Quantitative genetics of traits associated with hip dysplasia in a canine pedigree constructed by mating dysplastic Labrador Retrievers with unaffected Greyhounds

Stuart Bliss, DVM; Rory J. Todhunter, BVSc, PhD; Richard Quaas, PhD; George Casella, PhD; Rongling Wu, PhD; George Lust, PhD; Alma Jo Williams, BS; Samuel Hamilton, BVSc; Nathan L. Dykes, DVM; Amy Yeager, DVM; Robert O. Gilbert, BVSc, MMedVet; Nancy I. Burton-Wurster, PhD; Gregory M. Acland, DVM

Objective—To determine the genetic influence on expression of traits associated with canine hip dysplasia.

Animals—193 dogs from an experimental canine pedigree.

Procedure—An experimental canine pedigree was developed for linkage analysis of hip dysplasia by mating dysplastic Labrador Retrievers with nondysplastic Greyhounds. A statistical model was designed to test the effects of Labrador Retriever and Greyhound alleles on age at detection of femoral capital epiphyseal ossification, 8-month distraction index, and 8-month dorsolateral subluxation score.

Results—The additive effect was significant for age at detection of femoral capital epiphyseal ossification. Restricted maximum likelihood estimates (± SD) for this trait were 6.4 ± 1.95, 10.2 ± 2.0, 10.8 ± 3.1, 11.4 ± 2.1, and 13.6 ± 4.6 days of age for Greyhounds, Greyhound backcross dogs, F1 dogs, Labrador Retriever backcross dogs, and Labrador Retrievers, respectively. The additive effect was also significant for the distraction index. Estimates for this trait were 0.21 ± 0.07, 0.29 ± 0.15, 0.44 ± 0.12, 0.52 ± 0.18, and 0.6 ± 0.17 for the same groups, respectively. For the dorsolateral subluxation score, additive and dominance effects were significant. Estimates for this trait were 73.5 ± 4.1, 71.3 ± 6.5, 69.1 ± 6.0, 50.6 ± 12.9, and 48.4 ± 7.7%, respectively, for the same groups.

Conclusions—in this canine pedigree, traits associated with canine hip dysplasia are heritable. Phenotypic differences exist among founder dogs of each breed and their crosses. This pedigree should be useful for identification of quantitative trait loci underlying the dysplastic phenotype. (Am J Vet Res 2002;63:1029–1035)

Canine hip dysplasia (CHD) is a common developmental trait that affects primarily large breed dogs and is characterized by poor hip joint congruity, joint laxity and subluxation, and development of secondary coxofemoral joint osteoarthritis (OA).1 Hip dysplasia is a quantitative trait, the expression of which is influenced by genetic, nutritional, and possibly hormonal factors.2 Heritability estimates for CHD range from 0.11 to 0.68.3,4 The complex pattern of inheritance of CHD suggests that expression of the trait is controlled by genes located at several quantitative trait loci (QTL).5 Alleles that contribute to the development of a complex trait such as CHD may act in an additive or dominant fashion, and the magnitude of the effect of an individual locus is independent of its mode of inheritance. Development of CHD undoubtedly results from complex interactions among multiple genetic loci and environmental factors. Nevertheless, a few major QTL are likely to be involved in trait expression, and a single major locus may have a substantial influence on this trait on the basis of biometric methods outlined by Leighton.6

Hip dysplasia is most commonly diagnosed by examination of ventrodorsal hip-extended radiographic views of the pelvis. Radiographic criteria for subjective grading of dogs on the basis of identification of dysplastic conformational features and OA have been proposed.7 Selective breeding programs determined on the basis of this form of radiographic assessment have been applied in a number of dog populations; however, because of the modest sensitivity of this test in immature dogs, success in reducing the prevalence of CHD has been limited.8,9,10-14 Alternative methods for measurement of the dysplastic phenotype include the distraction index (DI),2,9,15,16 dorsolateral subluxation (DLS) score,17 and radiographic determination of the age of detection of femoral capital epiphyseal ossification (OSS).18,19 These tests measure different features of hip conformation and differ with respect to their sensitivity and specificity as predictors of development of hip joint OA in an experimental pedigree.4

Because neither the genetic potential to develop CHD nor the carrier status of an individual dog can be unequivocally inferred from its phenotype, selective breeding programs determined on the basis of phenotypic evaluation of adult dogs are likely to remain inefficient. Genetic testing would aid breeders and
prospective owners in selection of immature dogs that
do not carry susceptibility alleles for CHD.
Unfortunately, the molecular genetic basis of CHD is
unknown, and elucidation of the QTL that underlie
expression of a complex trait such as CHD is a formi-
dable task. Linkage analysis is a statistical method for
mapping and identification of QTL that has been used
extensively in experimental settings as well as for
genetic analysis of several human diseases. In
veterinary medicine, linkage analysis has led to the iden-
tification of loci or mutations underlying a number
of monogenic disorders. However, linkage analysis for
identification of QTL associated with a complex canine
trait of clinical veterinary importance has not been
reported.

Detection of linkage between a set of polymorphic
genetic markers and a complex trait requires that a
pedigree be informative with respect to mapped genetic
markers and the QTL associated with the trait of
interest. Informativeness refers to the overall confi-
dence with which the parental source of a marker allele
or a QTL can be determined for members of a pedigree.
The presence of significant measurable phenotypic dif-
fferences between members of a pedigree is a necessary
condition for observation of linkage and thus is an
indication of QTL informativeness. We have developed
an outcrossed pedigree for linkage analysis of CHD.
The purpose of the study reported here was to describe
a biometrical model for evaluation of the differences
among the founder breed dogs and their crosses in this
pedigree with respect to the traits OSS, DI, and DLS
score. Our results demonstrate that the pedigree is
informative with respect to the QTL underlying
expression of these traits. This information provides a
necessary foundation for the development of statistical
models for linkage analysis that incorporate molecular
data from genome-wide analysis of genetic markers.

Materials and Methods

Pedigree—A canine pedigree was constructed for link-
age analysis of CHD by outcrossing dysplastic Labrador
Retrievers (LR) with unaffected Greyhounds (GH). Briefly,
trait-free GH (2 males and 5 females) were purchased from
racing stock. Dysplastic LR (5 males and 3 females) were
selected from an inbred pedigree that has been maintained
at the James A. Baker Institute for Animal Health, Cornell
University, for the study of CHD since 1968. Seven dogs
from the first filial generation (F1) were bred back to GH
and LR parents of other F1 litters or intercrossed to encour-
gage maximum recombination across the entire genome
(Fig 1). Two GH founder dogs were bred to each other and
produced a litter of 9 puppies; measurements from these
dogs were used to estimate the phenotype of GH founder
dogs at 8 months of age. Siblings of 6 LR founder dogs
(n = 22) were similarly used to improve the accuracy of 8-
month trait value estimates for this breed.

Dogs were bred by artificial insemination on the basis of
an increase in serum progesterone concentrations. Dogs were
inseminated between days 3 and 6 after their serum proges-
terone concentrations reached 1.0 ng/ml. Feeding regimens
were designed to achieve maximum growth rate for maxi-
mum expression of CHD. Pregnant and postpartum bitch-
es were fed a standard diet of canned and ad libitum dry food.
Rice cereal and canned and dry food were introduced into the
diet at 4 weeks, and puppies were weaned at 6 weeks of age.

Figure 1—Diagram of an outcrossed pedigree developed for linkage analysis of hip dysplasia. Squares and circles represent males and
females, respectively. Filled and open portions of each symbol represent the proportion of Greyhound and Labrador Retriever alleles,
respectively, possessed by that dog. The first letter of a litter indicates the temporal sequence of litter for that year (ie, A is the first
litter born, B the second). X = F1 dogs, 2F = F2 dogs. B = Backcross (BC). 2B = BC X BC. The first numeral is the birth order for each
dog in that litter and the last numeral is the year born (ie, 5 = 1995, 6 = 1996). For example, FX16 is the first F1 dog in the Fth (6th) lit-
ter born in 1996.
Dogs were examined regularly for lameness or other clinical signs of OA. The Institutional Animal Care and Use Committee approved all aspects of the study, including provisions for medical treatment of OA.

Detection of OSS—Femoral capital epiphysal ossification was determined radiographically or ultrasonographically. For radiographic imaging, puppies were positioned in sternal recumbency, and dorsoventral radiographic views of the pelvis were obtained. Imaging was performed every other day starting at 4 days of age until ossification was observed in each proximal femoral chondroepiphysis. For ultrasonographic imaging, puppies were positioned in ventral recumbency. Images of each femoral capital epiphysis were obtained in the transverse view with a 12- to 5-MHz linear array transducer. Imaging was performed every other day from 4 days of age until ossification was observed twice consecutively in each capital femoral epiphysis. Ossification was observed as an echogenic region in the developing capital femoral chondroepiphysis. For all dogs, OSS was expressed as the radiographic age at detection of epiphysal ossification. For dogs that were examined ultrasonographically, OSS was determined by adding 2 days to the age at which epiphysial ossification was observed ultrasonographically, as previously described.4

Distraction index—Radiographic views for DI determination were obtained for each dog under general anesthesia at 8 months of age.11 The maximum amount of lateral hip joint laxity was measured, and the DI was determined from these radiographic views.4

Dorsolateral subluxation score—Dorsolateral subluxation radiographic views were similarly obtained under general anesthesia at 8 months of age. Dogs were placed in sternal recumbency with the femora axially loaded in a neutral position, and dorsoventral radiographic views were obtained.26 Percentage of the femoral head covered by the craniodorsal acetabular rim was calculated by 1 author (AJV).

Standard radiographic evaluation—Standard ventrodorsal hip-extended radiographic views of the pelvis were also obtained under general anesthesia at 8 months of age. Hip joint conformation of each dog was assessed by a board-certified radiologist (NLD). Dogs were considered dysplastic if typical radiographic signs of coxofemoral joint subluxation or degenerative joint disease were identified in either hip.

Genetic modeling—We developed a statistical model that has allowed us to show the genetic contribution of each founder breed (LR, GH) and crossbreed groups (F1 dogs, F2 backcrosses to Greyhounds [BCG dogs]) to traits associated with the development of CHD in dogs in this pedigree. This model attributes to each breed or crossbreed that proportion of genes (as a proportion of GG and LL alleles, whereas the coefficient of additive effect (α) and a dominance effect (δ) were assumed to be fixed. The dominance effect is assumed to be fixed. The coefficient of the additive effect (β1) is the difference between the expected proportion of GG and LL alleles, whereas the coefficient of the additive effect (β1) is the expected probability that a dog is heterozygous for alleles from the GG and LL at any given locus. For ease of calculation, we set the F1 genotype to 0, the GG genotype to 1, and the LL genotype to -1 (Table 1). Model 2 thus incorporates an “in-bred” contrast between the GG and LL genotypes that allows their relative contribution to additive and dominant components to be tested simultaneously. The dominance effect is assumed to reflect the collective dominance of alleles carried by a single breed or crossbreed. Epistatic effects are not accounted for in this model. Point estimates for the mean values for each trait (OSS, DI, and DLS) for each group were calculated as follows:

\[
Y = \beta_0 + \beta_1(\text{gender}) + \beta_2(\text{litter}) + \beta_3(\alpha) + \beta_4(\delta) + \text{residual}
\]

where \( Y \) is the mean value of an individual trait (OSS, DI, or DLS) in a given group of dogs, and \( \beta_0 = \) the overall mean value for a given trait within the entire study population.

The GG and LL indicate the effects of alleles derived from GH or LR founder dogs, respectively, whereas GL represents the effect of alleles derived from the F1 dogs. Litter was modeled as a random variable; all other variables were considered fixed. For the OSS trait, the model was run with and without body weight at detection of ossification as a covariate. Also, to test for a sex effect on OSS, we modeled body weight as the dependent variable. Trait values were averaged over both hips for each dog. Separate analyses for the trait measures on the left and right hips were also performed.

To test specifically for additive and dominant genetic components of each trait, the 3 variables GG, GL, and LL in model 1 were further collapsed into 2 variables, an additive effect (α) and a dominance effect (δ) (Table 1). The model derived from new variables (model 2) was as follows:

\[
Y = \beta_0 + \beta_1(\text{gender}) + \beta_2(\text{litter}) + \beta_3(\alpha) + \beta_4(\delta) + \text{residual}
\]

where \( Y \) is the mean value of an individual trait (OSS, DI, or DLS) in a given group of dogs, and \( \beta_0 = \) the overall mean value for a given trait within the entire study population.

The GG and LL indicate the effects of alleles derived from GH or LR founder dogs, respectively, whereas GL represents the effect of alleles derived from the F1 dogs. Litter was modeled as a random variable; all other variables were considered fixed. For the OSS trait, the model was run with

### Table 1—Coefficients used in a mixed linear genetic model to adjust restricted maximum likelihood estimates of mean trait values for additive and dominant effects in an experimental outcrossed canine pedigree

<table>
<thead>
<tr>
<th>Breeds</th>
<th>GG</th>
<th>GL</th>
<th>LL</th>
<th>Additive</th>
<th>Dominant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greyhound (GG)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Labrador (LL)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>F1 (GL)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>BCG</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BCL</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
<td>-0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>F1 X BCL</td>
<td>0.25</td>
<td>0.5</td>
<td>0.25</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BSC X BCL</td>
<td>0.0625</td>
<td>0.375</td>
<td>0.5625</td>
<td>-0.5</td>
<td>0.375</td>
</tr>
</tbody>
</table>

GG = Homozygous alleles from Greyhounds. GL = Heterozygous alleles. LL = Homozygous alleles from Labrador Retrievers. F1 = First filial generation dogs. BCG = F1 backcrosses to Greyhounds. BCL = F1 backcrosses to Labrador Retrievers. F2 = Second filial generation dogs. BCL X BCL intercross = 1/16 GG, 6/16 GL (F1), and, 9/16 LL. Additive coefficient calculated as 1/16 – 9/16 = -0.5. Dominant coefficient calculated as 6/16 = 0.375.
Results

One hundred ninety-three dogs were included in the analysis. Data were available for 162 dogs in the outcrossed pedigree, including LR founder (n = 8), F1 (41), BCG (33), BCL (57), F2(16), and BCL X BCL intercrossed dogs (7; Fig 1). A litter of 9 GH bred on site from 2 GH founder dogs was used to estimate trait values for GH founder dogs at 8 months of age. In addition, 22 siblings of 6 LR founder dogs were included to improve trait estimates for this breed. Data for OSS, DI, and DLS score were available for 190, 175, and 135 dogs, respectively (Table 2). The DLS scores were unavailable for dogs that reached 8 months of age prior to the development of the DLS technique in 1996.

In the F1 generation, only 1 dog was unequivocally dysplastic on the basis of assessment of standard ventrodorsal pelvic radiographs. No dogs in the BCG generation had evidence of CHD, whereas dogs in the BCL generation had a broad distribution of phenotypes, from excellent hip joint conformation to severely dysplastic with advanced OA.

Summary data from the analysis with model 2 were calculated (Table 2). Results of analyses with model 1 are not shown because the focus of our study was on the additive and dominance effects contained in model 2. The OSS had a significant (P < 0.001) additive genetic effect whereby GH alleles decreased OSS by 3.6 ± 0.9 (REML ± SE) days (Fig 2). However, body weight at OSS had a significant (P < 0.001) effect whereby for every increase in body weight by 1 oz, OSS was delayed by 0.20 ± 0.03 days. Males were significantly heavier at OSS than females (increase of 34.4 ± 1.5 vs 31.8 ± 1.5 oz, respectively; P = 0.004); however, there was no significant additive or dominance effect on body weight itself.

For the DI, the additive genetic effect was significant (P < 0.001) whereby GH alleles decreased the DI by 0.2 ± 0.04. There was no dominance or sex effect on the DI (Fig 3).

For the DLS score, the additive genetic effect was significant (P < 0.001) whereby GH alleles increased the DLS score by 12.5 ± 2.8%. Additionally, there was a significant (P = 0.007) dominance effect whereby GH alleles increased the DLS score by a further 8.2 ± 3.0%. Consequently, the DLS scores for GH, BCG dogs, and the combined F1 and F2 dogs were indistinguishable (Fig 4). Females had higher DLS scores than males, but the difference was not significant (62.1 ± 1.6 vs 59.2 ± 1.6%, respectively; P = 0.06). Separate analyses for the trait measures on the left and right hips produced similar results (data not shown).
developing hip joint OA. Finally, results of a recent study indicate that a clear dose-response relationship exists between the DLS score and development of hip joint OA. In that study, the odds ratios for presence of a cartilage lesion at necropsy at 8 months of age in 106 dogs were 0.2, 2.6, and 8.0 for dogs with DLS scores > 55, 45 to 55, and < 45%, respectively. All 8-month-old dogs with DLS scores < 42% had characteristic periloveal cartilage lesions at necropsy. These results, in conjunction with the segregation of the loci underlying these traits observed in the pedigree of our study, support our strategy of decomposing the dysplastic phenotype into separate measurable traits for linkage analysis.

These results lend support to our power analysis for detecting linkage to OSS, DI, and DLS score. In that analysis, Monte Carlo breeding simulations of the founder and F1 dogs were conducted to project backcross phenotypes, and the power to detect linkage between a single genetic marker and the individual traits was calculated. The analysis assumed a normal distribution of phenotypic values for OSS, DI, and DLS scores in the founder and F1 populations. Independent variables included the recombination fraction (θ) of a hypothetical QTL associated with a given genetic marker, the mean heterozygosity (h) of the F1 dogs over all marker loci, and the effect sizes for each trait (calculated as the difference in the trait means between 2 breeding groups divided by the SD). The analysis estimated that the BCG has greater power for detection of linkage to the DI and OSS than the reciprocal backcross. Conversely, the BCL was predicted to be more powerful (all other factors being equal it will require fewer dogs) for detection of linkage to the DLS score than the reciprocal cross. Specifically, on the basis of h = 0.75, θ = 0.05, and the observed effect sizes in the founder and F1 populations, the analysis predicted that 35 BCL would be required to achieve a power of 0.8 for detection of linkage to the DLS score in that population. In contrast, detection of linkage to the DLS score in the BCG population at that power would require 120 dogs. Conversely, 35 and 45 BCG dogs, or 100 and 110 BCL dogs, would be required to obtain equal power for detection of linkage to the DI and OSS, respectively, in those populations. As illustrated (Fig 4), with respect to the DLS score, F1 dogs were indistinguishable from GH founder dogs. Therefore, on the basis of the genetic model described here, it would be easier to separate the mixture of distributions in DLS scores as a function of marker alleles from a cross between the F1 dogs and LR than between the F1 dogs and GH.

The significance of the dominant component for the DLS score is an important finding with regards to linkage analysis and indicates that the BCG when used alone will provide little or no information regarding the QTL underlying this trait. Both additive and dominance genetic effects on a particular trait are important components of statistical models developed for linkage analysis. The power of the test of significance of a QTL is a function of many factors including the number of progeny in the population, the magnitude of the QTL effect, the pedigree structure, and the dominance of the QTL. For additive QTL, an F2 intercross pedigree design is more powerful than a backcross. However, for dominant QTL, an informative backcross can be twice as powerful as an intercross. It is important to note...
that our model does not specify the mode of inheritance of any putative QTL associated with these traits. Rather, the significance of the dominant component in our model represents a net dominance, over all con- tributory loci, of GH alleles over LR alleles with respect to the DLS score. Nevertheless, these results suggest that a backcross design may be the most efficient pedigree structure for detection of QTL underlying the DLS score. This is consistent with the results of our recent power analysis.4 Fortuitously, the DLS score has also been shown to have higher sensitivity and specificity for diagnosis of CHD and coxofemoral joint OA in this pedigree than the DI or standard ventrodorsal radiographic hip joint scoring.39

A limitation of the model described here emerges from the fact that LR and GH founder dogs in the pedigree of our study were selected from separate inbred canine populations. We have assumed that generations of inbreeding have resulted in different alleles becoming fixed at 1 or more controlling loci in each respective founder population. Fixed alleles have no effect on phenotypic variation within a given population.43 However, in an outcrossed pedigree, if a fixed allele within 1 founder population is dominant and has a large effect, it will exert a major impact on the mean differences between founder breeds, as well as on the relative phenotypes of the various progeny. The model we used assumes such a locus. Therefore, no conclusions can be drawn regarding additive or dominance genetic effects on the DI, OSS, or DLS score within either founder breed. Moreover, because the traits we examined are understood to be polygenic, our results represent estimates of the typical additive or dominance effects of LR versus GH alleles on individual trait values within the various crosses of the pedigree. Epistatic effects are not accounted for in this model.

Demonstration of strong genetic control over these traits, as shown in this outcrossed pedigree, is an important prerequisite for mapping the positions of underlying QTL by use of molecular genetic marker data. In principle, current statistical methods for QTL mapping could be used for linkage analysis of CHD in the pedigree of our study.31,35 However, conventional methods generally require large sample sizes to detect multiple QTL or QTL with small to modest effects. In experimental pedigrees of higher mammalian species it is often difficult to generate adequate sample sizes within a single family. One alternative involves a combined analysis of F2 dogs along with dogs from backcross breeding to various founder parents. Our pedigree is well suited for this type of analysis. Theoretical work suggests that inclusion of multiple families in an integrated mapping strategy can improve the power of QTL detection and the precision of QTL effect estimation.32,33 An additional challenge imposed by the fact that the founder dogs of the pedigree of our study were selected from separate populations is the possible existence of multiple alleles at any given locus as well as varying degrees of heterozygosity over different loci. If marker and QTL loci segregate in different patterns, correct determination of parental linkage phases over all loci is crucial for precise QTL localization. A model based on Markov chain statistical methods was recent-ly developed for simultaneous estimation of linkage and linkage phases for all possible different marker types (fully vs partially informative, dominant vs codominant).34 The genetic model described here provides a necessary first step toward accurate mapping of QTL segregating in multiple families. This model should prove to be a useful tool for analysis of complex canine traits in this and other experimental pedigrees.

References
Correction: Effect of short-chain fatty acids on contraction of smooth muscle in the canine colon

In the article “Effect of short-chain fatty acids on contraction of smooth muscle in the canine colon” (AJVR, February 2002, pp 295–300), the last sentence in the Conclusions and Clinical Response section of the structured abstract on page 295 is incorrect. The correct statement is as follows:

These findings may account for some of the effects of fiber on canine colonic motility.

Correction: Mediation of acetylcholine and substance P induced contractions by myosin light chain phosphorylation in feline colonic smooth muscle

In the article “Mediation of acetylcholine and substance P induced contractions by myosin light chain phosphorylation in feline colonic smooth muscle” (AJVR, May 2002, pp 695–702), the following items were incorrect.

In the fifth line of the right-hand column of page 696, the concentration of W-7 was listed as 100 to 1,000 mM. The correct concentration is 100 to 1,000 μM.

On page 701, the first footnote was listed incorrectly. The correct listing for this footnote is as follows:

The authors gratefully acknowledge the provision of animal tissue by Dr. Mark Haskins, Department of Pathobiology, School of Veterinary Medicine, University of Pennsylvania (NIH grants No. DK54481 and DK25759).

On page 702, page numbers for reference No. 39 should be G937–G944.

The American Journal of Veterinary Research regrets these errors.