Systemic and Pulmonary Hemodynamic Changes Accompanying Thermal Injury

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THE PULMONARY response to nonthoracic trauma has been the subject of much discussion and speculation and is not well understood. Congestive atelectasis,[8] fat embolism,[4] and wet lung[10] are some of the names that have been given to the pulmonary problems occurring after trauma. Pulmonary complications are common sequelae of thermal trauma[12] and are significant sources of morbidity and mortality. Many of these complications occur during the first postburn week and are manifested by a poorly understood respiratory distress syndrome, hyperventilation, interstitial pulmonary edema or pneumonitis. This study evaluates the pressure and resistance changes across the pulmonary vascular bed subsequent to thermal trauma and compares these with the concurrent changes in the systemic circulation. The influence of two different fluid resuscitation regimens on circulatory hemodynamics was also evaluated. These studies were performed in unanesthetized dogs.[1] Gross and microscopic observations of the pulmonary vascular bed and electron microscopic studies of the lung were also made on selected dogs.

Methods

Conditioned, adult, mongrel dogs, weighing from 14 to 19 Kg., were used as study subjects. Number 8 French polyethylene feeding tubes were placed percutaneously into the main pulmonary artery, the left atrium, the aortic arch and the terminal superior vena cava and left indwelling (Fig. 1). This was done under fluoroscopic guidance 24 hours prior to burning, using Ketamine anesthesia, occasionally supplemented by a short-acting barbiturate, sodium methohexital. The next day, preburn blood samples for arterial hematocrit, pH, P_{CO_2}, P_{O_2} and mixed venous pH, P_{CO_2}, P_{O_2} and lactic acid were drawn from the aortic and pulmonary artery catheters respectively. Duplicate preburn cardiac output measurements were made along with simultaneous measurements of pulmonary artery, left atrial and systemic arterial pressures. Cardiac output was determined by a dye dilution technic using indocyanine green, the details of which have been reported previously.[11]

Arterial and venous pH, P_{CO_2} and P_{O_2} were measured using the Instrumentation Laboratory blood gas analyzer. Lactic acid was measured by the method of Ellis *et al.*[6] The pulmonary artery and left atrial cannulae were attached to the positive and negative sides of a differential pressure transducer (Sanborn model 268B) to measure the pressure difference across the pulmonary vascular bed. This difference was verified by independently measuring the left atrial and pulmonary arterial pressures on one side of the transducer and subtracting the former from the latter. The aortic cannula was attached to a Statham transducer to measure arterial pressure. Pressures and heart rate were recorded on a Sanborn four-channel recorder (model 964). The positions of all cannulae were confirmed at the time the animals were sacrificed. After these measurements had been performed, all animals were anesthetized for 10 to 20 minutes with sodium methohexital during which time they were shaved and subjected to a 40 to 45% scald burn (12 seconds in water at 99° to 100°C). The area

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In conducting the research described in this report the investigators adhered to the "Guide for Laboratory Animal Facilities and Care" as promulgated by the Committee on the Guide for Laboratory Animal Facilities and Care of the Institute of Laboratory Animal Resources, National Academy of Sciences—National Research Council.

of the body burned was the entire back and portions of the flanks and upper legs. The animals recovered from anesthesia in 45 to 90 minutes and were randomly divided into four groups of six each: (1) control unburned; (2) burned nonresuscitated; (3) burned and resuscitated with Plasmanate; and (4) burned and resuscitated with Ringer's lactate. The volume of Ringer's lactate or Plasmanate used was 2 cc./kg. body weight per per cent burn (90 ml./Kg.) in the first 24 hours, half being given in the first 8 hours and the remainder in the next 16 hours. Half this volume was administered at a constant rate during the second 24 hours and each dog was allowed to drink one liter of water per day. Measurements of cardiac output, pulmonary arterial, left atrial and systemic arterial pressure were made prior to beginning fluid administration (approximately 90 minutes after burning) and were repeated at 4 and 6 hours postburn and then every 6 hours until the animals were sacrificed at 48 hours. Arterial hematocrit, P_{CO_2} and P_{O_2} and mixed venous lactic acid, pH, P_{CO_2} and P_{O_2} were measured at the same time intervals. The dogs were sacrificed 48 hours postburn by injecting a bolus of potassium chloride mixed with a suspension of carbon particles into the superior vena cava. A template of the burned area was drawn and the surface area was measured with a planimeter; the per cent of total body surface burned was then calculated. Full thickness cutaneous necrosis was confirmed by histologic examination.

Results

All data were expressed as per cent of preburn value using the preburn determination as 100%. Pulmonary arterial, left atrial and systemic arterial pressures were expressed as mean pressure. The results shown in the graphs reflect mean values plus or minus the standard error of the mean. Resistance data were calculated by dividing mean systemic arterial pressure, or mean pulmonary artery minus mean left atrial pressure, by cardiac output. Systemic central venous pressure was not taken into account in calculating systemic resistance because of its negligible contribution.

Cardiac output. Cardiac output 90 minutes after burning and prior to resuscitation was between 55 and 60% of preburn value in all three groups of burned animals (Fig. 2). A rapid rise was observed thereafter in the Plasmanate resuscitated group so that cardiac output returned to preburn levels between 4 and 6 hours postburn, became significantly higher than preburn levels at 12 hours postburn, and remained so until the end of the 48-hour period. Both the Ringer's lactate resuscitated dogs and the non-resuscitated burned dogs had a much slower return of cardiac output to preburn levels, the former returning to normal at 24 hours and the latter at 30 hours. Ringer's lactate resuscitation produced a supernormal cardiac output 30 hours postburn

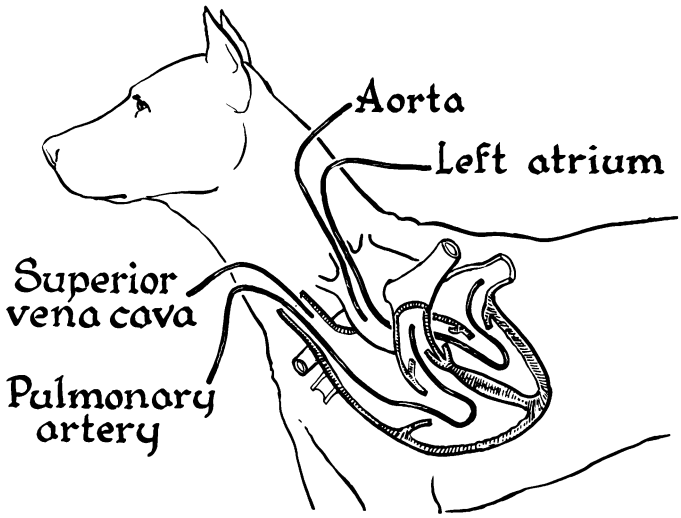

FIG. 1. Diagram illustrating placement of cannulas.

while the burned dogs that were not resuscitated maintained a cardiac output near preburn levels from 30 to 48 hours postburn. Cardiac output in the non-burned, control dogs remained stable throughout the 48 hours of observation.

Pulmonary and Systemic Resistance. Pulmonary and systemic resistances were calculated and tabulated separately for each of the three groups of burned dogs. In analyzing these data there was no consistent difference among the three groups. There was, however, a disproportion between pulmonary and systemic resistance changes in all burned dogs (Fig. 3). Mean pulmonary resistance rose to 211% of preburn values 2 hours after injury and gradually fell to preburn levels at 42 hours postburn. Mean systemic resistance rose to 181% 2 hours postburn and returned to preburn values 18 to 24 hours postburn. This difference between pulmonary and systemic resistance change was observed throughout most of the experiment.

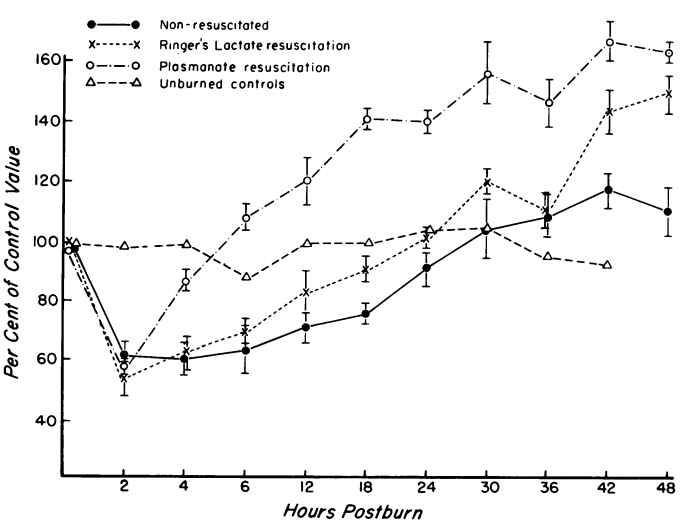

FIG. 2. Change in cardiac output resulting from burn and the influence of Plasmanate and Ringer's lactate fluid resuscitation.

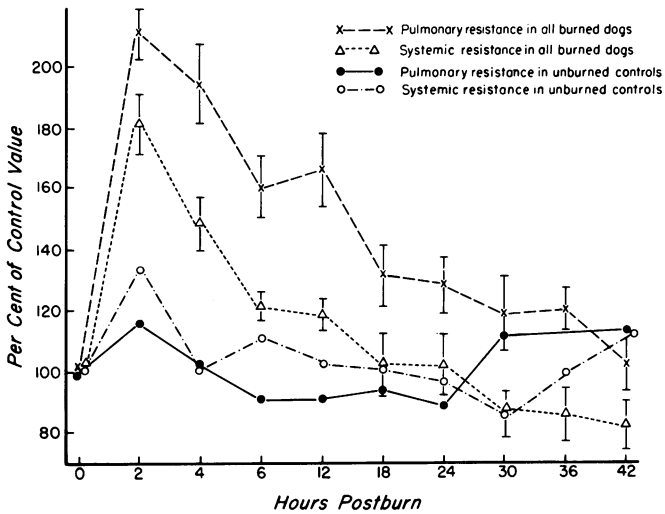

FIG. 3. The effect of thermal injury and resuscitation regimens on pulmonary and systemic vascular resistance compared to changes of resistances in unburned animals.

Pulmonary arterial, left atrial and systemic arterial pressure.

Systemic arterial pressure was relatively stable in all animals. In the resuscitated animals, an elevation of pulmonary arterial pressure occurred with little change of left atrial pressure, increasing the transpulmonary pressure gradient (Fig. 4). In the non-resuscitated animals, both pulmonary arterial and left atrial pressures decreased, with maintenance of a normal transpulmonary pressure gradient despite decreased flow.

pH, P_{CO_2}, P_{O_2} and Lactic Acid Measurements. Analysis of serial arterial and mixed venous pH, P_{CO_2} and P_{O_2} failed to reveal any consistent characteristic change. A decrease in pH and P_{O_2} in the pulmonary arterial blood occurred only occasionally and there was no correlation between these decreases and elevation of pulmonary arterial pressure. Lactic acid was elevated in only a few isolated instances throughout the experiment.

Burn Size. Burn size varied in each group from 37 to 46% of the total body surface. The mean burn size was 41% of the total body surface in the burned non-resuscitated dogs, 40% in the burned, Ringer's lactate resuscitated dogs, and 41% in the burned Plasmanate resuscitated dogs.

The lungs of burned dogs with or without resuscitation appeared more fully perfused than the nonburned. The latter often demonstrated segments of lung that were less dark than adjacent lobules due to variability in distribution of the carbon suspension. Although the lungs of the burned animals appeared darker throughout, the degree of alveolar capillary congestion did not vary by light microscopy among the four groups studied. There was marked variability of carbon distribution between areas of lung sampled and between animals.

Ultrastructural observations revealed alveolar lining cells, granular pneumocytes and pulmonary capillary endothelial cells to be intact in all groups. The interstitial compartment in the thick portion of the alveolocapillary membrane was generally compact. An isolated focus of interstitial dissection by edema and a few interstitial carbon particles were seen in two resuscitated dogs, the significance of which is uncertain. No edema or hemorrhage was apparent by light microscopy in any of the four groups.

Discussion

The merits of different fluid resuscitation regimens in burn shock have been debated at length. The criteria for an ideal fluid regimen are difficult to delineate and it is apparent that a variety of methods of fluid therapy will permit survival, keep patients out of clinical shock and evoke adequate urine output. Restoration of cardiac output would seem to be an important factor and the early restoration of cardiac output with Plasmanate resuscitation in this experiment is of interest and corroborates the earlier work of Moncrief done in anesthetized dogs.[11] Transcapillary leakage of protein and the inability of others[13] to show an increase in plasma volume with colloid administration seem to rule out a simple volume effect.

There is evidence that a myocardial depressant exists in both burn and hemorrhagic shock.[3,16] It is possible that plasma binding of such a factor by Plasmanate could account for earlier restoration of cardiac output in these animals.

The current report is the first study of pressure and resistance changes in the pulmonary vascular bed in burn shock. The disproportionately greater increase of pulmonary resistance than of systemic resistance is similar to the findings of Cook and Webb[5] in hemorrhagic

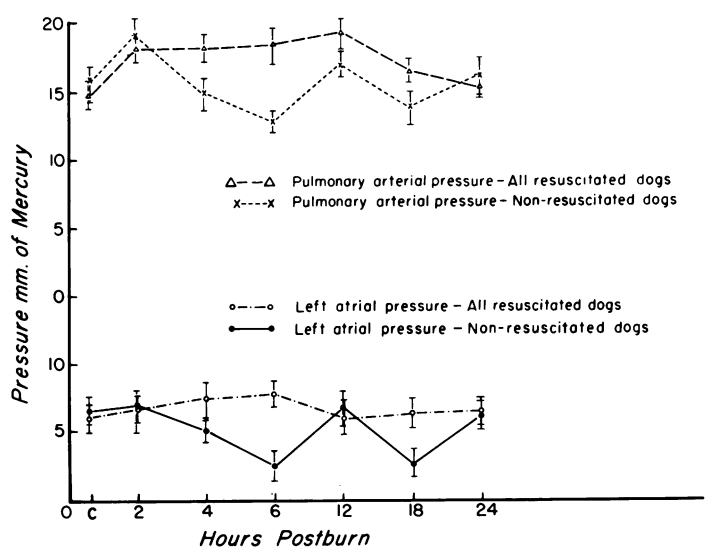

FIG. 4. The effect of thermal injury on pulmonary arterial and left atrial pressure and the difference between no resuscitation and fluid resuscitation.

shock. This may be accounted for by a disproportionate increase in pulmonary arterial vasoconstriction. Decrease in pH and decrease in oxygen tension of pulmonary arterial blood are known to produce pulmonary arterial vasoconstriction[7] but were not factors in the current experiment. A number of vasoactive agents are known to influence the pulmonary circulation[15] and may play a part in the observed elevation of pulmonary arterial pressure. Another possibility, described by West,[17] is that the observed rise in transpulmonary resistance is due to increased mean intra-alveolar and interstitial pressure due to hyperventilation, which occurs following burns[2] and other trauma.[9]

The very occasional lactic acid elevation agrees with a recent clinical study[18] but is at variance with previous work in the anesthetized dog.[11] This is probably explained by better perfusion in the conscious animals.

The gross appearance of the lungs in burned animals is consistent with an increase in pulmonary blood volume as reported in similar studies by Cook.[5] No differences were noted by light microscopy among the four groups studied but small differences would have been obscured by the marked variability in alveolar capillary congestion between areas and also by compression of alveolar capillaries in all groups by intratracheal instillation of fixative under pressure. Light microscopic lung changes following hemorrhagic shock have also been inconsistent.[19]

Ultrastructural pulmonary alterations which have been described in hemorrhagic shock in canine models include interstitial edema and swelling of alveolar epithelium, granular pneumocytes and endothelial lining cells.[14] The interstitial compartment of the lungs in the burned animals, whether resuscitated or not, remained intact for the most part, although rare isolated foci of interstitial edema were found associated with extravasation of particulate carbon in some of the resuscitated animals. In contrast to the ultrastructural cellular changes noted in hemorrhagic shock, no edema or swelling was present in the alveolar epithelium, granular pneumocytes or endothelial lining cells, but this may only reflect a difference in severity or duration of hypovolemia.

Summary

Changes in pulmonary and systemic hemodynamics have been studied in animals with large burns after recovery of consciousness. Increased resistances were observed in both systems and was somewhat more prominent in the pulmonary circulation. Cardiac output responded more promptly to colloid resuscitation than to administration of electrolyte solutions in these animals. Postmortem examination of the lungs revealed only minimal focal interstitial edema and a more uniform perfusion pattern than was observed in unburned control animals.

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