Experimental Aldosterone Hypertension in the Dog

YI-JEN PAN, PH.D., AND DAVID B. YOUNG, PH.D.

SUMMARY Sequential changes in arterial pressure, renal function, body fluid, and electrolyte balance, and several hemodynamic variables were examined during chronic intravenous infusion of aldosterone (14 μg/kg/day) in eight conscious dogs maintained on 250 mEq/day sodium and 140 mEq/day potassium intake. Arterial pressure gradually increased and stabilized at 132% ± 3% (p < 0.05) of the control value on the 16th day of aldosterone infusion, and cardiac output remained within the normal range. Coinciding with the rise in arterial pressure on the first 2 days of infusion was a marked retention of water and sodium and a rise in extracellular fluid volume and blood volume. Blood volume increased from a baseline value of 64.0 ± 0.3 ml/kg to 70.7 ± 1.9 ml/kg (p < 0.05) on Day 4 and extracellular fluid volume increased from 318 ± 5 ml/kg to 352 ± 11 ml/kg (p < 0.05) on Day 3 of infusion. Both blood volume and extracellular fluid volume remained elevated during infusion. Mean circulatory filling pressure increased from the baseline value of 9.7 ± 0.4 mm Hg to an average of 11.7 ± 0.3 mm Hg (p < 0.05) during the experimental period. The elevation of mean circulatory filling pressure suggested that this increase may be an essential component in the onset and maintenance of hypertension.

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KEY WORDS aldosterone · blood volume · mean circulatory filling pressure · cardiac output

THE syndrome of primary aldosteronism is generally associated with hypertension and suppressed renin activity, volume expansion, and increased peripheral resistance. Several studies have suggested that the administration of either sodium and/or mineralocorticoid causes a change in blood vessel function and that the altered vasculature plays a crucial role in the initiation and maintenance of hypertension. Other studies have shown that mineralocorticoid excess alters renal function, so that water and sodium are retained, leading to a hypervolemic state. Such a change in renal function and volume expansion are familiar aspects of many forms of clinical and experimental hypertension.

Although changes in renal function may be responsible for initiating or sustaining elevations of arterial pressure, the hemodynamic events that occur as a result of altered kidney function during mineralocorticoid excess are not completely understood. Until recently, there were few hemodynamic data on this form of hypertension. Some evidence supports the concept that some forms of experimental hypertension result from an initial increase in cardiac output and then, through an autoregulatory mechanism, shift to an increase in total peripheral resistance. However, reports on the mineralocorticoid-induced hypertension failed to corroborate this sequence. In hypertension induced by administration of metyrapone in dogs, which results in excess deoxycorticosterone secretion because of adrenocorticotropic overdrive, the cardiac response is variable. In both pig and dog, the development of DOCA hypertension does not appear to be associated with a phase of increased cardiac output. However, the cardiac output measurement is highly variable, especially in conscious animals. Thus, the change in cardiac output at the onset of hypertension might be indistinguishable from the noise in cardiac output measurement.

In contrast, the mean circulatory filling pressure has been consistently found to be elevated in various forms of hypertension. Mean circulatory filling pressure is a measure of the ratio of blood volume and the volume-holding capacity of the circulation. Both mathematically and experimentally, venous return has been shown to be directly proportional to the difference between mean circulatory filling pressure and right atrial pressure. Thus, mean circulatory filling pressure represents the mean driving force for venous return. Increased mean circulatory filling pressure may result from overfilling of the vascular system.
due to water and salt retention, or from an increase in vascular tone due to decreased capacitance and/or increased unstressed volume of the system. The consistent finding of increased mean circulatory filling pressure in hypertension suggests that an elevated mean circulatory filling pressure may be important in the maintenance of hypertension. In volume-loading hypertension, the increased mean circulatory filling pressure results from volume expansion correlated with changes in cardiac output and suggests that this increase is an essential component in the onset of hypertension. The relationship between mean circulatory filling pressure, blood volume and renal function in mineralocorticoid hypertension has not been previously described. Therefore, this study was designed to provide a more comprehensive analysis of hemodynamic events and renal function changes which occur during the onset and chronic stages of aldosterone hypertension.

Methods

Eight trained male and female mongrel dogs weighing 17-27 kg were used in this study. All dogs were splenectomized and had chronic indwelling catheters implanted in the aorta, vena cava, and right atrium through the femoral artery and vein under pentobarbital anesthesia and aseptic conditions. They were allowed to recover for at least 2 weeks before any experimental measurements were made, housed in specially designed metabolic cages to facilitate the continuous intravenous infusion of solutions and antibiotics, and daily measurement of body temperature, electrolytes, and water balance. Briefly, an arterial pressure transducer and infusing tubing were built into an aluminum harness fitted over the dogs' backs and held in place by a canvas jacket extending around the chest of the dog, with openings for the front legs. Cables from the pressure transducer and infusing tubing were brought to the top of the cages through a protective flexible tube attached to the top of the aluminum harness, thus permitting relatively unrestricted movement of the dog inside the cage but not enough to turn completely around.

Beginning 7 days before the control period, the animals were maintained on a total daily intake of 250 mEq NaCl and 140 mEq KCl; 150 mEq NaCl and 100 mEq KCl were infused continuously in the form of 50 ml 3M NaCl and 2M KCl solution intravenously. Tap water was provided ad libitum throughout the study.

Analytical Methods

The mean arterial pressure was measured daily at the same time each morning for 2 hours using a Statham P23AC pressure transducer connected to the chronic arterial catheter and Grass model 7 polygraph. The mean pressure values were obtained by inspection of several 5-minute segments of the record.

Cardiac output was determined by dye-dilution procedures using Cardio-Green dye (Hynson, Westcott and Dunning, Baltimore, Maryland) as an indicator, and a Gilford Model 103IR cuvette densitometer and a Gilford Model 105 constant flow system for withdrawal of arterial blood. Reported cardiac output values are an average of four to five determinations in which 2.5 mg Cardio-Green dye in 1 ml of solvent were injected into the dog through the right atrial catheter. The reliability of the average cardiac output measurements was estimated to be 0.988 by analysis of variance.

Mean circulatory filling pressure was measured by a method described by Young et al. The dogs were lightly sedated with 0.22 mg/kg hydromorphone (Dilaudid, 2 mg/ml, Knoll Pharmaceutical Company, Whippany, New Jersey) plus phenothiazine (Acepromazine, 10 mg/ml) at a dose of 0.11 mg/kg given by slow intravenous injection. The dogs were fully conscious and had near normal heart rates and blood pressure. Approximately 10 minutes after administration of the drug, the heart was stopped by a bolus injection of 8 ml of 0.5% acetylcholine solution into the central venous catheter. The heart was stopped for 5 seconds or longer, long enough to cause arterial and venous pressure to reach plateau values. In general, the arterial and venous pressure seldom reach a final equilibrium value. The lowest arterial pressure usually remained approximately 10 mm Hg above venous plateau pressure. However, the arterial compliance is much less than the venous compliance. Therefore, the MCFP can be extrapolated from the approach of the arterial and venous pressure according to the following relation:

$$MCFP = VPP + (FAP - VPP) \times \frac{arterial\ compliance}{venous\ compliance},$$

where VPP is venous plateau pressure and FAP is final arterial pressure. For the arterial-to-venous compliance ratio, 1/30 was used, based on the observation in dogs by Shoukas and Sagawa that venous compliance is 30 times greater than arterial compliance. In more recent studies, this ratio was found to be 1/100 in the spontaneously hypertensive rat and 1/75 in the Wistar-Kyoto rat. However, the exact value for the arterial-to-venous compliance ratio is not very critical in calculating MCFP as shown by Green in anesthetized open-chested dogs and by Yamamoto...
et al. in Wistar rats. They both demonstrated that MCFP as measured by the equilibrium pressure obtained by arterial-to-venous pumping is very close to the venous plateau pressure.

Blood volume was determined using $^{51}$Cr-tagged erythrocytes with a blood sample drawn 20 minutes after injection. Normally, red blood cells do not escape from the vascular system. Thus, the dilution space of red blood cells does not exceed the intravascular circulating blood volume. However, erythrocytes may circulate through the splenic reservoir of red cells and create a slow compartment separate from the "circulating" blood volume. In addition, splenic contraction can cause the hematocrit of the systemic blood to increase as much as 7% to 10% (3 to 4 hematocrit units). Therefore, for the purpose of better defining the term "blood volume" and increasing the precision of the measurements, the dogs were splenectomized. Glomerular filtration rate was estimated from the clearance of $^{131}$I iothalamate (Glofil, Abbott Laboratories) by the method of Hall et al., and the volume of distribution of $^{131}$I iothalamate, which is used as an index of changes in extracellular fluid volume, was measured using the technique of Sapirstein et al.

The plasma renin activity was measured by a radioimmunoassay technique and expressed as nanograms of angiotensin I generated per milliliter of plasma per hour incubation. Angiotensin $[^{125}I]$ and antiserum from New England Nuclear were used in the determination based on the method described by Haber et al. Plasma and urine concentration of sodium and potassium were determined by flame photometry (Instrumentation Laboratory, IL 343). Plasma creatinine concentration and plasma urea nitrogen were measured on a Technicon Autoanalyzer.

All values are expressed as means ± SEM. Data for experimental and post-control periods were compared to the last precontrol values for statistical significance using Dunnett's paired $t$ test for multiple comparisons; $p$ values of less than 0.05 were considered significant.

**Results**

Effects of Aldosterone Infusion on Mean Arterial Pressure, Sodium Iothalamate Space, Blood Volume, and Mean Circulatory Filling Pressure

Figure 1 illustrates the effects of aldosterone infusion on mean arterial pressure, sodium iothalamate space, blood volume, and mean circulatory filling pressure. Mean arterial pressure, which averaged 87 ± 2 mm Hg during the last control period, gradually increased during the first 4 days of aldosterone infusion. By Day 16 of infusion, the mean arterial pressure had

![Figure 1. Effects of chronic aldosterone infusion on mean arterial pressure (MAP), sodium iothalamate space, blood volume (BV), and mean circulatory filling pressure](http://hyper.ahajournals.org/Downloaded from)
stabilized at a level of 118 ± 3 mm Hg (p < 0.05). Following the termination of aldosterone infusion, mean arterial pressure progressively declined and was within 3% of the control value on the 8th day of the recovery period. Coinciding with the gradual rise in arterial pressure on Days 1-4 was a net retention of water and electrolytes, as evidenced by the increased sodium iothalamate space and blood volume. During the control period, the sodium iothalamate space and blood volume averaged 318 ± 5 and 64.0 ± 0.3 ml/kg, respectively. On Days 3 and 7, sodium iothalamate space increased to 352 ± 11 (p < 0.05) and 362 ± 12 ml/kg (p < 0.05), respectively. Blood volume increased to 70.7 ± 1.9 ml/kg (p < 0.05) on Day 4 and 72.4 ± 1.1 ml/kg (p < 0.05) on Day 8. After 16 days of aldosterone infusion, both sodium iothalamate space and blood volume remained elevated. However, the difference was not statistically significant. Along with the rise in mean arterial pressure, mean circulatory filling pressure also increased. Mean circulatory filling pressure averaged 9.7 ± 0.4 mm Hg during the control period and increased to 11.4 ± 0.3 mm Hg (p < 0.05) on Day 2 and 12.1 ± 0.7 mm Hg (p < 0.05) on Day 10 of aldosterone infusion. Like blood volume changes, the group average of mean circulatory filling pressure was elevated after 14 days of aldosterone infusion, but the difference was not statistically significant. The elevation in mean circulatory filling pressure was associated with a rise in blood volume. Thus, the data obtained in this study suggest that the increase in MCFP was due to overhydration caused by water and electrolyte retention although from these data, we cannot rule out the possibility that the changes in vascular compliance did not participate in raising MCFP.

Effects of Aldosterone Infusion on Cardiac Output and Right Atrial Pressure

The data on mean circulatory filling pressure are shown again in figure 2 to illustrate the relationship among the three variables. Cardiac output measurements were not obtained in all eight dogs. During the control period and Day 1 of infusion, cardiac output was measured in five dogs. For the remaining experimental and recovery period, cardiac output was determined in four dogs. Cardiac output did not exhibit consistent changes although it did transiently increase in three dogs. The two values measured during the control period were 2.9 ± 0.2 and 3.2 ± 0.2

![Figure 2](http://hyper.ahajournals.org/)

**Figure 2.** Effects of chronic aldosterone infusion on mean circulatory filling pressure, right atrial pressure, and cardiac output. During the control period and Day 1 of infusion, cardiac output was measured in five dogs. For the remaining experimental and recovery period, cardiac output was determined in four dogs.
liters/min, whereas during the period of aldosterone infusion, the values were 3.4 ± 0.2, 2.8 ± 0.1, 2.9 ± 0.2, and 3.1 ± 0.6 liters/min, measured on Days 1, 5, 9 and 13, respectively. Right atrial pressure showed a variable tendency to rise from a baseline value of 1.1 ± 0.3 to 2.0 ± 0.5 mm Hg (NS) on Day 2 of infusion. The group mean remained elevated (NS) throughout the infusion period. The pressure gradient for venous return, which was calculated by subtracting right atrial pressure from mean circulatory filling pressure from each dog, averaged 8.1 ± 0.9 and 9.0 ± 0.6 mm Hg during the control period and increased to 9.7 ± 0.7 mm Hg (NS) by Day 2 of aldosterone infusion. The pressure gradient remained elevated (NS) throughout the infusion period. The pressure gradient for venous return, which was calculated by subtracting right atrial pressure from mean circulatory filling pressure from each dog, averaged 8.1 ± 0.9 and 9.0 ± 0.6 mm Hg during the control period and increased to 9.7 ± 0.7 mm Hg (NS) by Day 2 of aldosterone infusion. The group mean remained elevated (NS) throughout the infusion period. The pressure gradient for venous return, which was calculated by subtracting right atrial pressure from mean circulatory filling pressure from each dog, averaged 8.1 ± 0.9 and 9.0 ± 0.6 mm Hg during the control period and increased to 9.7 ± 0.7 mm Hg (NS) by Day 2 of aldosterone infusion. The pressure gradient remained elevated (NS) throughout the infusion period.

**Effects of Aldosterone Infusion on Renal Function**

Figure 3 illustrates the effects of aldosterone infusion on glomerular filtration rate, filtered sodium load, and fractional sodium excretion. Glomerular filtration rate increased from a baseline value of 77.1 ± 0.5 ml/min to 121.4% ± 2% (p < 0.05) of the control value on Day 3 and gradually declined to 112.5% ± 4.8% (NS) of the control value on Day 15 of infusion. The change in glomerular filtration rate was associated with a change in filtered sodium load. Filtered sodium load increased from a control value of 11.3 ± 0.07 mEq/min to a maximum of 24% ± 2% (p < 0.05) above control on the third day of infusion and gradually decreased to 15% ± 5% above control on Day 15. During the aldosterone infusion, the fractional sodium excretion decreased about 25%. The fractional sodium excretion averaged 1.48% ± 0.08% and 1.35% ± 0.07% during the control period and fell to 1.13% ± 0.12% by Day 3 of infusion and remained at 1.0% ± 0.12% (p < 0.05) on Day 7, and 1.04% ± 0.08% (p < 0.05) on Day 11.

On the first and second days of aldosterone infusion, urinary sodium excretion decreased markedly, falling from an average control value of 225 ± 3 to 138 ± 10 (p < 0.05) and 175 ± 16 mEq/day (p < 0.05), respectively (fig. 4). Thus, approximately 135 mEq sodium was retained during the first 2 days of aldosterone infusion. Since GFR was significantly elevated during aldosterone infusion, the sodium and water retention that occurred during the first 2 days of infusion was due to an increased fractional reabsorption.

Potassium excretion averaged 141 ± 3 mEq/day during the control period but was highly variable. During aldosterone infusion, it averaged 131 ± 2

**Figure 3.** Effects of chronic aldosterone infusion on glomerular filtration rate, filtered sodium load, and fractional sodium excretion.
mEq/day and tended to decrease following infusion, falling to 107 ± 7 mEq/day on Day 2. It then returned toward the control value, averaging 137 ± 11 mEq/day.

Effects of Aldosterone Infusion on Plasma Sodium and Plasma Potassium Concentration, and Plasma Renin Activity

Figure 5 presents the data on plasma sodium and plasma potassium concentration; both changed significantly. Plasma sodium concentration increased from the control value of 145 ± 0.4 mEq/liter to a maximum value of 149 ± 1.5 mEq/liter (p < 0.05) on Day 3 of infusion and remained elevated during aldosterone infusion. Plasma potassium concentration decreased from the baseline level of 4.82 ± 0.07 mEq/liter to a minimum value of 3.21 ± 0.2 mEq/liter (p < 0.05) on Day 7 of infusion and stayed near this minimum value for the remaining period of aldosterone infusion. The decrease in plasma potassium occurred at times when urinary potassium loss in the first several days following aldosterone infusion was less than that excreted in the control period. Fecal excretion was not measured, which raised the possibility that fecal loss of potassium may have been increased and may have been responsible for the lowering of plasma potassium. However, in DOCA-treated pigs and in the rabbit given aldosterone, where potassium loss in both urine and stools was measured, the plasma potassium concentration also fell in the presence of a positive potassium balance. Therefore, it is also possible that an intracellular shift of potassium might have been responsible for the hypokalemia seen in dogs in the absence of kaliuresis.

Plasma renin activity (fig. 5) decreased from the baseline value of 0.36 ± 0.11 ng angiotensin I/ml/hr to 0.12 ± 0.03 ng angiotensin I/ml/hr on Day 1 of infusion. After Day 4 of infusion, plasma renin activity was undetectable. Even after the termination of aldosterone infusion, plasma renin activity remained depressed and was only 0.13 ± 0.04 ng angiotensin I/ml/hr on Day 8 of recovery.

Effects of Aldosterone Infusion on Plasma Urea Nitrogen Concentration and Plasma Creatinine Concentration

Plasma urea nitrogen decreased from the control value of 7.85 ± 0.25 mg/100 ml to 4.3 ± 0.4 mg/100 ml on Day 4 of the infusion and remained close to this concentration throughout the aldosterone infusion period. Plasma creatinine fell from a baseline value of 0.83 ± 0.03 mg/100 ml to 0.71 ± 0.09 mg/100 ml on Day 4 and remained below baseline value during aldosterone infusion.

Effects of Aldosterone Infusion on Pressure-Renal Diuresis Relationship

Figure 6 shows the relationship between steady-state arterial pressure and renal sodium excretion in normal dogs (solid line, from DeClue et al.29), and
Discussion

These studies indicate that administration of high physiological amounts of aldosterone along with a high sodium and potassium intake can produce hypertension within a short period of time. Blood pressure gradually increased to hypertensive levels after a continuous infusion of aldosterone has begun. A marked rise in mean circulatory filling pressure was observed that was due to fluid volume expansion. Cardiac out-
put change was insignificant. In contrast, total peripheral resistance initially changed little, then gradually increased until a constant level of hypertension was reached.

Chronic infusion of aldosterone caused an increase in glomerular filtration rate and filtered sodium load. These changes should lead to a greater percentage increase in urinary output of water and sodium, as has been shown by several investigators. However, the fractional sodium excretion was decreased about 25% and sodium excretion was within control levels throughout the aldosterone infusion period. These findings suggest that high levels of aldosterone impair the ability of the kidney to excrete sodium and water at normal renal perfusion pressure. Daily sodium balance was not achieved until arterial pressure (and renal perfusion pressure) had increased to approximately 30% above control. Therefore, the alteration in renal function by aldosterone infusion might be important in the development and maintenance of this model of hypertension as the recent theoretical and experimental evidence indicated.

The sodium-retaining effect of aldosterone resulted in fluid retention. Both extracellular fluid volume and blood volume were 10% greater than control values. The expanded blood volume lead to raised MCFP. Elevated MCFP in this study parallels the findings of several studies that have reported increased MCFP in other forms of experimental hypertension including: dogs with Goldblatt hypertension, angiotensin hypertension in the dog, perinephretic hypertension in the dog, and reduced renal mass plus sodium loading in the dog. In SHR, which is the closest analog to human essential hypertension, the MCFP was also found to be elevated. MCFP, which is determined by stopping the circulation of blood, is actually a measure of the degree of filling of the systemic circulation with blood. Mathematically, MCFP is determined by the total blood volume, vascular compliance, and unstressed volume of the cardiovascular system. Thus, the common finding of increase in MCFP of all forms of experimental hypertension supports the hypothesis that an alteration in fluid volume regulation is an important factor in hypertension.

In contrast to elevated MCFP, the change in cardiac output was variable. Three dogs showed a transient increase in cardiac output. This is similar to those hemodynamic studies on mineralocorticoid hypertension in dogs and pigs, in which a variability in cardiac output changes was observed. These observations may be interpreted in any one of several ways: First, the cardiac output measurements in conscious animals may be highly variable. Although the conditions under which cardiac output was determined were maintained as constant as possible, there are still many factors, such as the degree of anxiety, the metabolic rate, etc., that are impossible to control precisely. As is well known, all these factors can cause a tremendous change in cardiac output. Thus, the changes in cardiac output during the onset of hypertension might not be distinguishable from the noise in the measurements. Second, the total peripheral resistance gradually increased. It has been shown mathematically and experimentally that increasing the peripheral resistance will decrease the venous return (cardiac output). Therefore, the changes of observing a significant increase in cardiac output are decreased. Third, long-term autoregulation has been shown to be a high gain system. In salt-loading hypertension in partially nephrectomized dogs, Coleman and Guyton showed that cardiac output reached a maximum of 29% above control on the third day and then decreased toward control levels on Day 10 of saline loading. In human coarctation hypertension, Lewis reported that limb blood flows above and below the coarctation were within the normal range. Thus, the available evidence suggests that the gain of long-term autoregulation is quite high. Even in the short-term study on areflexic dogs, Granger and Guyton demonstrated that the negative feedback gain of acute autoregulation is about three and the time required to reach a steady state, in response to a step change in arterial pressure, is within 13-75 minutes (average, 35 minutes). Therefore, in a study such as this where the rate of sodium retention is gradual (2 days were required to retain 135 mEq NaCl), where long-term and acute autoregulation are superimposed on each other, and where cardiac output measurement of conscious dogs are highly variable, it is possible that no change in cardiac output did occur, or if it did, the change was too small to detect.

Other effects of aldosterone besides its renal effect may be responsible for the hemodynamic characteristics associated with this form of hypertension. First, plasma potassium was reduced significantly on the first day and stabilized around 3.2 mEq/liter (fig. 5). In acute studies, hypokalemia has been shown to reduce the activity of the Na$^{+}$—K$^{+}$ ATPase (Na$^{+}$—K$^{+}$ pump) located in the membrane of the vascular smooth muscle cell. Reducing the Na$^{+}$—K$^{+}$ pump could cause intracellular accumulation of positive charges, depolarization, and contraction. Therefore, the effect of hypokalemia could influence the inotropic state of the venous and arterial smooth muscle and contribute to the elevation in venous and arterial resistance. Second, the increase in sodium concentration could stimulate release of antidiuretic hormone. Cowley et al. infused antidiuretic hormones within physiological range into conscious, baroreceptor-denervated dogs and found that antidiuretic hormone exerts an acute direct pressor effect. Also, Haack et al. showed that plasma antidiuretic hormone concentration was elevated in DOCA-saline hypertensive rats. Thus, elevated plasma antidiuretic hormone concentration might influence vascular tone and contribute to the maintenance of aldosterone hypertension.

In summary, the present study has described the sequential changes in renal function, fluid and electrolyte balance, MCFP, cardiac output, and arterial pressure which occur during the onset and chronic stage of aldosterone hypertension. The data support the hypothesis that one mechanism by which aldosterone could cause sustained hypertension is by its effect on renal function. Aldosterone infusion caused an elevation in...
fractional reabsorption of sodium, which tended to cause retention of water and electrolytes until arterial pressure increased sufficiently to maintain balance between intake and output of fluids and electrolytes. The fluid retention produced an elevation in MCFP, no measurable change in cardiac output, and an increase in total peripheral resistance.

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