ABSTRACT

Further studies of hereditary patent ductus arteriosus (PDA) in the dog show the defect to have a graded phenotypic expression. A high proportion of offspring of test matings had a fully patent ductus arteriosus, while a smaller proportion had a blind diverticulum of the ductus arteriosus which communicated with the aorta. This is considered to be a forme fruste of PDA, representing incomplete closure. Approximately 50% of pups with fully patent ductus arteriosus developed signs of left heart failure, and about 15% developed severe pulmonary hypertension with right-to-left or bidirectional shunts. Genetic analysis indicated that hereditary PDA in the dog is not a simple mendelian trait. Rather, it resembles a quasi-continuous or threshold trait with a high degree of heritability. Results were analyzed using a polygenic model with two developmental thresholds. Liability to defective closure of the ductus arteriosus increased with the proportion of the genome received from dogs with PDA. Moreover, in pups which had PDA, the incidence of serious sequelae (left heart failure and severe pulmonary hypertension) increased in a parallel fashion, suggesting that an increased liability to PDA was accompanied by an increase in the severity of the lesion.

KEY WORDS ductus diverticulum threshold trait heritability quasi-continuous trait left heart failure pulmonary hypertension vascular shunt
preliminary genetic studies confirmed this hypothesis (5). In the initial genetic studies, it was demonstrated that PDA, unaccompanied by other malformations, was transmitted to the offspring of affected dogs in a manner consistent with autosomal dominant inheritance.

This paper will provide more recent evidence regarding the mode of hereditary transmission of PDA in the dog and will describe the range of gross anatomic and clinical abnormalities produced in the postnatal period.

**Materials and Methods**

**Breeding Stock and Husbandry**

Dogs with PDA and their normal first degree relatives were donated by their owners through the Heart Station of the Veterinary Clinic of the University of Pennsylvania and through cooperating veterinarians. Most of these dogs were purchased miniature or toy poodles, or were partially of poodle ancestry. Normal dogs used in outcrosses were beagles and black and tan coonhounds not known to be related to dogs with PDA. Studies in a clinic population show the prevalence of PDA to be low in these breeds (5). Test matings were designed to determine whether PDA is transmitted as a single gene defect.

The following crosses were made:

1. Reciprocal crosses of dogs with PDA to normal dogs with no family history of PDA (PDA x N, N x PDA).
2. Crosses of normal females that were mothers or full sisters of dogs with PDA to males with PDA [N (1° Rel. PDA) x PDA].
3. Crosses of two dogs with PDA (PDA x PDA).

Although crosses 2 and 3 involved mating pairs in which both members were partially or completely of poodle ancestry, in none of the pairs did the two members have common ancestors within five generations.

In the course of the study it was discovered that the offspring of the foregoing matings could not be placed in two distinct classes as regards patency of the ductus arteriosus. In addition to normal pups and pups with PDA, an intermediate class appeared in which the ductus arteriosus closed at the pulmonary arterial end, but remained patent over a portion of the rest of its length. This resulted in a blind ductus diverticulum (DD) which communicated with the aorta. Two males and three females with this defect were retained and used in the following crosses: 1. Reciprocal crosses of dogs with ductus diverticulum to normal dogs with no family history of PDA (DD x N and N x DD).

2. Crosses of normal females who were the first-degree relatives of dogs with PDA to males with ductus diverticulum [N (1° Rel. PDA) x DD].

3. Crosses of females with DD to males with PDA (DD x PDA).

**FIGURE 1**

Ductus diverticulum. Top: Lateral aortic angiogram of a 13-week-old male pup from a cross between a male poodle with a ductus diverticulum and a normal female coonhound. A funnel-shaped ductus diverticulum can be seen over the heart base. The distal extremity of the diverticulum extends well beyond the outer border of the aortic wall. The crista reuniens (CR) is formed by the adjacent walls of the ductus arteriosus and aorta (19). Bottom: Sagittal section of the aorta (A), ductus diverticulum, and pulmonary artery (P) of the same dog. The ductus diverticulum extends beneath the crista reuniens (CR) to about one-half the length of the ductus arteriosus.
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Cross 2 involved a moderate degree of inbreeding (average coefficient of inbreeding of the offspring 0.133).

All dogs were maintained indoors under colony conditions, breeding being done by artificial insemination. There was no known exposure of females to teratogenic agents and none showed signs of infectious or other disease during pregnancy.

Pups born of test matings were whelped in heated pens and weighed and examined daily for the first 6 weeks after birth. Electrocardiograms were recorded weekly in selected litters. Immunization for canine distemper and infectious canine hepatitis was carried out at 6 weeks of age. After this time, pups were observed daily and examined at intervals of approximately 1 week. Cardiac catheterization and angiocardiography were performed at 8-10 weeks of age. Following these studies, dogs not retained for further breeding experiments were killed. Complete gross postmortem examinations were performed on all pups that died or were killed; the hearts and great vessels were examined under a dissecting microscope when the pups were small. To preserve them for experiments, a number of pups with PDA were treated by surgical ligation of the ductus arteriosus.

NEONATAL DEATHS

According to previous investigations, the ductus arteriosus in the dog is anatomically closed (no longer probe patent) by the end of the first week of life, although histologic changes in the architecture of the vessel continue for some time after that (13-16). Gross anatomic or clinical evidence of patency of the ductus arteriosus beyond 1 week of age can thus reasonably be assumed to be abnormal in the dog, but patency prior to 1 week has uncertain significance. On this basis, only pups that survived the first week are included in the genetic analysis.

DIAGNOSTIC CRITERIA AND DEFINITIONS

In pups that survived the neonatal period but died before 8 weeks of age, final diagnosis was based on postmortem examination. All but one of these pups had unequivocal clinical and postmortem signs of PDA. Final classification of parents and offspring that survived to 8 weeks of age or beyond was based on postmortem examination or cardiac catheterization and angiocardiography or both.

Ductus Diverticulum—This malformation was diagnosed when it was demonstrated by postmortem examination or aortic angiography that a segment of the ductus arteriosus extending beyond the outer limit of the aortic wall remained patent but did not communicate with the pulmonary artery. Closure of the ductus arteriosus at the aortic end with a diverticulum extending into the ductus arteriosus from the pulmonary arterial end has not been observed in our material. We have occasionally seen ductus diverticula in dogs with other types of congenital heart disease and in otherwise normal dogs with no family history of PDA. The DD as defined here thus cannot be considered as exclusively a forme fruste of hereditary PDA, but probably represents incomplete closure of the ductus arteriosus from various causes.

PDA with Left to Right Shunt—Pups placed in this category had continuous murmurs which appeared within the first 2 weeks after birth and remained continuous until the time of death, surgical correction, or euthanasia. Electrocardiographic and roentgenographic evidence of left ventricular hypertrophy were usually present. Angiocardiography demonstrated a left-to-right shunt through a patent ductus arteriosus, without associated cardiac malformations. Pups that died had a patent ductus arteriosus and marked enlargement of the pulmonary arteries, pulmonary veins, left atrium, left ventricle and ascending aorta.

PDA with Severe Pulmonary Hypertension and Right-to-Left Shunts—In pups placed in this category, transssystolic or continuous murmurs were heard during the first few days of life, but these disappeared before the eighth week and the second heart sound became markedly split. Electrocardiograms were typical of right ventricular hypertrophy (3). Cyanosis of the caudal portion of the body was apparent in some pups. Cardiac catheterization revealed mean pulmonary arterial pressures that equaled or exceeded mean aortic pressures. In angiocardiograms, contrast medium injected into the right ventricle or pulmonary artery passed immediately to the descending aorta by way of a large patent ductus arteriosus. The main pulmonary artery and its major branches were enlarged, but the pulmonary veins, left atrium, left ventricle and ascending aorta were normal or decreased in size. In three pups that died, autopsy revealed a large patent ductus arteriosus, marked right ventricular hypertrophy and enlargement of the major branches of the pulmonary artery. The pulmonary veins, left atrium, left ventricle, and ascending aorta were not enlarged.

Left Heart Failure—This term is used to refer to a syndrome that occurred in a high proportion of pups having PDA with left-to-right shunts as defined above. It did not occur in pups that did
not have PDA or in pups that had PDA with severe pulmonary hypertension and right-to-left shunts. The syndrome was characterized by rapid, labored breathing and pulmonary rales, which had their onset between the second and the fifth week after birth. Progressive dyspnea and weight loss ensued, and affected pups invariably died before the end of the fifth week unless surgical ligation of the ductus arteriosus was carried out. On postmortem examination, the lungs were congested and edematous and there was massive enlargement of the pulmonary arteries and veins, left atrium, left ventricle, and ascending aorta.

**Results**

Forty-seven matings produced 247 pups, of which 39 (15.8%) died before 1 week of age and were excluded from this analysis. This neonatal death rate does not exceed that in other colonies of purebred dogs (17, 18). In the 208 pups that survived, postmortem or angiocardiographic evidence of a DD was found at 8 weeks of age or older in 32 (Fig. 1). In 61 other pups, the ductus arteriosus remained patent throughout its length. Of these, 52 (85.2%) had persistent left-to-right shunts (Fig. 2), and 9 (14.8%) developed severe pulmonary hypertension with right-to-left or bidirectional shunts (Fig. 3). Signs of left heart failure occurred in 30 (57.7%) of the 52 pups with left-to-right shunts: 25 died with pulmonary edema, 4 recovered following surgical ligation of the ductus arteriosus, and 1 died during surgery.

**GENETIC ANALYSIS**

The distribution of PDA and DD in the offspring of the 47 matings grouped according to parental phenotypes is shown in Table 1. Reciprocal cross differences were not significant, and these data are pooled. Combining data on all matings showed that the incidence of defective ductal closure (DD plus PDA) was not significantly different in males (45.4%) and females (44.1%), although there was a slightly higher incidence in the females of all mating types except N × DD. In further analyses, data on the sexes are combined.

The incidence of defective ductal closure in N × DD offspring (21.4%) did not differ significantly from that in N × PDA offspring.

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![FIGURE 2](image-url)

**FIGURE 2**

PDA with left-to-right shunt. Left: Left lateral aortic angiogram of a 12-week-old male mixed poodle with a large funnel-shaped PDA and left-to-right shunt. After injection of contrast medium into the aorta (A), the ductus arteriosus (D) and dilated pulmonary artery (P) were visualized. The opposed walls of the ductus arteriosus and aorta are seen as a radiolucent line (arrows). Right: Left lateral view of the heart of 16-week-old female poodle with a large funnel-shaped PDA (D); a left-to-right shunt was present in life.
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(21.8%). Likewise, the incidence of defective ductal closure in the offspring of N (1° Rel. PDA) x DD matings (63.2%) was similar to that in N(1° Rel. PDA) x PDA matings (67.5%), indicating that dogs with DD do not differ substantially from those with PDA in their ability to transmit defective ductal closure to their offspring.

The lowest incidence of defective ductal closure occurred in the offspring of N x DD and N x PDA matings (pooled incidence, 21.7%), and the highest in the offspring of PDA x PDA matings (82.9%). The incidence is N(1° Rel. PDA) x DD and N(1° Rel. PDA) x PDA matings was intermediate (pooled incidence, 66.1%).

As noted previously (5), the near 75% incidence of defective ductal closure in the offspring of matings in which both parents have PDA, and the transmission of PDA in outcrosses to normal dogs, are superficially consistent with autosomal dominant inheritance. However, the data in Table 1 differ in two important respects from that expected under the simple dominant hypothesis:

1. Under the simple dominant hypothesis, both fully patent ductus arteriosus and DD might be considered as being due to the same single gene mutation. However, even if DD and PDA are considered as equivalent for the purpose of genetic analysis, the number of offspring manifesting these in outcrosses of PDA and DD dogs to normal dogs with no family history of PDA falls short of the 50% expected. Combining reciprocal DD x N and PDA x N matings, 23 of 106 offspring (21.7%) had evidence of defective closure of the ductus arteriosus, while 53 were expected under the simple dominant hypothesis. ($X^2 = 33.962, P < 0.001$)

2. The normal first-degree relatives of dogs with PDA, though phenotypically equivalent, are genetically quite different from normal dogs with no family history of PDA. When mated to dogs with PDA or DD, the normal first-degree relatives of dogs with PDA produced a significantly higher proportion of pups with defective ductal closure (39/59 or 66.1%) than did normal dogs with no family history of PDA (23/106 or 21.7%). The probability of this or more extreme results occurring by chance is less than 0.001 ($X^2 = 31.860$). We must, therefore, conclude that the first-degree relatives of dogs with PDA transmitted genetic factors which enhanced the probability of defective ductal closure in the offspring of such matings, but which were in themselves insufficient to produce an overt defect in ductal closure.

These findings exclude any simple genetic interpretation and are similar to the results expected if hereditary PDA is transmitted as a threshold trait. Threshold, or quasi-continuous traits, as they have been called by Grineberg (20), are more or less discrete phenotypic traits, which depend on differences at multiple gene loci and often are influenced by environmental factors. The genetic basis of threshold traits is thus polygenic, as in continuously variable "quantitative" traits such as stature.

<table>
<thead>
<tr>
<th>Parental phenotypes (reciprocal crosses pooled)</th>
<th>No. surviving 7 days or more</th>
<th>No. with defective ductus</th>
<th>Defective ductus (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. matings</td>
<td>DD</td>
<td>PDA</td>
</tr>
<tr>
<td>DD x N</td>
<td>4</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>PDA x N</td>
<td>18</td>
<td>33</td>
<td>45</td>
</tr>
<tr>
<td>N(1° Rel. PDA) x DD</td>
<td>6</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>N(1° Rel. PDA) x PDA</td>
<td>7</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>DD x PDA</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>PDA x PDA</td>
<td>10</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>All matings</td>
<td>47</td>
<td>97</td>
<td>111</td>
</tr>
</tbody>
</table>

PDA = patent ductus arteriosus; DD = ductus diverticulum.

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and blood pressure, but in contrast to polygenic traits which show continuous variation at the phenotypic level, threshold traits are usually considered as being either "present" or "absent." In theory, the point of phenotypic discontinuity in threshold traits occurs when some underlying variable exceeds a critical "threshold" value.

The concept of threshold traits and methods for their analysis were introduced by Wright (21) and later extended by Falconer (22). In the present analysis, a two-threshold model was utilized. Below the first threshold, closure of the ductus arteriosus is complete and individuals are phenotypically normal. Between the first and second thresholds, there is partial closure of the ductus arteriosus, resulting in a ductus diverticulum. Beyond the second threshold, the ductus arteriosus remains open throughout its length, resulting in PDA. The two thresholds are assumed to represent critical values of some underlying variable important in closure of the ductus arteriosus, such as the concentration of some substance or the rate of growth or differentiation of some tissue element. In theory, if the variable could be measured directly, it would be found to be under polygenic control. Falconer has suggested that the underlying variable in diseases that behave as threshold traits be termed "liability," indicating not only the innate (genetic) tendency to develop disease, but the influence of environmental factors as well (23). Liability is assumed to be continuous and normally distributed. Its genetic determinants are assumed to consist of a large number of additive genes, each of small effect, or if there are a few genes, their combined effect is supposed to be small in comparison to random environmental sources of variation.

We may think of an individual as having some liability to defective ductal closure, but beyond observing from the phenotype that he lies below, between, or above the two thresholds (normal, DD, or PDA), we cannot determine his exact location on the continuous underlying scale of liability. However, the mean liability of a group of individuals can be

**FIGURE 3**
PDA with severe pulmonary hypertension. Two films from an angiogram of a 12-week-old male mixed poodle with a large PDA and severe pulmonary hypertension (pulmonary arterial pressure, 112/90 mm Hg; mean 98 mm Hg; aortic pressure, 106/50 mm Hg, mean 90 mm Hg. All pressures recorded under pentobarbital sodium anesthesia, breathing 100% oxygen). Top: Left lateral angiocardioogram immediately after injection of contrast medium into the right ventricle. The main pulmonary artery (P) and its branches, a large patent ductus arteriosus (D), and the descending aorta (A) are shown. Bottom: Five seconds after the exposure above, contrast medium filled the left atrium (LA), left ventricle (LV), ascending aorta (A), and ductus arteriosus (D). There is some left-to-right flow of contrast medium across the ductus, as indicated by minimal filling of the pulmonary artery (P).
described in terms of its incidence of the three phenotypic classes. The underlying scale is transformed to standard deviation units by referring to tables of the normal curve. With a given incidence, a table of "probits" gives the deviation in standard deviation units of the threshold from the mean of the population (24). To compare different groups with respect to their mean liability to defective ductal closure, the thresholds are used as fixed reference points on the scale of liability, and the mean of each group is determined in relation to these points. The two-threshold model has the advantage of allowing a comparison of standard deviations as well as means of liability (23). This possibility arises from the reasonable assumption that the distance between the two thresholds (threshold interval) represents a difference on the underlying scale which is constant from one group to another.

Threshold intervals are given in Table 2 for offspring grouped according to the proportion of genes they have in common with dogs with PDA. The threshold intervals as determined from the incidences in the three phenotypic classes do not differ significantly between groups ($X^2 = 1.090, P > 0.80, df = 4$), and we can assume that the various groups have the same standard deviation. A weighted threshold difference was calculated (0.5273), corresponding to a standard deviation of $1.8965 \pm 0.0912$. This was used to calculate the mean liability to defective ductal closure in groups of offspring receiving different proportions of their genomes from dogs with PDA (Table 2). The distribution of liability to defective ductal closure in three groups is depicted graphically in Figure 4. The threshold between normal and ductus diverticulum is used as the origin of the scale of liability, which is marked in "threshold standard deviation units" (one unit is equal to the weighted threshold interval). The mean liability of the offspring of PDA X PDA matings lies well above both thresholds, and the mean liability of the offspring of PDA X N matings lies below them. The mean liability of

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Threshold Intervals and Means of Liability to Defective Ductal Closure in Offspring Grouped According to the Proportion of Genes in Common with Dogs with PDA</strong></td>
</tr>
<tr>
<td>Prop. of genes in common with dogs with PDA</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>PDA</td>
</tr>
<tr>
<td>78</td>
</tr>
<tr>
<td>31</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

The threshold intervals are not significantly different from each other ($X^2 = 1.090, P > 0.80$). Weighted mean interval $= 1.8965 \pm 0.0912$. The threshold intervals are given in Table 2.

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Normal

\[ PDA \times PDA \]
\[ r = 1 \]

\[ PDA \times N(1^\circ \text{Rel. PDA}) \]
\[ r = 3/4 \]

\[ PDA \times R \]
\[ r = 1/2 \]

Distribution of liability to defective ductal closure in the offspring of three mating types. Assuming a common standard deviation, the means given in Table 2 are used to depict the distribution of liability to defective ductal closure with respect to the two developmental thresholds in the offspring of three types of matings. The mean liability of \( PDA \times N(1^\circ \text{Rel. PDA}) \) offspring (proportion of genes in common with dogs with \( PDA = r = 3/4 \)) lies approximately midway between the means of \( PDA \times PDA \) and \( PDA \times N \) offspring \( (r = 1 \text{ and } r = 5, \text{ respectively}) \). This information is used to estimate the heritability of liability to defective ductal closure in the Appendix.

PDA \( \times N(1^\circ \text{Rel. PDA}) \) offspring lies between the two thresholds and approximately midway between the means of the other two groups. From this, it is seen that as the proportion of the genome derived from PDA dogs \( (r \text{ value}) \) increased from 1/2 to 3/4 to 1, there was an increasing liability to defective ductal closure. This same relationship is found when offspring having other \( r \) values are considered. The liability to defective ductal closure increased with the PDA-derived proportion of the genome as would be expected in polygenic inheritance (Fig. 5).

**Heritability**

Polygenic traits are notoriously susceptible to environmental variation (22). It is therefore of interest to estimate what proportion, if any, of the phenotypic variation seen in hereditary PDA is nongenetic in cause. Heritability is defined as the proportion of total phenotypic variability due to the average or additive effect of genes \( \text{(heritability} = h^2 = \text{additive genotypic variance/total phenotypic variance} = VA/VP) \). This measure, which excludes nonadditive sources of genetic variance \( \text{(dominance and interaction)} \), expresses the extent to which the parental phenotypes are transmitted to the offspring. Heritability values range from 0 to 1. A value of 1 attributes all of the observed phenotypic variation in a trait to the additive effects of genes.

**Figure 4**

Distribution of liability to defective ductal closure in the offspring of three mating types. Assuming a common standard deviation, the means given in Table 2 are used to depict the distribution of liability to defective ductal closure with respect to the two developmental thresholds in the offspring of three types of matings. The mean liability of \( PDA \times N(1^\circ \text{Rel. PDA}) \) offspring (proportion of genes in common with dogs with \( PDA = r = 3/4 \)) lies approximately midway between the means of \( PDA \times PDA \) and \( PDA \times N \) offspring \( (r = 1 \text{ and } r = 5, \text{ respectively}) \). This information is used to estimate the heritability of liability to defective ductal closure in the Appendix.

**Figure 5**

Mean liability to defective ductal closure. The mean liability \( (\pm 1 \text{ se}) \) to defective ductal closure increases as the proportion of genes the members of the group have in common with dogs with PDA increases.
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Heritability is estimated by regression analysis of the resemblance between relatives. In the case of hereditary PDA, the information necessary to make a rough estimate of heritability is given in Table 2 and Figure 4. The location of the mean liability of \(N(1^o\) Rel. PDA) × PDA offspring with respect to the mean of \(N\times PDA\) and \(PDA\times PDA\) offspring is a function of heritability. If heritability has a value of 1, the mean liability of \(N(1^o\) Rel. PDA) × PDA offspring should lie halfway between the other two means. As can be seen in Figure 4, this is approximately the case. The value of heritability obtained using the method in the Appendix is \(1.167 \pm 0.276\). This value is not significantly different from 1. We may conclude from this estimate that the heritability of liability to hereditary canine PDA is high, and that under the conditions of the present experiments, environmental factors were not a major source of variation in determining liability to defective ductal closure.

RELATION OF THE INCIDENCE OF SERIOUS SEQUELAE OF PDA TO MATING TYPE

As already noted, left heart failure and severe pulmonary hypertension with right-to-left or bidirectional shunts occurred as separately identifiable sequelae to PDA in a substantial number of pups. Either of these syndromes can be considered as a sign of serious cardiovascular impairment, indicative of a PDA of large size. A higher incidence of these sequelae among PDA dogs of one group than another would, other factors being equal, suggest a higher proportion of large PDA’s. The distribution of left heart failure and severe pulmonary hypertension in the 61 pups with PDA is given in Table 3. Offspring were placed in three groups according to the proportion of their genomes derived from dogs with PDA: 50% or less, 50% to 75%, and 100%. The incidence of serious sequelae increased with the proportion of the genome derived from dogs with PDA. The probability of chance differences as great or greater than those observed is less than 1 in 1000 \((X^2 = 18.776, df = 2)\). This may be interpreted as evidence of additive effects above the threshold, these effects becoming more severe as the whole population is shifted to the right with respect to the threshold (Fig. 4).

Discussion

The results of this study confirm the previous indications that PDA in poodle dogs is a specific, localized developmental anomaly which is genetically determined. Preliminary test matings previously reported (5) gave results consistent with simple autosomal dominant transmission, but the more extensive studies outlined here indicate that PDA is not inherited as a simple mendelian trait. On closer examination, defective closure of the ductus arteriosus resembles a quasi-continuous or threshold trait of high heritability, both in its graded phenotypic expression and its behavior in test crosses. As the proportion of genes received from dogs with PDA increased,

<table>
<thead>
<tr>
<th>TABLE 3</th>
</tr>
</thead>
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Distribution of Left Heart Failure and Severe Pulmonary Hypertension in Pups with Hereditary PDA

<table>
<thead>
<tr>
<th>Parental phenotypes (reciprocal crosses pooled)</th>
<th>(r)</th>
<th>No. pup with PDA</th>
<th>No. left heart failure</th>
<th>No. pulmonary hypertension</th>
<th>Total sequelae</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD or PDA × N</td>
<td>0.375–0.50</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DD or PDA × N(1(^o) Rel. PDA) and DD×PDA</td>
<td>0.50–0.75</td>
<td>13</td>
<td>16</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>PDA × PDA</td>
<td>1.00</td>
<td>16</td>
<td>7</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>All matings</td>
<td></td>
<td>32</td>
<td>29</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>

\(r = \) Proportion of genes the offspring have in common with dogs with PDA.

Under the hypothesis that the incidence of left heart failure and pulmonary hypertension combined is not different in the three groups, the observed or more extreme distribution would be expected with \(P < 0.001\) \((X^2 = 18.776, df = 2)\).
there was an increase in both the incidence of
defective ductal closure and the incidence of
serious sequelae to PDA, indicating that an
increasing liability to PDA was accompanied
by an increase in the severity of the lesion. In
quasi-continuous traits, an increase in the
percent of abnormals usually goes together
with the appearance of more severely affected
individuals (20).

It should be understood that the threshold
model used in the present analysis is a
convenient simplification which is at the
opposite extreme from fully penetrant single-
gene inheritance. The results of test matings,
though not consistent with single-factor inher-
itance and in reasonable agreement with the
polygenic threshold model, do not insure that
all of the conditions of the threshold model
are in fact satisfied. In particular, the assump-
tion of “a large number of genes, each of small
effect,” is not proved. It might be argued that
the results presented are consistent with
transmission of a single dominant gene with
“variable penetrance and expressivity,” but if
this is so, the normal first-degree relatives of
dogs with PDA must possess specific modifiers
which enhance the penetrance and expressiv-
ity of that gene, while other normal dogs must
have modifiers which limit its full expression.
As has been pointed out by Edwards (25), the
model of a single gene with penetrance
may yield numerical results that are
difficult or impossible to distinguish from
those of the true quasi-continuous model, if
the penetrance is assumed to vary with
modifying genes in the genetic background.
The concept of a single gene with penetrance
thus approaches the true quasicontinuous
model as other genes in the genetic back-
ground have an increasing influence on its
expression (25).

It should also be emphasized that while the
present data are consistent with a high degree
of heritability, and thus indicate that environ-
mental factors were not a major source of
variability under the conditions of these
experiments, they do not rule out the possibil-
ity that the genetically determined processes
involved in ductal closure might be subject to
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environmental variation. Particularly where genetically determined liability to PDA lies just below threshold for abnormal ductal closure, certain environmental conditions (e.g., neonatal hypoxia) might have sufficient influence on the underlying developmental mechanisms to shift the individual beyond the threshold.

The superficial resemblance to simple dominant inheritance exhibited by hereditary PDA in the dog can be explained by the polygenic threshold model when it is understood that the liability of an individual to develop a threshold trait may lie in any position with respect to the threshold at which phenotypic discontinuity occurs. When an affected animal, whose liability lies above the threshold, is mated to a normal animal, a proportion of their offspring approximating 50% may fall above the threshold, depending upon the heritability of the trait and the position of both parents' liabilities with respect to the threshold. It is also possible for the pattern of transmission of threshold traits to simulate simple recessive inheritance. If the parents are themselves clinically unaffected, but their liabilities to the trait lie near the threshold, the mean liability of their offspring will be shifted to the right of the general population, and some proportion may fall above the threshold. If that proportion is near 1/4, the trait will appear to be inherited as a simple recessive in those families. An increase in the incidence of a trait with inbreeding (consanguinity) is well known as a feature of simple recessive inheritance, but it is no less characteristic of threshold traits, since the multiple genes responsible may be concentrated by the same process.

The confusing results of family studies of PDA in man also are perhaps best explained by the threshold model. The slightly increased rate of consanguinity in the parents of patients with PDA noted by Lamy et al. (6) and by Polani and Campbell (7) would be expected if the defect were inherited as a simple recessive trait, but Wilkins's observations that the incidence in siblings of patients with PDA is on the same order as that in their offspring is not consistent with that interpretation (12). Furthermore, although family pedigrees occasionally resemble dominant inheritance (8, 11), the low incidence of PDA in the offspring of patients (1.7%) is not expected with simple dominant transmission (12). These seemingly conflicting findings are, however, characteristic of threshold traits. Depending upon the mean liabilities of the parents of individual families, threshold traits behave sometimes as recessives and sometimes as dominants, but on careful examination fail to satisfy the criteria for either.

Appendix

A METHOD FOR THE ESTIMATION OF HERITABILITY OF THRESHOLD TRAITS

As pointed out by Falconer (23), an estimate of the heritability (h²) of a threshold trait can be obtained from the incidence of the trait in the general population and that in the near relatives of affected individuals. Assuming a continuous, normal distribution of multiple genetic and environmental determinants with a fixed threshold beyond which individuals are affected, incidence data are converted to means on a scale of standard deviation units by referring to a table of probits (24). The scale may be thought of as one of "liability" to the trait in question. By analogy with a selection experiment, the distance along the scale between the mean liability of affected individuals in the general population and the mean of the normal individuals may be thought of as the "selection differential." The distance between the mean of the normal individuals in the population and the mean of the near-relatives of affected individuals may be considered analogous to the "response to selection." That response being a function of the degree of relationship to affected individuals and the heritability of the trait. First-degree relatives have half of their genes in common. If heritability had a value of 1 (100% of phenotypic variance due to the additive effects of genes), the mean liability of the first-degree relatives of affected individuals would be expected to lie halfway between the mean of the normal individuals in the general population and the mean of the affected individuals. If heritability was zero, the mean liability of relatives would be the same as that of the normal individuals in the general population (there would be no response to selection).

In the present analysis, accurate data on the incidence of PDA in the general dog population are not available, precluding Falconer's method of estimating the mean liabilities of either normal or
abnormal individuals. However, an estimate of the mean liability of affected animals can be obtained from the incidence of the trait in the offspring of matings between two affected individuals, and heritability can be estimated from the relative positions of this mean and the mean liabilities of two other classes of relatives.

Three types of mating must be performed, and the mean liability of each group of offspring is determined from a probit transformation of the proportion falling beyond the threshold (Table 2 and Fig. 4). Inbreeding effects are minimized by choosing mating pairs that are not closely related (in the present study, mating pairs were not related within five generations).

The three mating types selected in the present study were:

<table>
<thead>
<tr>
<th>Type of Mating of Offspring</th>
<th>Mean Liability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affected X Affected</td>
<td>M₁</td>
</tr>
<tr>
<td>Affected X Normal (unrelated)</td>
<td>M₂</td>
</tr>
<tr>
<td>Affected X Normal (1° Rel. of Affected)</td>
<td>M₄</td>
</tr>
</tbody>
</table>

The position of M₂ on the scale of liability is assumed to represent the mean liability of affected animals. The mean liability of unrelated normal animals (M₃) is unknown. The positions of M₄ and M₄ would be expected to lie between M₁ and M₂ on the liability scale.

By analogy with a selection experiment, the following relationships are meaningful: D = (M₁ - M₄); Selection Differential. From the relationships in Figure 4 let A = M₁ - M₄ and C = M₁ = M₄.

Y = the shift in the mean liability to the trait due to selection of genes for the trait. Therefore: Y₁ = D - A; this would represent the shift when affected animals are mated to normal unrelated animals. The offspring would have one-half of their genes in common with affected animals (rₐ = 0.50). Y₂ = D - C; this would represent the shift when affected animals are mated to phenotypically normal first-degree relatives of affected animals. The offspring would have three-fourths of their genes in common with affected dogs (r₄ = 0.75).

Substituting now into formula 1 we find the estimate of heritability to be:

\[ h^2 = \frac{4(X₃ - X₄)}{3X₃ - 2X₄ - X₁} = \frac{C}{B}. \]  

where X₃ = the probit representing the deviation of thresholds from the mean in standard deviation units (Table 2).

The standard error of h² can be obtained from

\[ SE(h^2) = \sqrt{\frac{(h^2)^2 \cdot Var.(G) + Var.(B)}{G^2 + B^2}}, \]

where \( Var.(G) = 16(V(X₃) + V(X₄)). \)

\[Var.(B) = 9V(X₃) + 4V(X₄) + V(X₁), \]

and

\[ V(X₃) = 2πe²\left(\frac{(N - b)b}{N^4}\right).\]

with N = total offspring of the mating, and b = number of offspring with PDA.

Utilizing the data in Table 2 and Figure 4, Table 4 demonstrates the application of the technique.

From formula 6 we obtain:

- Variance of \( X₄ = V(X₄) = 0.0136; \)
- Variance of \( X₃ = V(X₃) = 0.0995; \)
- Variance of \( X₁ = V(X₁) = 0.0370. \)

From formulas 4 and 5 it follows that:

\[ Variance\ of\ G = 16(0.0136 + 0.0370) = 0.8096 \text{ and,} \]

\[ Variance\ of\ B = 9(0.0136) + 4(0.0370) + 0.0995 = 0.3699. \]

Substituting now into formula 1 we find the estimate of heritability to be:

\[ h^2 = 0.817 + 1.478 \]

\[ = 0.75(1.799 - (-1.478)) - 0.50(1.799 - 0.817). \]

or by means of formula 2,

\[ h^2 = 1.1669, \]

\[ = \frac{4(0.7792 - (-0.4308))}{3(0.7792) - 2(-0.4308) - (-0.9486) - 4.8400 = 4.1478. \]

\[ h^2 = 1.1669, \]

and the standard error of the estimate of heritability is obtained from formula 3.

\[ SE(h^2) = \sqrt{\left(\frac{1.1669^2}{0.8096 + 0.3699} + \frac{1.1669^2}{4.1478}\right)}, \]

\[ SE(h^2) = 0.2763. \]
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