Ventricular compliance in dogs with and without aqueductal obstruction

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In 10 dogs with stereotaxically-produced aqueductal blocks and in five dogs without aqueductal blocks, multiple small, equal volumes of Conray-60 were injected rapidly into one lateral ventricle while changes in the ventricular and cisterna magna pressure were recorded. In both groups of dogs the pressure rose exponentially with successive injections into the lateral ventricle. The rise was more rapid in the presence of an aqueductal block. These experiments give a measure of the response of the intracranial structures to increased pressure. Formulas are given to predict this response in animals with and without aqueductal obstruction under the conditions of the experiment. Findings are discussed in relation to the increase in ventricular size observed during fractional pneumoencephalography.

KEY WORDS: aqueductal obstruction, ventricular pressure and compliance, fractional pneumoencephalography

In previous publications, evidence has been presented showing that when the ventricles fill with air during pneumoencephalography the lateral, third and fourth ventricles increase in size within minutes after the introduction of air into the lumbar subarachnoid space. The data suggest that the compliance of the ventricular system decreased with progressive ventricular dilatation. The present work is a study of the pressure-volume relationship of the ventricles in dogs with and without aqueductal obstruction, and from these data compliance values are computed.

Materials and Methods
The dogs studied weighed 18 to 22 kg. All experiments were conducted with intravenous pentobarbital anesthesia and artificial respiration. The animal was fixed rigidly in the supine position in a stereotaxic frame (Fig. 1). The femoral artery and vein were catheterized for monitoring the arterial and venous pressures. A midline incision about 4 cm in length was made in the posterior parietal area, and the cranial vault was exposed. A point was identified 9 mm lateral to the median sagittal plane and 1 cm anterior to the center of the external auditory meatus, measured perpendicular to the stereotaxic base plane. Two 1/16 in. drill holes were made, one 2 mm anterior and one 2 mm posterior to this chosen point. Two 18-gauge needles held in a single needle holder were inserted simultaneously through the drill holes into one lateral
ventricle in a direction perpendicular to the stereotaxic base plane. One needle was used for recording ventricular pressure and the other for injecting known increments of Conray-60. An 18-gauge needle was also inserted percutaneously into the cisterna magna for recording subarachnoid pressure. All pressures were recorded with a Statham P23BB strain gauge and Beckman dynograph. The external auditory meatus was chosen as the zero reference point. The animals were divided into two groups. In 10 dogs, an aqueductal obstruction was produced. The remaining five dogs were studied without an obstruction.

The aqueductal obstructions were produced by a modification of the technique described by Deck, et al.2 A small amount of Conray-60 was injected through one of the lateral ventricular needles to outline the ventricular system and demonstrate the aqueductal recess. Anteroposterior and lateral radiographs were taken to obtain the coordinates of the aqueductal recess. On the lateral radiograph the perpendicular dis-
tance of the aqueductal recess from the external auditory meatus was measured. On the anteroposterior radiograph, the angle between the sagittal plane and a line joining the center of the aqueductal recess to a point 9 mm from the midline on the outer table of the cranial vault was measured. After identification of these coordinates, a drill hole was made through the cranial vault, and the tip of an 18-gauge needle was guided into the aqueductal recess by stereotaxic technique. The position of the aqueductal needle was checked radiographically and by the free backflow of cerebrospinal fluid; then 0.2 to 0.3 cc of radiopaque Microfil* was injected into the aqueductal recess when the Microfil was just about to solidify. Radiographs were again taken to verify the site of the Microfil injected. While the aqueduct obstruction was being produced, the ventricular and cisterna magna needles were allowed to drain at approxi-

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Fig. 2. Diagram of the position of the Microfil in the aqueduct and adjacent structures in each of the
10 dogs with aqueductal block (numbers in cerebellum identify specific dogs).

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10 dogs with aqueductal block (numbers in cerebellum identify specific dogs).

mately 2 cm H₂O to prevent any untoward
rise in cerebrospinal fluid (CSF) pressure.
In all 15 dogs, increments of 0.2 cc of
Conray-60 were injected rapidly through
one of the ventricular needles at 15- to 25-
sec intervals. The ventricular and cisterna
magna pressures were recorded continuously. Anteroposterior and/or lateral radio-

TABLE 1

<table>
<thead>
<tr>
<th>Dog No.</th>
<th>Ventricular Pressure (cm H₂O)</th>
<th>Cisternal Pressure (cm H₂O)</th>
<th>Gradient (cm H₂O)</th>
<th>Total Vol. Injected (cc)</th>
<th>Site of Leak</th>
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<tbody>
<tr>
<td>4-4</td>
<td>23</td>
<td>22</td>
<td>1</td>
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<tr>
<td>4-5</td>
<td>25</td>
<td>20</td>
<td>5</td>
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<td>5-4</td>
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<td>19</td>
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<td>fourth ventricle</td>
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<td>5-5</td>
<td>29</td>
<td>25.5</td>
<td>3.5</td>
<td>1.6</td>
<td>velum interpositum</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>and needle track</td>
</tr>
<tr>
<td>5-8</td>
<td>24</td>
<td>21</td>
<td>3</td>
<td>1.4</td>
<td>fourth ventricle</td>
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<tr>
<td>5-9</td>
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<tr>
<td>5-12</td>
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<tr>
<td>6-12</td>
<td>23</td>
<td>17</td>
<td>6</td>
<td>1.8</td>
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<td>no leak</td>
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<tr>
<td>mean*</td>
<td>25.7</td>
<td>20.4</td>
<td>4.8</td>
<td>1.58</td>
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<td>2.9</td>
<td>2.5</td>
<td>.26</td>
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<tr>
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<td>.77</td>
<td>.98</td>
<td>.8</td>
<td>.08</td>
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*The mean for cisternal pressure and gradient excluded Dog 6-13. S.D. = standard deviation; S.E. = standard error.

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graphs were taken immediately after each injection. The injection was started when the mean ventricular and cisterna magna pressures were approximately equal and in the range of 3 to 6 cm H$_2$O. The incremental injections were continued until the ventricular pressure reached 25 to 35 cm H$_2$O. The experiment was completed within 5 minutes from the start of the injections. Leakage of the aqueductal block was checked in the animals with aqueductal obstructions by two methods: by detection of contrast material (Conray-60) outside the ventricular system in the sequential radiographs and by instillation of Berlin blue at 30 cm H$_2$O for 30 minutes into the lateral ventricle at the end of the experiment. The CSF in the subarachnoid space was checked for discol-

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**FIG. 3.** Dog 5-12. *Left*: Lateral radiograph showing initial condition before start of experiment. *Right*: Lateral radiograph after injection of 2 cc of Conray-60. *Open arrow* points to the needle and Microfil in the aqueductal recess.

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**FIG. 4.** Dog 5-10 with aqueductal block. Typical tracing of lateral ventricle and cisterna magna pressure responses to rapid incremental injections of 0.2 cc of Conray-60 into one lateral ventricle. *Arrows* indicate times of injections.
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Fig. 5. Dog 5-4. Left: Volume change (scale on left) plotted against pressure change (solid line). $V_0$ represents the initial ventricular volume in the collapsed state. Dotted line indicates the compliance values (scale on right) plotted against the ventricular pressure. Right: Composite graph of volume change plotted against pressure change in all 10 dogs with aqueductal block.

oration when the brain was removed. All brains with aqueductal obstructions were sectioned to check the exact position of the Microfil in the aqueduct.

In three additional dogs with aqueductal block, a special cannula was also inserted into the subarachnoid space as described by Bito, et al. In the experiments described above were then performed. This technique was abandoned for reasons explained under "Results."

Results

Dogs with Aqueductal Block

In eight dogs, the Microfil was shown to be entirely within the aqueduct and adjacent fourth ventricle (Fig. 2). In two dogs, there was some dissection of the material into the adjacent brain stem and/or cerebellum, but the aqueductal obstruction appeared satisfactory in these two animals (Dogs 5-8 and 5-10, Fig. 2).

In all 10 animals, there was progressive enlargement of the lateral ventricles as increasing quantities of Conray-60 were introduced. In four animals, the ventricular system remained intact even at the highest ventricular pressure levels (Table 1). In six animals, leakage occurred as shown in Table 1. The pressure and volume data after ventricular leakage in these six dogs were

### TABLE 2

<table>
<thead>
<tr>
<th>VP = 7.5 cm H$_2$O</th>
<th>VP = 10 cm H$_2$O</th>
<th>VP = 15 cm H$_2$O</th>
<th>VP = 20 cm H$_2$O</th>
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<tr>
<td>Aqueductal Block</td>
<td>Aqueductal Block</td>
<td>Aqueductal Block</td>
<td>Aqueductal Block</td>
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<tr>
<td>(cc/cm H$_2$O)</td>
<td>(cc/cm H$_2$O)</td>
<td>(cc/cm H$_2$O)</td>
<td>(cc/cm H$_2$O)</td>
</tr>
<tr>
<td>No Block</td>
<td>No Block</td>
<td>No Block</td>
<td>No Block</td>
</tr>
<tr>
<td>(cc/cm H$_2$O)</td>
<td>(cc/cm H$_2$O)</td>
<td>(cc/cm H$_2$O)</td>
<td>(cc/cm H$_2$O)</td>
</tr>
<tr>
<td>mean VC</td>
<td>.13</td>
<td>.098</td>
<td>.063</td>
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<tr>
<td>S.D.</td>
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<td>.02</td>
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<tr>
<td>S.E.</td>
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<td>.24</td>
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<td>.033</td>
<td>.023</td>
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</table>
discarded. Selected serial radiographs of Dog 5-12 (Fig. 3) demonstrated the obvious increase in volume of the ventricular system with successive increments of Conray-60. No significant leakage of contrast material was noted in this animal either by the radiographic method or by the Berlin blue method. In Dog 5-5, the last picture of the series showed leakage of contrast material through the roof of the third ventricle. This occurred at a ventricular pressure of 29 cm H$_2$O, a cisterna magna pressure of 25.5 cm H$_2$O, and after an injected volume of 1.6 cc of Conray-60. A minor leak in the needle track was also shown. The Berlin blue injected into the ventricle at 30 cm H$_2$O at the end of the experiment did not show detectable discoloration of the brain surface, however, suggesting that the leak demonstrated in the radiograph had been sealed off in the interim. In none of these cases where leakage was detected radiographically was discoloration of the subarachnoid cerebrospinal fluid and brain surface by Berlin blue noted when the brain was removed after the experiment.

A typical tracing of the ventricular and cisterna magna pressures during incremental injections of Conray-60 is shown in Fig. 4. in all 10 dogs when the ventricular pressure was low, the incremental increases in pressure caused by an injection of 0.2 cc of Conray-60 were smaller than in the latter part of the experiment when the ventricular pressure was higher. Figure 5 A shows the ventricular volume increase plotted against the ventricular pressure change in Dog 5-4. The slopes of the curve at pressures of 7.5, 10, 15, 20 and 25 cm H$_2$O were calculated by graphical methods and plotted in the same figure. The slopes represent dV/dP which by definition is the compliance of the system. At 7.5 cm H$_2$O ventricular pressure, the compliance was 0.15 cc/cm H$_2$O; at 10 cm H$_2$O, 0.11 cc/cm H$_2$O; at 15 cm H$_2$O, 0.07 cc/cm H$_2$O; at 20 cm H$_2$O, 0.04 cc/cm H$_2$O; at 25 cm H$_2$O, 0.02 cc/cm H$_2$O. Figure 5 B is a composite graph showing the trend of volume change relative to pressure change in the ventricles in all 10 dogs. For each dog the compliances were calculated at selected pressure levels, and the average values are shown in Table 2. Data were available in only four dogs to calculate the slopes at a ventricular pressure of 25 cm H$_2$O. It is seen (Fig. 6) that the compliance of the blocked ventricles drops exponentially from an average value of 0.13 cc/cm H$_2$O at a ventricular pressure of 7.5 cm H$_2$O to 0.043 cc/cm H$_2$O at a ventricular pressure of 20 cm H$_2$O, with an exponential constant of 0.091/cm H$_2$O. The intercept of the curve had a value of 0.25 cc/cm H$_2$O.

The pressure gradients between the lateral ventricle and cisterna magna during the experiment are shown in Fig. 7. The ventricular pressure always exceeded the cisternal pressure after the injection of an average volume of 1.58 cc of Conray-60. The average gradient was 4.8 cm H$_2$O ± 2.5

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**Fig. 6.** Semilogarithmic plot of average compliance against ventricular pressure. Line with open circles shows the compliance values in dogs with aqueductal block. Line with open triangles shows the compliance values in dogs without block.
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Fig. 7. Differential pressure (ventricular pressure minus cisterna magna pressure) plotted against ventricular pressure in all 10 dogs with aqueductal block.

(S.D.). The development of the gradient was quite variable. In one dog (Dog 6-13) the cisterna magna pressure rose only 4.5 cm H₂O while the ventricular pressure rose by 26.5 cm H₂O. This may have been due to subdural positioning of the cisterna magna needle.

In the three additional dogs in which the supratentorial subarachnoid pressure was measured by a special cannula, initially the subarachnoid pressure rose in a fashion similar to the ventricular and cisternal pressures. The subarachnoid pressure recording, however, became damped quite early, and it was necessary to manipulate the cannula frequently by pulling the cannula base plate with the attached leptomeninges away from the brain surface and to readjust the position of the cannula relative to the cannula holder. The manipulations resulted in CSF leakage around the base plate of the cannula. For this reason the use of the cannula in the distal subarachnoid space was abandoned.

Dogs without Aqueductal Block

Selected lateral radiographs demonstrating slight ventricular enlargement in the initial stages of Conray-60 injection are shown in Fig. 8. Due to leakage of contrast medium out of the fourth ventricle into the subarachnoid spaces, particularly the posterior fossa and spine, the ventricles did not distend to the degree seen in the group with aqueductal block. Figure 9 shows a typical tracing of the ventricular and cisterna magna pressures during incremental injections of Conray-60. In contrast to the tracings with aqueductal block, the pressure rose more gradually with each incremental injection, particularly in the initial stages, indicating that the compliance was greater when the ventricular system communicated freely with the subarachnoid spaces. There was no pressure gradient between the lateral ventricle and the cisterna magna. A typical example (Dog 6-14) of the relation of the ventricular-subarachnoid space volume increases to the ventricular pressure increases is shown in Fig. 10 A. The slopes at 7.5, 10, 15, 20, and 25 cm H₂O are plotted on the same figure. The relationship of volume increases to pressure increases in all five dogs is shown in Fig. 10 B. The average compliances in the unblocked aqueduct group are higher than in those with aqueductal block at the same ventricular pressure levels (Table 2 and Fig. 6). At 7.5 cm H₂O the average compliance in the unblocked group was 0.24 cc/cm H₂O; at 10 cm H₂O, 0.18 cc/cm H₂O; at 15 cm H₂O, 0.12 cc/cm H₂O; and at 20 cm H₂O, 0.074 cc/cm H₂O. The compliance values in both groups of dogs dropped exponentially, with an exponential constant that was almost identical. In the group with aqueductal block the constant was 0.091/cm H₂O and in the group without aqueductal block the constant was 0.092/cm H₂O.

Discussion

The intracranial contents which are enclosed in a rigid container form a complex system, and the techniques available to
characterize its physical properties in situ are fairly limited. The spinal subarachnoid pressure is often the only physical information readily obtainable. Occasionally the ventricular pressure may be known. Pneumoencephalography may demonstrate changes of brain mass or the sizes of the ventricular and intracranial subarachnoid space caused by various diseases. Positive contrast or air myelography may be used to display the spinal cord and spinal subarachnoid space. The unaltered size of the lateral ventricles may be demonstrated during angiography by the subependymal veins. In a recent publication it was shown that the ventricles expand rapidly during pneumoencephalography, suggesting that the ventricular measurements made during pneumoencephalography are estimates of the ventricular size with the brain slightly deformed and expanded. The mechanism for this ventricular expansion was discussed, and the

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Fig. 8. Dog 6-14 without aqueductal block. Selected lateral radiographs showing the degree of ventricular enlargement after incremental injection of Conray-60. *Left*: After 0.2 cc. *Right*: After 1.8 cc. The contrast medium has leaked out of the ventricular system into the cisterna magna and upper spinal subarachnoid space (arrows).

Fig. 9. Dog 6-15 without aqueductal block. Typical tracing of lateral ventricle and cisterna magna pressure responses to incremental injection of 0.2 cc of Conray-60 into one lateral ventricle. Arrows indicate times of injections.
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![Graph showing ventricular compliance](image)

**Fig. 10.** Dog 6-14 without aqueductal block. *Left:* Volume change plotted against pressure change (solid line). Dotted line indicates the compliance values (right-hand scale) plotted against the ventricular pressure. *Right:* Composite graph of volume change plotted against pressure change in all five dogs without aqueductal block.

Analysis suggested that the compliance of the ventricular system is nonlinear. To study further the concept of compliance of the ventricular system experimentally, the present work was undertaken in dogs.

Due to the complex nature of the intracranial structures, and in order to study them *in situ*, the system was tested as a "black-box." Sequential increments of Conray-60 injected rapidly into the lateral ventricle were used as step-function inputs, and the ventricular and cisternal pressure output responses were recorded. Each test was conducted under two conditions, with and without aqueductal block, and completed in a relatively short period of time (maximum of 5 minutes) in order to render negligible the influence of CSF formation and absorption relative to the volume of Conray-60 injected. The volume change plotted against the pressure change represents the input-output characteristic of the system. The first derivative of the above curve represents, by definition, the compliance of the system. The compliance value expressed as a function of ventricular pressure was, therefore, regarded as a parameter characterizing the behavior of a lumped system.

The average compliance, $C$, expressed as a function of the ventricular pressure, $P$, was calculated by graphical methods in the range of 7.5 to 20 cm H$_2$O, and was found to have an exponential form. In the group of animals with aqueductal block, the compliance, $C_b$, was found to be:

$$C_b = 0.25e^{-0.091P}.$$  

(1)

In the animals without aqueductal block, the compliance, $C_o$, was found to be:

$$C_o = 0.47e^{-0.082P}.$$  

(2)
These equations are mathematical approximations and hold true only in the range values for which they were calculated. From these derived equations, important information may be deduced. First, by simply substituting values for \( P \), the compliance of the system at certain selected ventricular pressures may be estimated. Second, by dividing Equation 1 into Equation 2, it is seen that the compliance of the system without aqueductal block was approximately 1.9 times, or roughly twice that in the group with aqueductal block at any ventricular pressure level. Third, the compliance of the system in both groups drops exponentially with increasing ventricular pressure. The exponential constant is almost identical in both groups. This finding cannot be fully explained due to the complex nature of the system. Finally, by integrating Equations 1 and 2, two expressions can be derived that describe the ventricular volume as a function of ventricular pressure. In the group of animals with aqueductal block, the equation will have the form:

\[ V_b = -2.7e^{-0.091P} + K_b. \] (3)

In the group of animals without aqueductal block, the equation will have the form:

\[ V_o = -5.1e^{-0.092P} + K_o, \] (4)

where \( K_b \) and \( K_o \) are integration constants. To obtain an estimate of the volume increase, \( \Delta V \), corresponding to a ventricular pressure increase from one level, \( P_1 \), to a higher level, \( P_2 \), the integration may be carried out between the two chosen pressure limits. In the group of animals with aqueductal block, Equation 3 becomes:

\[ \Delta V_b = 2.7(e^{-0.091P_1} - e^{-0.091P_2}). \] (5)

In the group of animals without aqueductal block, Equation 4 becomes:

\[ \Delta V_o = 5.1(e^{-0.092P_1} - e^{-0.092P_2}). \] (6)

For example, if the pressure is changed from 12 to 18 cm H\(_2\)O, the volume increase in the system will be expected to rise roughly twice as much in the blocked ventricle as in the unblocked ventricle at any ventricular pressure between 7.5 and 20 cm H\(_2\)O.

The response of the system to intraventricular volume loads will be determined by the interaction of the physical and geometrical deformation properties of the brain substance, the interstitial and vascular spaces, the subarachnoid space, leptomeninges, and extradural tissues. Although the present study was not designed to identify the relative roles played by the different components of the system in producing the observed findings, it provided certain indirect indications of the events that occurred when the ventricles were tested in the manner described.

The finding that the group with aqueductal block had a set of average compliance values roughly one-half of those in the group without aqueductal block suggests that, in the former group, the compliance measured was probably mainly that of the supratentorial compartment, while in the latter group the compliance measured probably also included the posterior fossa and spine. This conclusion is supported by the fact that in the unobstructed animals, contrast material was observed to pass into the posterior fossa and upper cervical spine in the early part of the experiment, and the ventricles were not as distended as in the obstructed animals.

With aqueductal obstruction the cisternal pressure rose in a similar fashion to the ventricular pressure, with the ventricular pressure only slightly higher than the cisternal pressure (average final gradient of 4.8 cm H\(_2\)O). The relatively small gradient suggests that the brain substance deforms easily and acts as a compliant barrier between the intraventricular and extraventricular compartments. This conclusion was further supported by the observations made in the three dogs with aqueductal block where a special subarachnoid cannula was used to measure the supratentorial subarachnoid pressure.

It was necessary to repeatedly pull the cannula outward to prevent damping of the pressure recording. This was interpreted to be due to outward displacement of the brain surface as the ventricles were distended,
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thus occluding the opening of the cannula. Associated deformations and displacements would also be expected to occur in the vascular and interstitial spaces in the brain, subarachnoid cisterns, leptomeninges and extradural space.

The leakage of Conray-60 into the velum interpositum at pressure gradients of 3.5, 6, and 8 cm H₂O in three dogs suggested that the wall of the ventricular system is weakest adjacent to the velum interpositum. The other points where leakage occurred were through the fourth ventricle, presumably by seepage around the Microfil plug, and along the needle tract. The radiographic technique was particularly valuable because it indicated the exact times and positions of minor leaks. In no instance was Berlin blue detected over the brain surface when the brain was removed at the end of the experiment. This was probably due to spontaneous seals of minor leakages.

The present study proves that the ventricles increase in volume acutely when subjected to small increments of pressure and confirms the observations made during fractional pneumoencephalography that the ventricles expand when air is introduced via the lumbar route. The source of the small increments of pressure during pneumoencephalography was discussed in previous publications. The finding that the compliance of the ventricular system becomes smaller with greater degrees of ventricular distention is consistent with the observation made during fractional pneumoencephalography that the degree of ventricular enlargement is greatest after the initial air is introduced and smallest after the later fractions of air are introduced.

Summary

The compliance of the ventricular system in the dog with and without an aqueductal block was studied. The compliance of the system was defined as dV/dP and regarded as a lumped parameter to partially characterize the behavior of a complex system. The compliance values in the group with aqueductal block were roughly one-half those in the group without block at corresponding ventricular pressures. The compliance decreased exponentially with increasing ventricular pressure with an exponential constant almost identical in both groups. These findings are discussed in relation to the increase in ventricular size observed during fractional pneumoencephalography.

References


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