.2 ±2.0
pH	7.422±0.022	7.422± 0.036	7.444±0.025	7.418±0.034

TABLE 4. Measured P_aO_2, P_aCO_2, and pH of 5 sugjects determined for each experimental condition (reported by Besch *et al.*, 8) mean ± standard error.

	1 G	+3 G_z	+5 G_z	+7 G_z
P_aO_2	91.3 ±3.1	76.2 ±7.7	53.6 ±2.9	46.4 ±3.0
P_aCO_2	37.9 ±1.4	32.7 ±1.2	30.0 ±0.6	30.3 ±0.9
pH	7.410±0.004	7.466±0.013	7.474±0.011	7.450±0.019

The arterial hemoglobin saturation was calculated using the Hill equation (40); the relationship between field strength and S_aO_2 is presented in Figure 7. The relationship between S_aO_2 and field strength for chickens is consistent with the linear relationship reported by others for man:

Man (16)	$S_aO_2 = 99.0 - 1.59\ G$
Chickens	$S_aO_2 = 90.1 - 1.015\ G$

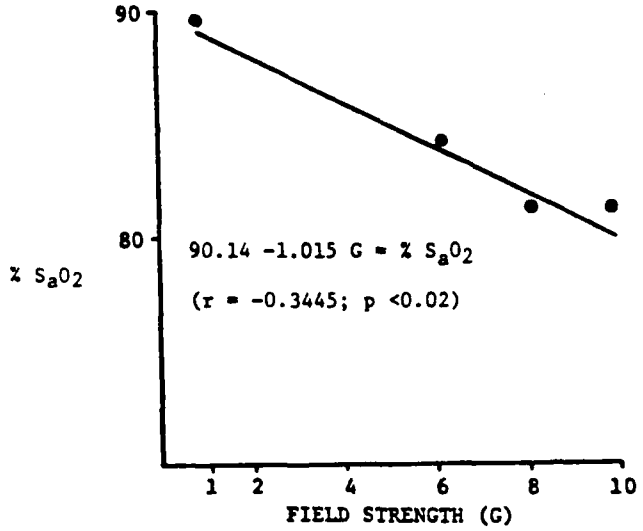

Figure 7. Linear regression of hemoglobin saturation (% S_aO_2) on field strength.

Increasing field strength has a greater affect on the change in saturation levels in humans than in chickens. However, the initial S_aO_2 in chickens (90.1) is much less than that for man.

Chickens exhibit a relatively low resting arterial oxygen saturation. An arterial saturation level of 88% for chickens is cited by Sturkie (48) which is comparable to our experimentally determined value of 90.7% arterial saturation at 1 G. Although arterial oxygen saturation is relatively low, oxygen availability is maintained due to the displacement of the O_2 dissociation curve of the blood to the right (38). Mixed venous blood in the chicken is 40 to 45% saturated (38). The characteristically low arterial saturation is not generally true for birds but is specific to chickens (14).

The reduction in arterial O_2 tensions during exposure to acceleration fields is resolved rapidly upon return to a 1 G environment. Ten minute postacceleration P_aO_2 values were determined and indicate recovery is complete since mean P_aO_2 value before and 10 minutes after acceleration exposure were not different.

O_2 Content: Oxygen content in the blood was calculated using the Hill equation (40) and standard parameters for chicken blood obtained from Sturkie's book (48 -- see appendix). Mean oxygen content of blood calculated at each field strength, are summarized in Table 5:

TABLE 5. Mean Oxygen Content (mmoles/L) ± Standard Error.

1 G Field (n=11)	+6 G_z Field (n=11)	Pre-acceleration (n=10)	+8 G_z Field (n=10)	Pre-acceleration (n=13)	+10 G_z Field (n=13)
3.2 ±0.09	2.6 ±0.36	3.0 ±0.13	2.8 ±0.16	3.5 ±0.08	3.2 ±0.14

The relatively higher oxygen content in the blood at +10 G_z as compared to that found at +6 G_z indicates a possible effect of multiple exposures, an experimentally induced reduction in hematocrit. In all cases, the order of acceleration exposures began with a +10 G_z exposure, followed by an +8 and +6 G_z exposure.

Barr (4) found a lower P_aO_2 upon multiple exposures of humans. Hematocrits were recorded throughout this experiment and were found to decline with duration of the experiment. Mean hematocrit values of 35, 30 and 29% were recorded at +10, +8 and +6 G_z, respectively. The method of blood sampling required that the sampling catheter be flushed periodically with heparinized saline, and this may have been a factor in the observed decline in hematocrit with continuing experimentation. The carotid cannulation procedure may have induced the observed reduction in hematocrit, as well. Student's t-test for paired variables indicated no statistical significance for differences between the Earth gravity control values for O_2 content and those obtained during exposure at any $+G_z$ field.

P_aCO_2 and C_aCO_2: The mean values for arterial carbon dioxide tension during $+G_z$ exposure are summarized in Table 2. The P_aCO_2 value of 38.3 mm Hg recorded at 1 G is slightly higher but within range of the values from the literature. Besch *et al.*, (7) reported a P_aCO_2 value of 34.1 mm Hg, while Kawashiro and Scheid (30) reported a value of 33 mm Hg. Burton *et al.*, (16) and Besch *et al.*, (8) reported a decline in P_aCO_2 values in humans during acceleration exposure, although the differences from preacceleration levels are very small. In contrast, P_aCO_2 values in birds show no significant changes during acceleration (Student's t-test paired data).

Burton *et al.*, (16) explain the observations seen in humans as being due to an increased respiratory rate, tidal volume and physiologic dead space. Increased ventilation alone would lower P_aCO_2.

In our experiments, respiratory frequency increased above Earth gravity control levels during acceleration exposure, but this increase was not proportional to the field strength and was highly variable. The unchanged P_aCO_2 values found during $+G_z$ exposure could reflect an increase in anatomical or physiological dead space and a reduction in ventilation.

C_aCO_2 was calculated from P_aO_2 and P_aCO_2 values using the Hill equation (40), and this is summarized in Table 6.

TABLE 6. Mean Calculated Arterial CO_2 Content (mmoles/L) ± Standard Error.

	1 G Field	+6 G_z Field	+8 G_z Field	+10 G_z Field
(n)	(34)	(11)	(10)	(13)
C_aCO_2	27.86±0.32	28.81±0.41	29.07±0.65	28.90±0.48

This lack of a sigmoidal dissociation curve, as exists for oxygen, simplifies the relationship between P_aCO_2 and C_aCO_2.

pH: The values obtained for pH are summarized in Table 2. Respiratory compensation most likely is involved in the regulation of pH. Very little change in pH occurs during acceleration exposure.

Heart Rate: Heart rate increases with the onset of acceleration. The rapid rise in heat rate may, in part, reflect movement, induced by excitement or be a direct effect of the acceleration. Heart rate begins to increase when the centrifuge mechanism is switched-on, before any movement occurs. Noise generated from the centrifuge appears to provide a stimulus for increasing

heart rate. Once the centrifuge begins to move, heart rate increases, even though the G level is low. As the final level of acceleration is reached, maximum heart rate is attained.

The initial rise in heart rate occurs regardless of previous acceleration exposures. Birds accelerated up to 9-times in one day displayed the initial tachycardia in every case.

The initial increase in heart rate is consistent with the results reported by Smith *et al.*, (46) for birds and by several investigators for man (16,29,37). It reflects a physiological reflex of an elevated heart rate to maintain arterial pressure. The acceleration-induced decrease in venous return caused by venous pooling promotes a decline in blood pressure, and heart rate increases, reflexly, to compensate from this hypotension.

At the end of the one-minute of acceleration, heart rates were more variable. Birds displayed higher, lower or the same heart rates as compared to preacceleration levels, but in all but one case, the heart rate recorded at the end of one minute exposure at +6, +8 and +10 G_z was lower than the initial heart rate. Heart rate changes reflect pressure variations occurring during acceleration. A summary of percent change from the resting heart rate at the beginning and end of a one minute acceleration exposure is presented in Table 7.

TABLE 7. % Change in Heart Rate (mean ± standard error).

+10 G_z		+8 G_z		+6 G_z	
initial	final	initial	final	initial	final
(n=13)	(n=13)	(n=10)	(n=10)	(n=11)	(n=11)
+39±6.9	+3±5.8	+32±9.8	+3±6.3	+47±9.3	+13±6.0

The lesser relative change in heart rate occurring after one minute of acceleration exposure indicates some mechanism other than elevated heart rate is predominately involved in maintaining blood pressure. Perhaps an increase in total peripheral resistance is primarily responsible for maintaining arterial pressure at this time.

As described in our discussion of methods, a bradycardia provides an acceleration tolerance endpoint, and a rate of 120-180 beats per minute (bpm) sustained for 3 to 5 seconds is the criterion. However, during the course of most acceleration exposures, heart rate varies. Occasionally, heart rate fell momentarily to 180 bpm or below, and such an occurrence was followed immediately by electromyographic (EMG) interferance on the EKG tracing. Concomitant with the EMG activity, noises could be heard from the centrifuge carriage indicating the bird was struggling. Immediately following the EMG activity, heart rate increased dramatically (Figure 8). Frequency of these bursts increased with the length of time of acceleration exposure. As the acceleration tolerance was approached, this activity increased. The appearance of the EMG activity and the subsequent elevation in heart rate indicates that the muscular effort increases venous return.

Straining efforts, such as employed by aviators, could aid the bird in maintaining venous return through the compressive effects of the skeletal muscle on the vascular bed. The venous capacitance would be reduced, venous return increased and heart rate reflexly elevated.

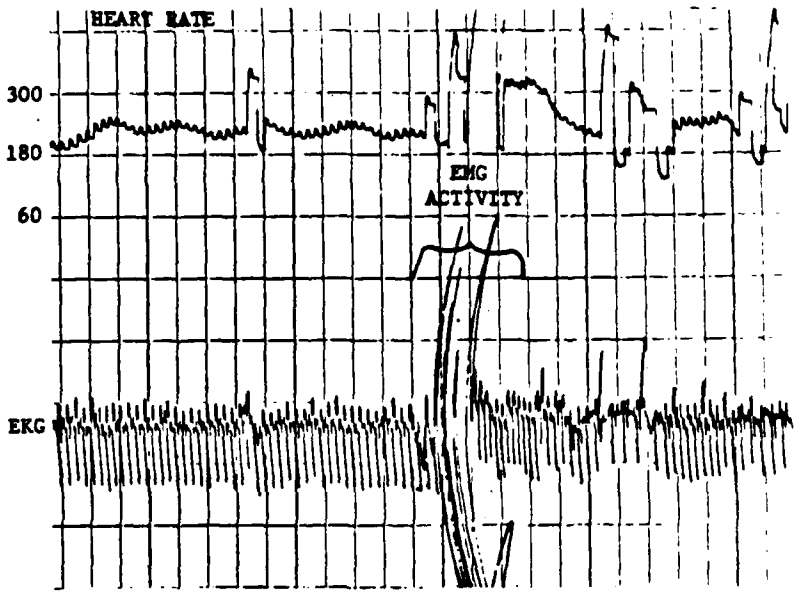

Figure 8. Heart rate showing EMG activity.

End-Tidal CO_2: In the nonventilated bird, end-tidal CO_2 concentrations reflect changes in several parameters: minute ventilation, concentration of CO_2 in mixed venous blood, ventilation-perfusion inequalities and cardiac output. Note the respiratory oscillations in CO_2 tracing (Figure 9). End-tidal CO_2 is related to the amount of blood perfusing in the lung (cardiac output), the relative perfusion of tissues displaying various metabolic rates (metabolism-perfusion inequalities), as well as a slight influence of the distribution of blood and gas flows within the lung ($\dot{V}/\dot{Q}$ inequalities).

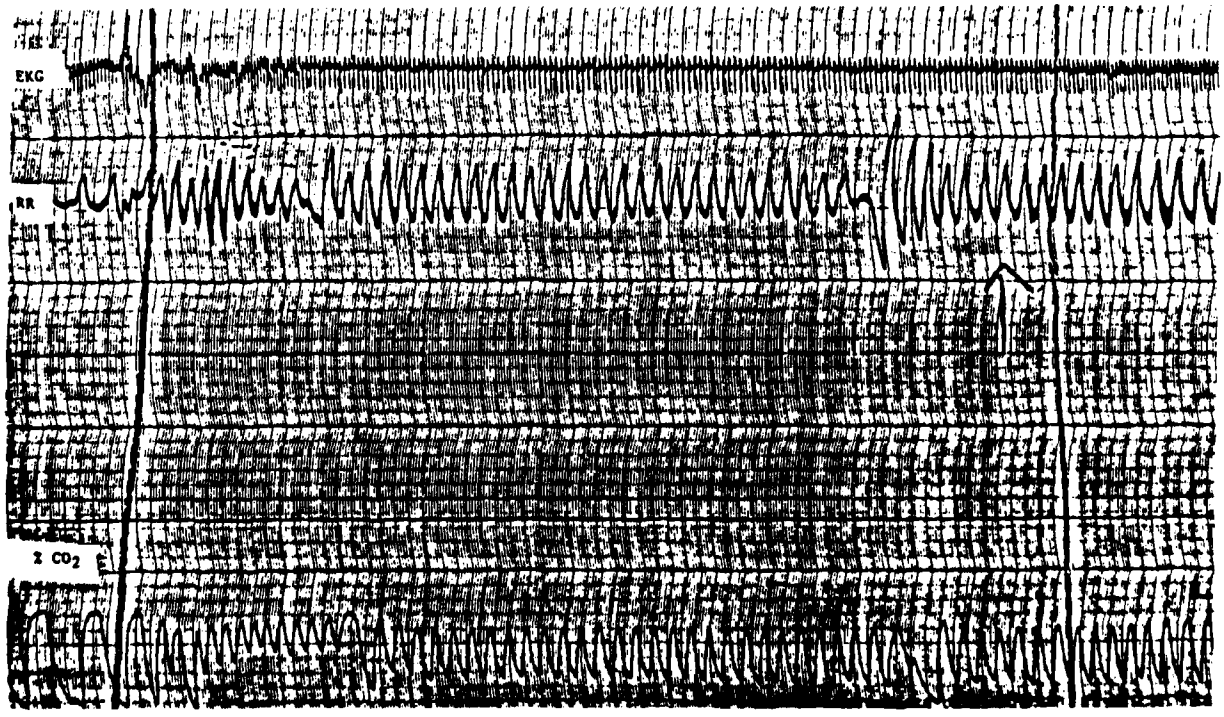

Figure 9. End-tidal CO_2 relationship to ventilatory frequency. Bird No. 1253, one minute at +10 G_z (nonventilated). EKG, respiratory rate (RR) and end-tidal CO_2 (% CO_2).

A transient fall in end-tidal CO_2 occurred with the onset of acceleration in the majority (53%) of birds at +10 G_z. Initial declines also occurred during exposure to +8 G_z (11%) and +6 G_z (36%). The reduction in end-tidal CO_2 most likely reflects a decreased cardiac output and not reduced ventilation; a nasal thermister recording tidal flow indicated that ventilation increased.

The CO_2 tracings did not show consistent changes during one minute acceleration exposures. The tracings showed an increase, decrease or no change in the percentage of CO_2 in the expired air. At +10 G_z, end-tidal CO_2 equally decreased or remained the same. At +8 G_z, end-tidal CO_2 remained the same (55%) or decreased (33%). End-tidal CO_2 increased (36%) or stayed the same (63%) at +6 G_z. The percent changes ranged from 0.5% to 7.0% change. The large variations of CO_2 in the expired air cannot be explained by ventilation-perfusion inequalities. The changes are much too large to reflect ventilation-perfusion abnormalities that would also generate observable changes in P_aCO_2 and P_aO_2. Respiratory flow was also recorded during periods of low CO_2 output, excluding hypoventilation as a cause of low end-tidal CO_2. Most of the changes observed in end-tidal CO_2 must have reflected changes in cardiac output and metabolism-perfusion inequalities. The observed changes in end-tidal CO_2 suggest that at +10 G_z little or no change occurs in the average ventilation-perfusion ratio and little or no increase develops in the metabolism-perfusion inequalities. With decreasing field strength, greater cardiac outputs and/or metabolism-perfusion inequalities must have been seen. At +8 G_z more birds show no change in end-tidal CO_2 than a decrease, and at +6 G_z, decreases in end-tidal CO_2 were not observed; in fact, 36% of the animals showed increased end-tidal CO_2 during acceleration.

End-tidal CO_2 increased in all but six trials (n = 34) after acceleration exposure. [In two birds at +6 G_z and four at +10 G_z end-tidal CO_2 did not change after return to 1 G.] In some cases, the change was as much as 2% above control values and 4% above acceleration values. The postacceleration elevation in CO_2 indicates an oxygen debt has been incurred. The higher end-tidal CO_2 postacceleration as compared to acceleration levels further suggests blood is not returning to the lungs from all peripheral tissues during acceleration.

Respiratory Frequency

Respiratory frequency increases during acceleration. The initial apneic period reviewed by Glaister (23) for man and reported by Barr *et al.*, (3) for dogs, in general, did not occur in chickens. With the onset of acceleration, respiratory rate increased. Chickens have no Hering-Breuer reflex which may explain the absence of the initial apneic period. Respiratory rate increased at all +G_z levels above 1 G control values, but the magnitude of the increase did not appear to be proportional to field strength. Respiratory rate remained elevated for minutes after acceleration exposure as expected from the high end-tidal CO_2 levels recorded.

Ventilated Birds

Acceleration Tolerance Time: The mean acceleration tolerance times for birds accelerated with and without 100% O_2 ventilation are presented in Table 8. No significant differences were found between ventilated and nonventilated acceleration tolerance times at +6 or +10 G_z. However, the difference between

ventilated and nonventilated tolerance time at +8 G_z were significant at the $p < 0.025$ level. At each field strength, two birds were excluded from the analysis; in each case, nonventilated tolerance times reached the maximum in 20 minutes. The experimental protocol did not allow measurements of acceleration tolerance time above the 20 minutes recorded for the nonventilated run, generating artifically low tolerance times.

TABLE 8. Mean Tolerance Time (minutes) ± Standard Error.

$+G_z$ Field	(n)	Nonventilated	Ventilated	
6	(5)	5.4 ± 1.6	6.4 ± 3.7	(ns)
8	(5)	7.3 ± 2.0	14.7 ± 3.2	($p < 0.025$)
10	(4)	3.9 ± 2.5	1.7 ± 0.45	(ns)

The lack of effect of ventilation on acceleration tolerance at +6 and +10 G_z indicates that ventilatory impairment does not contribute to acceleration limitations. It does not indicate that ventilation is unimpaired. At +6 G_z, ventilation has no effect on tolerance time, suggesting that either ventilation is unimpaired or it does not become a limiting factor. At +8 G_z, artificial ventilation improves acceleration tolerance; either a ventilatory impairment occurs, limiting acceleration tolerance or the increase in O_2 content carried in blood (provided by the 100% O_2) positively affects tolerance characteristics. In a field of +10 G_z, the lack of effect of artificial ventilation probably reflects a more severe cardiovascular limitation. The relatively short duration of acceleration tolerance supports this possibility.

Oxygen Ventilation

Respiratory Rate: Birds unidirectionally ventilated with 100% O_2 showed no spontaneous respiratory activity at rest. However, during acceleration exposure, respiratory oscillations developed in some birds (38% at +6, 83% at +8 and 71% at +10 G_z) and they began breathing movements during acceleration despite the fact that they were receiving an adequate O_2 supply and generally had depressed end-tidal PCO_2. The increase in respiratory activity may be caused by the excitement and/or a reduced blood pressure from the fall in cardiac output.

Blood Gas

Arterial Oxygen Tension (P_aO_2): Ventilating birds with pure oxygen results in an elevation of P_aO_2 levels over air-breathing controls. Mean values of P_aO_2 obtained from birds at Earth gravity, +6, +8 and +10 G_z are summarized in Table 9:

TABLE 9. P_aO_2 and P_aCO_2 from 100% O_2 Ventilated Birds (mean mm Hg ± standard error).

	1 G	+6 G_z	+8 G_z	+10 G_z
(n)	(21)	(7)	(7)	(7)
P_aO_2	488.4±14.6	459.4±38.6	435.5±66.7	439.2±42.6
P_aCO_2	28.7± 1.2	33.8± 2.2	35.3± 2.3	38.1± 4.1

Data obtained between 1 and +6 G_z, 1 and +8 G_z and 1 and +10 G_z were analyzed using Student's t-test for paired variables. With O_2 ventilation, the differences in P_aO_2 between any groups were not statistically significant. Acceleration-induced decreases in arterial saturation are eliminated with oxygen ventilation, indicating no pulmonary shunting occurs in the chicken lung during acceleration exposure.

P_aCO_2: P_aCO_2 increases with increasing field strength. The relationship between P_aCO_2 and field strength in the ventilated animals is presented in Figure 10:

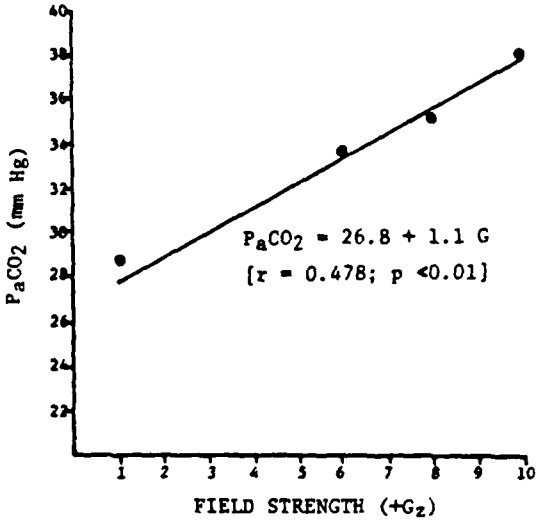

Figure 10. Linear regression of P_aCO_2 on field strength for the O_2 ventilated birds (n = 7).

The elevation in P_aCO_2 during simultaneous ventilation and acceleration, in part, reflects a 50% experimentally-induced shunt of CO_2 because only one lung was ventilated with pure O_2. The opposite lung was provided oxygen by diffusion, however, CO_2 from the nonventilated lung increases in the absence of convection. The increase in P_aCO_2 is seen only during acceleration exposure, suggesting the increase may be related to an increase in metabolism and/or perfusion changes generated during acceleration. An increased percentage of venous return from tissues with high metabolic rate would elevate P_aCO_2 without affecting P_aO_2. Elevation in P_aCO_2 could occur without an increase in end-tidal CO_2, since the nonventilated lung would be contributing little CO_2 content to the "expired" air.

C_aCO_2: C_aCO_2 was calculated, as in the nonventilated conditions, from the equations derived by Burger *et al.*, (15) and it reflects the observed elevation in arterial carbon dioxide tensions. The mean values for C_aCO_2 are presented in Table 10:

TABLE 10. C_aCO_2 Mean Values in mm Hg from O_2 Ventilated Animals.

	Preaccel-eration	+6 G_z	Preaccel-eration	+8 G_z	Preaccel-eration	+10 G_z
C_aCO_2	24.2	26.2	24.5	26.8	23.9	27.7
pH	7.50	7.47	7.50	7.46	7.51	7.44
(n)	(7)	(7)	(7)	(7)	(7)	(7)

pH: Mean values for calculated arterial pH before and during acceleration are summarized in Table 10. The progressive decrease in calculated arterial pH is a respiratory acidosis and related to the increased P_aCO_2. Respiratory reflexes that regulate pH in nonventilated birds are suppressed with 100% O_2 ventilation. Ventilation of both lungs could eliminate the respiratory acidosis. The effect of suppressing respiratory reflexes during acceleration becomes very apparent; the same birds accelerated at the same $+G_z$ level with reflex mechanisms functioning show a maintenance of constant arterial pH while in the ventilated, nonreflexive conditions, demonstrate a decrease in pH.

Heart Rate: Oxygen ventilation during acceleration exposure did not affect the changes in heart rate seen when the animals were nonventilated. Heart rate increased at the onset of acceleration and it either increased, decreased or stayed the same after one minute of acceleration exposure compared to pre-exposure conditions.

A summary of percent change of resting heart rate at the beginning and end of a one minute acceleration exposure is given in Table 11:

TABLE 11. Relative % Change in Heart Rate (mean ± standard error).

+10 G_z		+8 G_z		+6 G_z	
initial (%)	final (%)	initial (%)	final (%)	initial (%)	final (%)
+42±21	+2±8	+26±6	-0.3±5	+26±6	+6±5
(n=7)	(n=7)	(n=7)	(n=7)	(n=7)	(n=7)

The lesser relative change in heart rate after one minute of acceleration exposure was observed in nonventilated birds.

Expired CO_2: In the ventilated bird, changes in CO_2 content of expired air (which is comparable to end-tidal CO_2 in nonventilated birds) over a short time reflect changes in lung perfusion. Constant ventilation eliminates ventilatory impairments from affecting end-tidal CO_2. Any change in cardiac output would be evident in the end-tidal CO_2 concentration; a decrease in cardiac output reduces the amount of CO_2 delivered to the lung and CO_2 level in the expired gas. Changes in the distribution of venous return also would affect expired CO_2 levels. If, for example, tissues with a high rate of metabolism are subject to pooling, the CO_2 content in the returning venous blood would be depressed, while CO_2 in the tissue as a whole would increase or vice versa. The large relative changes in expired CO_2 are of interest in these experiments since they are so large that they probably reflect perfusional changes. In particular, a decrease in expired CO_2 to zero indicates severely depressed cardiac output. Lesser change may reflect decreased cardiac output as well as a reduction in perfusion to specific tissues giving rise to metabolism-perfusion changes.

A transient increase in expired CO_2 occurred in some birds at each $+G_z$ level; the increase occurred in 25% of the birds at +6 G_z, 25% of the birds at +8 G_z and in 10% of the birds at +10 G_z. This is in contrast to the transient declines observed in the end-tidal CO_2 of nonventilated animals. During the entire one minute acceleration exposures, CO_2 in the expired air could decrease, increase or stay the same. At the higher $+G_z$ fields, a decrease in end-tidal CO_2 predominated; 75% and 70% of the animals showed a decline in end-tidal CO_2 at +8 and +10 G_z, respectively, while only 38% showed a decline at +6 G_z. An

increase in CO_2 occurred in 10%, 13% and 25% of the animals at +10, +8 and +6 G_z, respectively. Thus, a progressive decrease in expired CO_2 occurs with increasing field strength, indicating a progressive decline in cardiac output with field strength. Expired CO_2 fell to zero in some birds at each $+G_z$ field. The percentage of birds displaying a severely depressed cardiac output increased with increasing field strength (13%, 38% and 40% at +6, +8 and +10 G_z, respectively). Most birds in which acceleration was continued until the tolerance bradycardia developed, demonstrated this fall (to zero) in expired CO_2 just prior to the onset of the bradycardia.

The compensatory increase in end-tidal CO_2 that occurs in the nonventilated bird following acceleration exposure is apparent in the ventilated bird, as well. An increase in end-tidal CO_2 postacceleration over the preacceleration levels was evident in 90%, 100% and 57% of the birds at +10, +8 and +6 G_z, respectively. Even with high O_2 content in arterial blood, an oxygen debt developed, suggesting that stagnant hypoxia developed during high $+G_z$ acceleration exposure.

Air Ventilated Birds

Birds unidirectionally ventilated with air through one lung have an experimentally-induced 50% perfusive shunt. Only one lung was ventilated convectively, while the other lung was taking up O_2, releasing CO_2 and increasing nitrogen content in the respiratory exchange region. In the O_2-ventilated bird, the nonventilated lung was being supplied with oxygen through diffusion ventilation, which is not possible in the air-ventilated birds. One would anticipate that acceleration would exaggerate this condition owing to the increase in O_2 demand as evidence by the postacceleration oxygen debt.

Blood Gas

P_aO_2, S_aO_2: Arterial oxygen tension declined during acceleration exposure. The fall in P_aO_2 was independent of $+G_z$ level (approximately 34% at each field strength). No proportionality is apparent between the magnitude of decline and field strength (summarized in Table 12).

Arterial hemoglobin saturation falls during acceleration exposure at all $+G_z$ fields tested. The decline is not proportional to field strength and approximates a 20% reduction from the preacceleration values at each field strength studied (summarized in Table 12).

P_aCO_2 and C_aCO_2: Arterial carbon dioxide increased during centrifugation. The increase is detected in the elevation of arterial CO_2 content. Both parameters increase the same amount from Earth's gravity controls at each $+G_z$ field. No proportionality exists between P_aCO_2 or C_aCO_2 and field strength during air ventilation (summarized in Table 12).

pH: We calculated the fall in pH during acceleration exposure. At the end of one minute of +6, +8 or +10 G_z exposure, the pH had a mean value of 7.45. The calculated control values did vary but, were not related to field strength (summarized in Table 12).

TABLE 12. Mean Values of Air Ventilated Birds (± standard error; n = 5).

	+6 G_z		+8 G_z		+10 G_z	
	Preaccel	Accel	Preaccel	Accel	Preaccel	Accel
P_aO_2 mmHg	102.8 ±9.1	66.8 ±5.9	104.0 ±9.4	68.4 ±5.7	108.6 ±11.9	73.8 ±8.1
P_aCO_2 mmHg	33.1 ±1.7	37.9 ±2.1	32.1 ±2.5	38.0 ±2.1	30.2 ±2.5	37.0 ±4.4
S_aO_2 %	88.0 ±3.0	71.9 ±7.4	88.1 ±3.8	68.9 ±6.3	88.3 ±5.0	72.0 ±7.6
O_2 cont. mmole/L	3.1 ±0.13	2.4 ±0.22	3.1 ±0.10	2.4 ±0.22	3.2 ±0.22	2.6 ±0.29
CO_2 cont. mmole/L	26.2 ±0.85	28.4 ±0.67	25.7 ±0.98	28.2 ±0.77	24.9 ±1.08	27.5 ±1.43
pH	7.47 0.01	7.44 0.01	7.47 0.01	7.45 0.02	7.49 ±0.02	7.47 ±0.03

Respiratory Rate

Air ventilation blocked normal respiratory activity during control periods (1 G). With the onset of acceleration, only 50% of the birds showed spontaneous respiration.

DISCUSSION

Critique of Methods

Centrifuge

The animal centrifuge used in these experiments is well designed for studies such as these. The animal carriage had one degree of freedom which exposed chickens to one vector -- the resultant vector from the centrifugal field and the Earth's gravitational field. The radius of rotation (7 ft) was large enough to prevent any excessive rotatory stimulation. The moderate onset rate (1.25 G/sec) introduces a small uncertainty into the time-intensity relationship, but since the duration of acceleration greatly exceeded the time necessary to generate the ultimate acceleration field, this is of little relative importance. The slowing of the centrifuge is initially quite rapid (47) providing a discrete termination to the acceleration exposure. However, total time needed for the centrifuge to stop completely is approximately 1.5 to 2 minutes. This long period delayed the analysis of the blood samples and increased the sampling error *via* diffusional changes in blood gas composition. The moderate onset rate and field-reduction rate does reduce vestibular stimulation and subsequent postural abnormalities. The centrifuge generates a great deal of noise during operation, in general, and specifically at the initiation of acceleration. The noise appears to have direct physiological effect on the chickens.

Respiratory Gases

Respiratory gases were sampled using nylon tubing from the animal carriage to the gas analyzer in the control room. Gases have a tendency to bind to the wall of the nylon tubing, dispersing the wave front slightly. Stainless steel tubing would have been an improvement in that wave front dispersion would be minimized and the total volume of the system might have been reduced. However, the CO_2 recordings were still good; the system generated only a three second delay because the tubing was evacuated. Accurate recordings were difficult to obtain during polypnea because of the damping occurring in the nylon tubing and the response of the LB-2. Therefore, the improvement in recordings utilizing stainless steel tubing would be only marginal without a better CO_2 analyzer.

Respiratory gas analysis should have included an O_2 analysis; however, equipment for this was not available.

Problems arose from gas sampling at the nostril. The cannula tip tended to plug with mucous from the nostril, and some uncertainty arose during polypnea as to whether or not the sample accurately reflected expired CO_2. During polypnea, the contribution of breathing through the mouth was unknown.

Blood Gas

Experimental error in blood gas determinations were generated from several areas. The extended delay time affected the blood gas concentrations, causing an increase in diffusional changes in gas concentrations as well as a greater utilization of oxygen by respiring erythrocytes. The polyethylene catheter was permeable to O_2 and CO_2 which resulted in a large loss of oxygen from the high P_aO_2 samples and some gain of oxygen in the samples whose P_aO_2 was less than atmospheric P_{O_2}. The fall in P_aO_2 in the high oxygen tension samples were calibrated and correction factors were utilized. However, the permeability increases the uncertainty of the true P_aO_2 levels. It would have been better to use stainless steel catheters pretreated with an inner layer of plastic to prevent blood coagulation which would otherwise occur when blood contacts rough steel surfaces. The stainless steel catheter would also require a suitable holding device during acceleration, so that the mass of the catheter does not tear the vessel.

In these experiments, pH was not measured. In retrospect, metabolic changes from underperfused tissues may have occurred in the one minute of exposure, affecting arterial pH. These measurements should be included in future experiments.

Respiratory Recordings

The nasal thermister, used to record respiratory rate, was sensitive but substantial artifacts were generated in the recordings during onset of acceleration and termination of exposure. In addition, quantitative measurement of ventilation was not possible using this method. Although it was convenient, a plethysmographic recording of ventilation would have been much better. Measurement of tidal volumes as well as respiratory frequency would have provided useful information as to the degree of ventilatory impairment induced by HSG_z.

Artificial Ventilation

The method used to artificially ventilate birds during acceleration required prior surgical intervention. The surgical stress had an unknown contribution to the physiological responses during HSG_z exposure. The caudal-cranial unidirectional ventilation from the abdominal air sac insured that one lung was ventilated in the normal direction. During ventilation with pure oxygen, the nonventilated lung was provided with ample oxygen by mass transport as can be seen from the high P_aO_2 values. CO_2 in the nonventilated lung, however, increases because of the lack of convection and results in an increase in P_aCO_2. During air ventilation, P_aO_2 in the ventilated lung is high but P_aO_2 in the nonventilated lung is low. With the onset of acceleration, the observed polypnea increases oxygen delivery to the nonventilated lung by an indeterminate amount. Air ventilation provided by plethysmographic pumping would generage adequate oxygen delivery to both lungs as well as provided quantitative information for the study of $\dot{V}/\dot{Q}$ relationships.

Tolerance Limitations

The duration of acceleration exposure was determined by the onset of bradycardia or limited to 20 minutes. At the outset of the experiments, 20 minutes was selected as the maximal exposure. Smith *et al.*, (45) utilized 20 minute acceleration exposure to +6 G_z in their studies on Rhode Island Red birds. Their data indicate that two-thirds of the population reach bradycardia within 20 minutes. Extension of acceleration exposures beyond that point would begin to involve other factors besides circulatory and respiratory function. Factors such as damage to the gut by prolonged circulation impairment, for example, could significantly affect acceleration tolerance on succeeding days. The 20 minute celing, however, was too short a duration for the White Leghorn birds. Being of lesser mass than the Rhode Island Red chickens, they had longer tolerances, and two-thirds of the population would not be included in a 20 minute ceiling. The limitation of acceleration exposure affected only the +6 G_z values significantly. Tolerance times for greater field strengths were generally well below 20 minutes.

Critique of Model

One of the primary objectives of this study was to study the responses of the chicken to HSG_z so that these might be compared to man. If comparable responses were found, then other investigators may be encouraged to use chickens as a animal model to separate components of the response to HSG_z. Human responses to HSG_z include arterial desaturation, hypocapnia, polypnea, initial tachycardia, reduced cardiac output, and bradycardia if the time-intensity of exposure is severe. The chicken shows great similarity in all these responses but the first two. Arterial desaturation in mammals is presumably caused by pulmonary distortion. It was predicted that specific responses related to pulmonary dysfunction generated by HSG_z would be absent in the chicken. There was no evidence that pulmonary dysfunction develops during HSG_z, so the chicken provides an excellent model of responses to HSG_z uncomplicated by pulmonary impairment. The lack of hypocapnia exhibited by the bird in HSG_z is probably related to specific intrapulmonary chemoreceptors which guard the animal against low intrapulmonary P_{CO_2}. These responses can be duplicated in the chicken by the procedure employed of ventilation could easily duplicate or even accentuate the changes in arterial blood gases noted spontaneously in humans exposed to HSG_z. Conversely, these changes can be reversed by ventilation with oxygen, giving investigators additional experimental control.

Blood Gas

In contrast to humans and other mammals, acceleration induces a relatively small decline in arterial saturation in birds. Pulmonary impairments that generate arterial desaturation in mammals are absent in accelerated chickens. The possible mechanism for reduced P_aO_2 and S_aO_2 are:

(1) a reduction of ventilation;
(2) the development of $\dot{V}/\dot{Q}$ inequalities and,
(3) the development of pulmonary shunts.

Many of the investigators studying arterial desaturation during HSG in mammals attribute the development of pulmonary shunts as the principle factor in arterial desaturation (5,22,24,35,49,51). They also agree that ventilation/perfusion inequalities will contribute to the desaturation. A reduction in ventilation is not involved in mammals since direct measurements indicate ventilation increases during acceleration exposure in man (16).

The decline in P_aO_2 and subsequent reduction in S_aO_2 seen in birds during acceleration is much less than that observed in humans. Figure 6 illustrates the relationship between the two species. The decline in P_aO_2 in birds most likely reflects a reduction in ventilation rather than the development of V/Q abnormalities or pulmonary shunts. Ventilation of these birds with pure O_2 blocked the decline in P_aO_2 with acceleration. However, this is not the case with man or dogs. Inhalation of 100% O_2 during a +5 G_z exposure did not block the decline in P_aO_2 in men (5). Breathing pure oxygen did delay the fall in saturation and reduced its severity. Barr *et al.*, (5) attributes the delayed decline in S_aO_2 during oxygen breathing to "gas trapping" in the alveoli. Airway closures develop during $+G_z$ exposure, but the oxygen within the "sealed-off" alveoli still contributes to blood oxygenation. Barr *et al.*, (5) suggest that in order to determine if pulmonary shunts develop, subjects must be exposed to acceleration fields for more than one minute during oxygen ventilation. His argument does not apply to birds, however. Birds have no alveoli and convection in the lung is continuous and unidirectional during O_2 ventilation. No gas trapping can occur in the avian lung. In addition, the volume of gas within the airways within the bird lung is relatively small; any underventilated areas that developed during acceleration would be indicated by a substantial decline in P_aO_2 within one minute exposure time. This decline did not occur, eliminating the possibility that pulmonary shunts develop during acceleration exposure of birds.

Burger *et al.*, (15) described a method for calculating the perfusive shunt (venous admixture) in the duck lung. Utilizing the equations from Burger *et al.*, (15), the fractional shunt was calculated for the chicken at 1, +6, +8 and +10 G_z. In the nonventilated bird, the calculated shunt will reflect reductions in ventilation and $\dot{V}/\dot{Q}$ abnormalities as well as pulmonary shunts:

$$f_Q = \frac{\alpha(P_i - P_a)}{\alpha(P_i - P_a) + (C_a - C_v)}$$

$\alpha = 0.00125$ [α = O_2 solubility in blood, from Scheipers (43)].

It was assumed venous blood was 45% saturated (Besch *et al.*, 7) and O_2 content was calculated in arterial and venous blood from the experimental hematocrits and P_aO_2 values. At 1 G, the perfusive shunt was calculated to be 2.11%. The value compares with the value obtained by Burger *et al.*, (15) of 2.7% for ducks. The shunt values calculated for the various acceleration fields were:

G Field	"% Venous Admixture"
1	2.11
6	4.43
8	4.01
10	3.95

As stated earlier, these values reflect a ventilatory impairment, if it exists, $\dot{V}/\dot{Q}$ inequalities, if they develop, and perfusive shunts around the gas exchange region. The relatively small increase in the calculated "venous admixture" suggests that no perfusive shunts or $\dot{V}/\dot{Q}$ inequalities develop during acceleration in the bird. Barr (4) calculated an effective shunt during +5 G_z exposure in man that was equal to one-fifth of the total cardiac output.

The lack of arterial desaturation during oxygen ventilation and acceleration exposure also indicates that no perfusive shunts developed in the bird. As oxygen ventilation abolishes $\dot{V}/\dot{Q}$ inequalities and reduces the effect of ventilatory impairments remain unknown.

P_aCO_2 increases while P_ECO_2 decreases in oxygen-ventilated animals during acceleration. An increase in cardiac output cannot account for the change in P_aCO_2 in that the PCO_2 of the expired air declines. The increase in P_aCO_2 may be caused by an increase in perfusion (over 1 G levels) to the nonventilated lung with a concommitant reduction in perfusion to the ventilated lung. The lack of convection in the nonventilated lung serves to increase CO_2 concentration in that lung which would result in an elevated P_aCO_2 if it were perfused. The P_aCO_2 values in the O_2 ventilated bird at 1 G are comparable to those in the nonventilated animal, suggesting that the nonventilated lung of the O_2 ventilated bird is being underperfused. Oxygen can be absorbed in the nonventilated lung normally by mass transport, but CO_2 excretion cannot occur. Thus, a mechanism is provided whereby mixed arterial P_{CO_2} increases despite constant P_aO_2.

Oxygen initially within the airways of the nonventilated lung is rapidly absorbed. Oxygen depletion and nitrogen elevation occurs in the nonventilated lung. In addition to these factors, CO_2 builds up in the airways of this lung as well. Blood gas values during air ventilation at 1 G do not indicate a substantial perfusive shunt, however. During acceleration exposure, P_aO_2 falls substantially at all $+G_z$ levels. The decline in P_aO_2 during air ventilation is significantly larger than the small decline in P_aO_2 seen in the nonventilated animals. This data again suggests the possibility that at 1 G in the ventilated bird, the nonventilated lung is underperfused while perfusion is high in the ventilated lung.

The lower percentage of birds exhibiting spontaneous respiration during air ventilation as compared to oxygen ventilation during acceleration may be attributable to the higher binding affinity of hemoglobin for CO_2 in the absence of oxygen (25). Lower CO_2 concentrations result in an increased firing frequency of intrapulmonary chemoreceptors within the lung and inhibit respiratory activity.

The significant decline in S_aO_2 of air ventilated birds as compared to non-ventilated birds during acceleration demonstrates the importance of $\dot{V}/\dot{Q}$ inequalities in determining arterial saturation. Artificial air ventilation during acceleration produced a $\dot{V}/\dot{Q}$ abnormality; one lung was perfused but not ventilated. The result of this induced $\dot{V}/\dot{Q}$ inequality was the reduction in arterial saturation to the levels recorded. The availability of an animal model which can give either no perfusive shunt or a perfusive shunt as large as occurs in man suggests its further use in understanding the role of arterial desaturation and acceleration physiology.

P_aCO_2 decreases somewhat during acceleration (8,16) in man. P_aCO_2 in spontaneously breathing birds increases slightly or does not change during acceleration. The decrease in P_aCO_2 in man reflects hyperventilation in acceleration. Barr (4) suggests that the increased ventilation is induced by hypotension. Respiratory frequency increases with acceleration in birds. The increased rate indicates an increase in dead space ventilation. The increase or lack of change in P_aCO_2 during acceleration clearly indicates that no hyperventilation occurs in the bird. The increase in respiratory frequency seen in chickens exposed to HSG_z may be stimulated by a hypotension. The possibility of a ventilatory impairment during $+G_z$ in birds is consistent with the P_aCO_2 data.

Heart Rate

Heart rate increases during acceleration in both humans and chickens. The frequency of heart rate in man is reflexly increased by hypotension. As systemic arterial pressure falls, heart rate increases. Systemic arterial pressure was not monitored in the birds, however, the heart rate changes occur in the same direction and time as is seen in man, suggesting a similar fall in blood pressure in chickens.

Chickens exhibit a severe bradycardia when acceleration exposures are maintained for durations near their lethal limits. Shubrooks (44) noted an acceleration bradycardia in humans exposed to +6.5 and +9 G_z. He postulated an increase in vasovagal activity leading to syncope that was generated by a reduced venous return. This reduction in heart rate is similar to the response seen in hypovolemic shock. Intraventricular mechanoreceptors may be involved in mediating the reflex slowing of the heart rate in mammals. Severe reductions in end-diastolic volume may trigger the bradycardia. Intraventricular receptors in birds are of only one type -- as compared to the two receptors that are found in mammalian hearts. Estavillo and Burger (19,20) characterized these end-net receptors within the wall of the ventricles and determined them to be CO_2-sensitive mechanoreceptors involved in the reflex control of heart rate in the maintenance of blood pressure. It is possible that these receptors are also involved in the development of bradycardia during acceleration. Birds develop subendocardial hemorrhages during $+G_z$ exposure (47) similar in pathology to those seen in miniature swine after acceleration exposure (17) and dogs during hypovolemic shock (28). The development of bradycardia in dogs in shock and in accelerated man and chickens suggests similar mechanisms may be involved.

Cardiac Output

Cardiac output in humans and dogs falls significantly during acceleration exposure (23,26,39,50). Wood *et al.*, (50) determined that the decline in cardiac output declined to 18% of preacceleration levels. In these experiments, changes

in cardiac output were indicated by changes in P_{CO_2} in the expired gas of oxygen ventilated birds. In most birds, cardiac output declined with acceleration exposure, and in some cases, fell to zero for several seconds. The fall in P_{CO_2} in the expired air occurred in spite of an elevation in heart rate and an increase in arterial P_{CO_2}, further substantiating the severe reduction in cardiac output. In experiments in which birds were accelerated to their tolerance end-points, the appearance of a zero cardiac output was often followed by the development of acceleration bradycardia. Transient declines in cardiac output were also seen in these birds. Straining behavior and subsequent elevation in heart rate were observed in some of these cases, which resulted in an increase in cardiac output. This straining behavior observed in chickens also occurs in pigs during acceleration (Burton, personal communication) and is similar to the M-1 maneuver that men utilize during $+G_z$ exposure.

These straining efforts increase venous return by reducing blood pooling in the venous side of the extremities. Nunnely (36) indicated that muscular exercise increases venous return during acceleration exposure by a muscle-pump mechanism. It appears that humans, pigs and chickens utilize similar mechanisms to maintain cardiac output and, hence, systemic arterial pressure.

Experimental Questions

Acceleration induces no significant pulmonary impairments in chickens. This response is in direct contrast to the substantial pulmonary dysfunction developed during acceleration exposure in mammals. The alveolar shunts, and ventilation-perfusion abnormalities generated by HSG_z exposure in mammals do not occur in birds. The slight reduction in arterial saturation that occurs during acceleration can be attributed to a reduction in ventilation.

The slight decline in P_aO_2 during HSG_z is blocked by artificial ventilation with oxygen, eliminating the contribution of a perfusive shunt in the development of the desaturation and further substantiating the possibility of a reduction in spontaneous ventilation. However, in general, ventilatory impairments generated by acceleration exposure do not appear to influence significantly tolerance characteristics in the chicken. The lack of affect of ventilation on acceleration tolerance time in birds at +6 and +10 G_z suggest ventilatory impairments do not affect tolerance limitations. The possibility exists that at +8 G_z, some ventilatory impairment may contribute to acceleration tolerance limitations. It seems plausible that at +6 G_z either no ventilatory impairment exists or the impairment is so small that it does not influence tolerance. At +8 G_z the ventilatory impairment may increase and contribute to tolerance characteristics. At +10 G_z, any ventilatory impairment generated by the acceleration field is masked by the overwhelming circulatory impairment; cardiovascular limitation determine tolerance characteristics at extreme (+10 G_z) acceleration fields. In any event, ventilatory impairments generated during acceleration exposure are easily eliminated through the use of unidirectional artificial ventilation of the bird. This preparation suffers no pulmonary impairment during HSG_z and can be used to study the effects of acceleration exposure on the circulatory system without the contribution of a pulmonary dysfunction. This isolation of circulatory function during HSG_z is not possible in any mammal.

The question still remains, however, "is the bird a good circulatory model for man during HSG_z exposure?" These studies indicate that although respiratory function at HSG_z differs substantially from mammals, many if not all, of the

responses are similar. Heart rate and cardiac output are affected and respond in a similar way in both birds and mammals. A major factor affecting human response to acceleration fields is that of the normal upright posture. Birds are one of the few animals that are normally bipedal, and have a proportionally similar head-heart orientation to that of humans. Circulatory adaptations to the upright posture would have common elements to those of humans.

The development of bradycardia during acceleration exposure appears to follow the same mechanism as observed in some human subjects exposed to HSG_z. The acceleration bradycardia resembles the bradycardia observed in orthostatic insufficiency (2) and in the late stages of hemorrhagic shock (28). In all of these cases effective circulating fluid volume is reduced; during shock the reduction occurs through the actual loss of circulating fluid and in orthostatic insufficiency and acceleration, extreme increase in venous pooling and reduction in venous return generate a functional reduction in circulating fluid volume. Similar cardiac pathologies are also generated in acceleration-exposed chickens and swine and in dogs subjected to hemorrhagic shock (28).

Much of the work of Bjurstedt *et al.*, (9,10,11) indicates that the peripheral vascular responses are substantially more important than cardiac responses in maintaining acceleration tolerance. Total peripheral resistance and venous capitance characteristics are of primary significance in physiological adjustments to HSG_z in humans, dogs and swine. Although there was no direct measurement of total peripheral resistance in these experiments, the observed reductions in heart rate after the initial tachycardia with acceleration onset suggest that peripheral resistance increased to maintain systemic arterial blood pressure. In addition, straining maneuvers performed by chickens during periods of reduce cardiac output resemble similar maneuvers performed by pilots during aerial combat maneuvers and pigs during HSG_z exposure. Increased muscular contractions from the legs of birds increase venous return by compressing the veins and decreasing their volume.

Other characteristics of birds make them a desirable animal model. Recently, the effects of prior conditioning (exercise) on acceleration tolerance have become of increasing interest. The influence of endurance training, specifically running, on acceleration tolerance has been examined (18) and continues to be explored. Chickens are runners, like man, and can be trained on a treadmill. Effects of preconditioning or no conditioning on acceleration tolerance can be studied using these animals. In addition, compound effects of exercise and various drug pretreatments can also be studied, providing valuable information that cannot be directly collected from human studies.

CONCLUSION

No significant pulmonary impairment occurs in the chicken during exposure to HSG_z. The lack of pulmonary dysfunction in addition to cardiovascular adjustments that are similar to those which occur in mammals make the chicken an excellent model for man in the study of circulatory function during HSG_z exposure.

REFERENCES

1. Abdalla, M. A., and A. S. King, 1975. The functional anatomy of the pulmonary circulation of the domestic fowl. Resp. Physiol. 23:267-90.

2. Allen, S. C., C. L. Taylor and V. E. Hall, 1945. A study of orthostatic insufficiency by the tiltboard method. Am. J. Physiol. 143:11-20

3. Barr, P.-O., H. Bjurstedt and J. C. G. Coleridge, 1959. Reflex control of respiration in the anesthetized dog during prolonged exposure to positive radial acceleration. Acta physiol. Scand. 47:1-15.

4. Barr, P. O., 1963. Pulmonary gas exchange in man as affected by prolonged gravitational stress. Acta physiol. Scand. 58 suppl. 207:1-46.

5. Barr, P.-O., J. Brismar and G. Rosenhamer, 1969. Pulmonary function and G-stress during inhalation of 100% oxygen. Acta physiol. Scand. 77:7-16.

6. Besch, E. L., 1966. Respiratory activity of avian blood cells. J. Cell. Physiol. 67:301-06.

7. Besch, E. L., R. R. Burton and A. H. Smith, 1971. Influence of chronic hypoxia on blood gas tensions and pH in the domestic fowl. Am. J. Physiol. 220:1379-82.

8. Besch, E. L., F. W. Baumgardner, R. R. Burton, K. K. Gillingham, R. R. McPherson and S. D. Leverett, Jr., 1978. Calibration of a new ear oximeter in humans during exposure to centrifugation. J. Appl. Physiol.:Respirat. Environ. Exercise Physiol. 44(3):483-87.

9. Bjurstedt, H., G. Rosenhamer and G. Tydén, 1974. Acceleration stress and effects of propranolol on cardiovascular responses. Acta physiol. Scand. 90:491-500.

10. Bjurstedt, H., G. Rosenhamer and G. Tydén, 1975. Cardiovascular responses to change in carotid sinus transmural pressure in man. Acta physiol. Scand. 94: 497-505.

11. Bjurstedt, H., G. Rosenhamer and G. Tydén, 1976. Gravitational stress and anatomic cardiac blockade. Acta physiol. Scand. 96:526-31.

12. Bouverot, P., 1978. Control of breathing in birds compared with mammals. Physiol. Rev. 58:604-55.

13. Burger, R. E., and F. W. Lorenz, 1960. Artificial respiration in birds by unidirectional flow. Poultry Sci. 39:236-37.

14. Burger, R. E., and J. A. Estavillo, 1977. Pulmonary circulation-vertebral venous interconnections in the chicken. The Anatomical Rec. 188:39-44.

15. Burger, R. E., M. Meyer and W. Graff, 1979. Gas exchange in the parabronchial lungs of birds: Experiments in unidirectionally ventilated ducks. Res. Physiol. 36:19-37.

16. Burton, R. R., S. D. Leverett, Jr., and E. D. Michaelson, 1974. Man at high sustained $+G_z$ acceleration: A review. Aerospace Med. 45(10):1115-36.

17. Burton, R. R., and W. F. MacKenzie, 1976. Cardiac pathology associated with high sustained $+G_z$. I. Subendocardial hemorrhage. Aviat. Space Env. Med. 47(7):711-17.

18. Cooper, K. H., and S. D. Leverett, Jr., 1966. Physical conditioning versus $+G_z$ tolerance. Aerospace Med. 37(5):462-65.

19. Dale, W. F., and H. Rahn, 1952. Rate of gas absorption during atelectasis. Am. J. Physiol. 170:606-15.

20. Duncker, H.-R., 1972. Structure of avian lungs. Resp. Physiol. 14:44-63.

21. Fedde, M. R., 1976. Respiration. Ch. 6 in: *Avian Physiology*. P. D. Sturkie, ed. Springer-Verlag (New York).

22. Glaister, D. H., 1968. Transient changes in arterial oxygen tension during positive ($+G_z$) acceleration in the dog. Aerospace Med. 39:54-62.

23. Glaister, D. H., 1970. The effects of gravity and acceleration on the lung. AGARDograph 133. England Technivision Services.

24. Glaister, D. H., 1977. Effect of Acceleration. In: *Regional Differences in the Lung*. J. B. West, ed. Academic Press (New York) pp. 323-380.

25. Henning, B., P. Scheid and J. Piiper, 1971. Determination of the Haldane effect in chicken blood. Resp. Physiol. 11:279-84.

26. Howard, P., 1959. Changes in the cardiac output during positive radial acceleration. J. Physiol. (London) 147:49P.

27. Hughes, J. M. B., J. B. Glazier, J. E. Maloney and J. B. West, 1968. Effect of extra-alveolar vessels on distribution of blood flow in the dog lung. J. Appl. Physiol. 25:701-12.

28. Jones, C. E., E. E. Smith, E. DuPont and R. D. Williams, 1978. Demonstration of nonperfused myocardium in late hemorrhagic shock. Circ. Shock 5: 97-104.

29. Jongbloed, J., and A. K. Noyons, 1934. Der Einfluss von beschleunigungen auf den Kreislaufapparat. Pflüg. Arch. ges Physiol. 233:67-97.

30. Kawashiro, T., and P. Scheid, 1975. Arterial blood gases in undisturbed resting birds: Measurements in chicken and duck. Resp. Physiol. 23:337-42.

31. Leverett, S. D., Jr., R. R. Burton, R. J. Crossly, E. P. Michaelson and S. J. Shubrooks, Jr., 1973. Human physiological responses to high sustained $+G_z$ acceleration. USAF SAM-TR-73-21. School of Aerospace Med. (Brooks AFB, Texas).

32. Lorenz, F. W., R. E. Burger, E. B. Bennett and W. Reinmann, 1962. Hepatic and renal effects on potency of estrogenic stilbene derivatives in chickens. Endocrinology 71:649-56.

33. Magnussen, H., H. Willmer and P. Scheid, 1976. Gas exchange in air sacs: Contribution to respiratory gas exchange. Resp. Physiol. 26:129-46.

34. Michaelson, E. D., 1972. Blood oxygenation in man during high sustained $+G_z$. Aerospace Med. Preprints 89-90.

35. Nolan, A. C., H. W. Marshall, L. Cronin, W. F. Sutterer and E. H. Wood, 1963. Decreases in arterial oxygen saturation and associated changes in pressures and roentgenographic appearance of the thorax during forward ($+G_x$) acceleration. Aerospace Med. 34:797-813.

36. Nunneley, S. A., 1976. Gas exchange in man during combined $+G_z$ acceleration and exercise. J. Appl. Physiol. 40:491-95.

37. Parkhurst, M., S. D. Leverett, Jr., and S. J. Shubrooks, Jr., 1972. Human tolerance to high sustained $+G_z$ acceleration. Aerospace Med. 43(7):708-12.

38. Piiper, J., F. Drees and P. Scheid, 1970. Gas exchange in the domestic fowl during spontaneous breathing and artificial ventilation. Resp. Physiol. 9:234-45.

39. Rosenhamer, G., 1967. Influence of increased gravitational stress on adaptation of cardiovascular and pulmonary function to exercise. Acta physiol. Scand. 68 Suppl. 276.

40. Roughton, F. J. W., 1964. Transport of Oxygen and Carbon Dioxide. Ch. 31 in: *Handbook of Respiration.* W. O. Fenn and H. Rahn, eds. Am. Physiol. Soc., Washington, D. C. Waverly Press (Baltimore).

41. Scheid, P., and J. Piiper, 1971. Direct measurement of the pathway of respired gas in duck lungs. Resp. Physiol. 11:308-14.

42. Scheid, P., and T. Kawashiro, 1975. Metabolic changes in avian blood and their effects on determination of blood gases and pH. Resp. Physiol. 23 291-300.

43. Scheipers, G., T. Kawashiro and P. Scheid, 1975. Oxygen and carbon dioxide dissociation of duck blood. Resp. Physiol. 24:1-13.

44. Shubrooks, S. J., Jr., 1972. Changes in cardiac rhythm during sustained high levels of positive ($+G_z$) acceleration. Aerospace Med. 43:1200-06.

45. Smith, A. H., W. L. Spangler, J. M. Goldberg and E. A. Rhode, 1979. Tolerance of domestic fowl to high sustained $+G_z$. Aviat. Space Env. Med. 50:120-25.

46. Smith, A. H., W. L. Spangler, B. Carlisle and G. Kinder, 1979. Effects of brief exposure of domestic fowl to very intense acceleration fields. Aviat. Space Env. Med. 50:126-33.

47. Smith, A. H., E. A. Rhode and W. L. Spangler, 1979. Cumulative aspects of repeated HSG exposure. USAF-SAM-TR-79-17. USAF Chool of Aerospace Med. (Brooks AFB, Texas).

48. Sturkie, P. C., 1954. *Avian Physiology*. Comstock Publ. Assoc. (Ithaca, New York). 1976 Third Ed. Springer-Verlag (Heidelberg).

49. Vandenberg, R. A., A. C. Nolan, J. H. Reed, Jr., and E. H. Wood, 1968. Regional pulmonary arterial-venous shunting caused by gravitational and inertial forces. J. Appl. Physiol. 25:516-27.

50. Wood, E. H., W. F. Sutterer, H. W. Marshall, E. F. Lindberg and R. N. Headley, 1961. Effect of headward and forward acceleration on the cardiovascular system. Tech. Rpt. 60-634. USAF, Wright Air Develop. Div. (Wright-Patterson AFB, Ohio) pp. 48.

51. Wood, E. H., A. C. Nolan, D. E. Donald and L. Cronin, 1963. Influence of acceleration on pulmonary physiology. Fed. Proc. 221024-34.

APPENDIX

Determination of hemoglobin saturation, O_2 content, pH, and CO_2 content

The following calculations were made from the experimentally collected data of P_aO_2, P_aCO_2 and hematocrit. Other values necessary for the calculations but not experimentally determined were obtained from the literature.

1. Calculation of C_aCO_2 (CO_2 content in arterial blood) from P_aCO_2:

$$C_aCO_2 = (1-Y)(b_{1t}+m_{1t}/P_aCO_2)^{-1} + Y(b_{2t}+m_{2t}/P_{CO_2})^{-1}$$

[Haldane effect; best fit approximation of avian blood data (Henning *et al.*, 25).]

where: Y = arterial hemoglobin saturation (initial guess 100%)

b_{1t} = 0.0211 $\quad$ b_{2t} = 0.020

m_{1t} = 0.484 $\quad$ m_{2t} = 0.612

[From R. E. Burger, personal communication.]

2. Calculation of $[HCO_3^-]$:

$$[HCO_3^-] = C_aCO_2 - 0.03\ P_aCO_2$$

3. Calculation of pH:

$$pH = 6.07 + \log_{10}([HCO_3^-]/0.03\ P_aCO_2)$$

[Henderson-Hasselbach equation.]

4. Calculation of P_{50}:

$$\log_{10} P_{50} = 4.96 - 0.445\ pH$$

where: P_{50} = partial pressure of O_2 in blood at 50% saturation.

[Bohr effect; influence of pH on hemoglobin affinity for oxygen (Scheipers, 43).]

5. Calculation of P'_{O_2} (partial pressure of O_2 in blood at standard conditions):

$$P_{O_2}/P'_{O_2} = P_{50}/P'_{50}$$

where: $P'_{50} = 41.7$

[Hemoglobin dissociation relation.]

6. Calculation of hemoglobin saturation:

$$\log_{10} [Y/(1-Y)] = \log_{10} k + n \cdot \log_{10} P'_{O_2}$$

where: Y = hemoglobin saturation
k = 0.0000229
n = 2.9

[Hill equation (Roughton, 40).]

7. Calculation of O_2 content:

$$C_aO_2 = O_2 \text{ capacity} \cdot Y$$

where: O_2 capacity = mmoles O_2/liter blood

The following values were obtained from Sturkie (48) to determine O_2 capacity:

Standard hematocrit	48%	(page 59)
Hemoglobin/100 ml blood	9.2 g	(page 63)
mmoles O_2/g Hb	0.060	(page 134)

$$O_2 \text{ capacity} = \left(\frac{92 \text{ g/L blood}}{48}\right) \cdot Hct \cdot (0.060 \text{ mmoles/g Hb})$$

where: Hct = experimental hematocrit.

Fractional hemoglobin saturation was calculated iteratively using a Texas Instruments programmable calculator. The program included the above equations and utilized the values for P_aO_2, P_aCO_2 and O_2 capacity to initialize. The initial guess for arterial hemoglobin saturation was 100%. Absolute error in hemoglobin saturation was less than 10^{-6}.