A Candidate Gene Study of Canine Joint Diseases

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Abstract

Canine osteoarthritis (OA) commonly occurs in association with articular diseases, such as hip dysplasia (HD), elbow dysplasia (ED), or cranial cruciate ligament rupture (CCLR). We hypothesized that a common genomic risk for the development of canine joint disease and canine OA would be identified by evaluating the allele frequencies of candidate gene single nucleotide polymorphisms (SNPs) in dogs with OA associated with different articular diseases when compared with a general population of breed-matched dogs. DNA was extracted from blood samples obtained from Labrador Retrievers and Golden Retrievers surgically treated for ED, HD, and CCLR and confirmed to have radiographic evidence of OA. One hundred and thirteen SNPs in 20 candidate genes were genotyped. No significant associations were identified for SNPs or haplotypes in the candidate genes for the diseases evaluated. The candidate gene approach for the study of genetic association is unlikely to be successful for complex canine diseases such as OA without prior trait mapping evaluation.

Key words: association, canine, gene, joint, osteoarthritis

Osteoarthritis (OA) is a common, debilitating condition of mammalian joints, characterized by the destruction of articular cartilage, resulting in pain and dysfunction of the affected joint. OA is estimated to affect up to 20% of dogs over one year of age (Paradis et al. 2003) in the general dog population. The joints most commonly affected by OA in the dog are the hip, the elbow, and the stifle. Historically, OA of these joints has been considered to be secondary to primary diseases, such as hip dysplasia (HD), elbow dysplasia (ED), and cranial cruciate ligament rupture (CCLR).

Breed risks for the development of HD, ED, and CCLR are marked. The Labrador Retriever demonstrates a 3.4-fold increase in risk for the development of HD (LaFond et al. 2002), a 20.5-fold increase in risk for developing the primary component of ED (LaFond et al. 2002; fragmented coronoid process [FCP]), and a 5.5-fold increase risk for developing CCLR (Duval et al. 1999). Sex predisposition to the development of each of these diseases also exist, with male dogs being a greater risk for developing hip OA (Hays et al. 2007) and ED FCP; Salg et al. 2006, and neuter status conferring an increased risk for developing CCLR (Whitechair et al. 1993; Duval et al. 1999). The estimates of heritability for HD vary between 0.18 and 0.74 (Reed et al. 2000; Wood et al. 2000, 2002; Todhunter et al. 2003; Janutta et al. 2005), estimates for ED vary between 0.10 and 0.77 (Guthrie 1989; Guthrie and Pidduck 1990; Grondalen and Lingaas 1991; Studdert et al. 1991; Makie et al. 2000), and estimates for CCLR vary between 0.27 and 0.31 (Nielen et al. 2003; Wilke et al. 2006). A genetic correlation between HD and ED has also been identified in a population of Rottweilers (Makie et al. 2000), suggesting that these traits may be influenced by the same genetic and/or environmental factors in certain breeds. As both ED (Lang et al. 1995) and HD (Wood et al. 2002) are phenotyped by radiographic measures including osteophytosis, the genetic risk factors which are common between these 2 diseases may code for a risk of developing osteophytosis.
Recent evidence suggests that genetic factors may additionally affect the development of OA in dogs affected by articular disease. Differences in the breed tolerance of passive hip laxity for the development of hip OA imply that genetic differences affect the development of canine hip OA (Smith et al. 2001). The severity of OA in dogs presenting with ED, HD, and CCLR can vary widely, which is a function of disease duration, animal activity, nutrition status, and genetic profile. Thus, although the significance of primary versus secondary canine OA is underdetermined, canine OA per se is likely to have a significant genetic background.

In contrast to human OA (Clements et al. 2006), the genomic basis of joint disease in dogs has received limited investigation to date. A previous case-control candidate gene study of single nucleotide polymorphisms (SNPs) in 4 candidate genes (Fibronectin 1, type 9 collagen alpha 1 chain, type 9 collagen alpha 2 chain, and cartilage oligomeric protein) failed to identify any significant associations between SNPs and the development of CCLR in a population of Newfoundland dogs (Wilke et al. 2005). A study of microsatellite markers adjacent to 14 candidate collagen genes for ED also failed to identify significant associations with the development of the disease (Salg et al. 2006). A microsatellite marker (FH2320) on canine chromosome 3 (CFA3) has been linked with the development of osteoarthrosis of the cranial and caudal acetabulum in Portuguese water dogs (Chase et al. 2005). In a separate study of a Labrador Retriever and Greyhound cross pedigree, putative quantitative trait loci contributing to macroscopic evidence of hip OA were identified on CFA05, 18, 23, and 31 (Mateescu et al. 2008). Further qualitative assessment of the same pedigree also revealed that hip OA was inherited additively and without dominance (Hays et al. 2007).

The majority of candidate genes studies in human OA have evaluated genes that were associated with the molecular pathogenesis of the disease, such as cytokines and structural components of the extracellular matrix (Clements et al. 2006). The most successful study investigating candidate gene associations with human OA focused on genes that are differentially expressed in human OA synovium and cartilage (Valdes et al. 2004). Subsequently, a number of these gene polymorphism associations have been reproduced in different disease cohorts (Valdes et al. 2007). Furthermore, a prediction of OA risk in individuals could be attained by combining several of the genes that were consistently shown to be involved in OA susceptibility (Valdes, Doherty, et al. 2008).

We hypothesized that genomic risk for the development of joint disease per se and canine OA would be similar across the 3 most common articular diseases affecting dogs (ED, HD, and CCLR) and between different breeds of dog for the same disease (CCLR). We further hypothesized that these genomic risks could be elucidated by evaluating the allele frequencies of SNPs in candidate genes in populations of dogs with ED, HD, and CCLR of a single breed and between 2 breeds with a common disease (CCLR).

**Materials and Methods**

**Candidate Gene Selection**

Candidate genes were selected on the basis of previous association of polymorphisms reported with OA in man or from differential gene expression in articular tissues from canine or human OA joints. A full list of the genes evaluated the SNP positions, gene function, and justification for inclusion as a candidate gene are reported in Table 1.

The genes selected were ankyrin repeat domain 10 (ANKRD10), adenosine triphosphatase, Class VI, Type 11B (ATP11B), interleukin 1 alpha (IL1A), -2 (IL2), -4 (IL4), -6 (IL6), -10 (IL10), -12β (IL12β), leptin receptor (LEPR), matrix metalloproteinase 3 (MMP3), -9 (MMP9), -13 (MMP13), secreted protein, acidic, cysteine rich (osteonectin/SPARC), tissue inhibitor of metalloproteinase 1 (TIMP1), -2 (TIMP2), -3 (TIMP3), -4 (TIMP4), tenascin C (TNC), tumor necrosis factor α (TNFα), Zinc finger, and SWIM-type containing 2 (ZWIM2).

**Cohort Collection**

Genomic DNA was extracted from residual clotted and ethylenediaminetetraacetic acid (EDTA) preserved blood samples using a standard phenol–chloroform extraction method. Samples were suspended in Tris–EDTA and normalized to 5 ng/μl. All case samples were obtained from the United Kingdom DNA Archive for Companion Animals (http://pccwww.liv.ac.uk/DNA_Archive_for_Companion_Animals), and all control samples were obtained from a population of breed-matched dogs from the United Kingdom undergoing vaccination. Control dogs were not phenotyped for disease. The breeds and orthopedic diseases evaluated were selected by choosing cohorts for which at least 30 samples had been collected from individuals within a single breed, for a given condition. All samples from cases were collected by veterinary orthopedic specialist surgeons from dogs surgically treated for ED, HD, or CCLR and with no clinical evidence of a concurrent orthopedic condition (ED, HD, or CCLR) at the time of treatment. All cases had radiographic evidence of OA of the affected joint at the time of surgery. Samples were collected from Labrador Retrievers and Golden Retrievers being surgically treated for ED (FCP; Labrador Retrievers, \( n = 81 \) [11 females, 7 female neutered, 61 males, 1 male neutered, 1 male neutering status unknown]), HD (Labrador Retrievers, \( n = 32 \) [9 females, 7 female neutered, 14 males, 1 male neutered, 1 male unknown neutering status]), CCLR (Labrador Retrievers \( n = 51 \) [10 females, 19 female neutered, 15 males, 7 male neutered], Golden Retrievers 45 [5 females, 26 female neutered, 10 males, 4 male neutered]), and a population of dogs undergoing vaccination (Labrador Retrievers \( n = 344 \) [89 females, 29 female neutered, 105 males, 28 male neutered, 93 sex and neuter status unknown]), Golden Retrievers \( n = 94 \) [42 females, 11 female neutered, 34 males, 6 male neutered, 1 sex and neuter status unknown]). The control samples were not...
evaluated for disease status. An internal genotyping control was included on each plate.

### SNP Identification

Selected regions of each candidate gene were amplified by polymerase chain reaction (PCR). The PCR product was assessed for the presence of a polymorphic product using denaturing high-performance liquid chromatography (Spiegelman et al. 2000), and amplicons with melt curve analyses indicating a SNP were sequenced. SNPs identified were annotated to a genomic position by alignment of the sequence with the canine genome (www.Ensembl.org), and

<table>
<thead>
<tr>
<th>Name</th>
<th>CFA</th>
<th>U</th>
<th>P</th>
<th>E</th>
<th>I</th>
<th>D</th>
<th>Function</th>
<th>Justification for evaluation inclusion</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankyrin repeat domain 10 (ANKRD10)</td>
<td>22</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Structural component of muscle</td>
<td>Increased expression in canine ruptured CCL</td>
<td>(Clements et al. 2008)</td>
</tr>
<tr>
<td>Adenosine triphosphatase, Class VI, Type 11B</td>
<td>34</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cell membrane transport</td>
<td>Increased expression in canine ruptured CCL</td>
<td>(Clements et al. 2008)</td>
</tr>
<tr>
<td>Interleukin 1 alpha (IL1a)</td>
<td>17</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td>Proinflammatory cytokine</td>
<td>Increased expression in canine OA synovium and ruptured CCL. SNPs associated with human OA synovium</td>
<td>(Loughlin et al. 2002; Smith et al. 2004, 2005; Maccoux et al. 2007)</td>
</tr>
<tr>
<td>Interleukin 10 (II.10)</td>
<td>7</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td></td>
<td>Antiinflammatory cytokine</td>
<td>Increased expression in canine OA synovium</td>
<td>(Maccoux et al. 2007)</td>
</tr>
<tr>
<td>Interleukin 12 (II.12B)</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td>Proinflammatory cytokine</td>
<td>Increased expression in human OA synovium</td>
<td>(Sakkas et al. 1998)</td>
</tr>
<tr>
<td>Interleukin 2 (IL2)</td>
<td>19</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T and B cell proliferation</td>
<td>Expressed in human OA synovium</td>
<td>(Kardel et al. 2003)</td>
</tr>
<tr>
<td>Interleukin 4 (IL4)</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td></td>
<td>Antiinflammatory cytokine</td>
<td>Demonstrates role in sexual dimorphisms OA susceptibility in experimental animal model</td>
<td>(Mahr et al. 2003)</td>
</tr>
<tr>
<td>Interleukin 6 (IL6)</td>
<td>14</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td></td>
<td>Proinflammatory cytokine</td>
<td>Increased expression in canine OA synovium and ruptured CCL</td>
<td>(Maccoux et al. 2007)</td>
</tr>
<tr>
<td>Leptin receptor (LEPR)</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adipokine receptor</td>
<td>Increased agonist (leptin) expression in human OA synovium and ruptured CCL</td>
<td>(Dumond et al. 2003)</td>
</tr>
<tr>
<td>Matrix metalloproteinase 13 (MMP13)</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>Collagenase (cartilage break down)</td>
<td>Increased expression in canine hip OA cartilage and ruptured CCL</td>
<td>(Clements et al. 2006b, 2008)</td>
</tr>
<tr>
<td>Matrix metalloproteinase 3 (MMP3)</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Collagenase (cartilage break down)</td>
<td>Increased expression in canine hip OA cartilage</td>
<td>(Hegemann et al. 2003)</td>
</tr>
<tr>
<td>Matrix metalloproteinase 9 (MMP9)</td>
<td>24</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>Gelatinase</td>
<td>Increased expression in canine hip OA cartilage and ruptured CCL</td>
<td>(Clements et al. 2006b, 2008)</td>
</tr>
<tr>
<td>Secreted protein, acidic, cysteine rich (osteonectin/SPARC)</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Matrix-associated protein</td>
<td>Increased expression in canine hip OA cartilage</td>
<td>(Clements et al. 2006b)</td>
</tr>
<tr>
<td>Tissue inhibitor of metalloproteinase 1 (TIMP1)</td>
<td>X</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>Inhibition of metalloproteinase activity</td>
<td>Increased expression in canine hip OA cartilage</td>
<td>(Clements et al. 2006b)</td>
</tr>
<tr>
<td>Tissue inhibitor of metalloproteinase 2 (TIMP2)</td>
<td>9</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inhibition of metalloproteinase activity</td>
<td>Reduced expression in canine hip OA cartilage and ruptured CCL</td>
<td>(Clements et al. 2006b, 2008)</td>
</tr>
<tr>
<td>Tissue inhibitor of metalloproteinase 3 (TIMP3)</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Inhibition of metalloproteinase activity</td>
<td>Increased expression in human OA cartilage</td>
<td>(Kevorkian et al. 2004)</td>
</tr>
<tr>
<td>Tissue inhibitor of metalloproteinase 4 (TIMP4)</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>Inhibition of metalloproteinase activity</td>
<td>Reduced expression in canine hip cartilage OA</td>
<td>(Clements et al. 2006b)</td>
</tr>
<tr>
<td>Tenasin C (TNC)</td>
<td>11</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td>Extracellular matrix protein</td>
<td>Increased expression in ruptured CCL/OA cartilage</td>
<td>(Salter 1993; Clements et al. 2006b, 2008)</td>
</tr>
<tr>
<td>Tumor necrosis factor alpha (TNFα)</td>
<td>12</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>Proinflammatory cytokine</td>
<td>Expressed by canine OA synovium</td>
<td>(Fujita et al. 2005; Hegemann et al. 2005)</td>
</tr>
<tr>
<td>Zinc finger, SWIM-type containing 2 (ZSWIM2)</td>
<td>36</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>Metabolism</td>
<td>Increased expression in OA cartilage and ligament</td>
<td>(Clements et al. 2008)</td>
</tr>
</tbody>
</table>

CFA, canine chromosome; U, upstream; P, Promotor; E, Exon; I, Intron; D, Downstream and their justification for evaluation as candidate genes.
the Ensembl gene annotations (exon numbers, size, and position) were used to define the SNP positions. SNPs were designated a genomic location on the basis of their position (pre-gene ≤ 10 000-bp upstream of exon 1, promoter <1000 bp of the start of exon 1, post-gene ≤ 10 000-bp downstream of the last exon). Forty-six SNPs were selected from a previous study (ATP11B, ANKRD10, LEPR, MMP13, SPARC, TNF, ZSWIM2). A further 43 SNPs were selected from the published canine genome sequence (www.ncbi.nlm.nih.gov) and the Broad Institute canine SNP database (http://www.broad.mit.edu/tools/data/genvar.html).

Genotyping

Genotyping was performed using the Sequenom MASSarray platform (Sequenom, Hamburg, Germany) as previously described (Short et al. 2007). Briefly, primers and probes were designed using the Sequenom assay design software version 3 and synthesized by Metabion AG (Martinsried, Germany). Primers and probes were pooled as recommended by the manufacturers instructions (http://www.sequenom.com). Multiplex PCR reactions, product cleanup, and probe extension reaction were performed in 384-well plates with 20 ng of DNA per well, using iPLEX Gold reagents. Samples were diluted and desalted with 6 mg of resin before dispensation onto a SpectroCHIP (Sequenom) using the Sequenom nanodispenser, before genotype identification by matrix-assisted laser desorption/ionization–time of flight mass spectrometry.

Data Analysis

Genotype and phenotype data were imported into BCgene software (www.bcplatforms.com), which was used to calculate genotyping rates, minor allele frequencies (MAFs), and Hardy–Weinberg equilibrium (HWE) for each control population. SNPs or individuals were not analyzed further if the call rates were below 80% or if the control population was not in HWE. Analysis of genotype associations with disease was performed by logistical regression to correct for the confounding variables (sex and neuter status) using PLINK, a web-based genetic analysis program (Purcell et al. 2007), with additive, dominant, and recessive models. The strength of the significant associations was checked with a multiple permutation test, using 10 000 permutations. Haplotype frequencies were calculated for each gene, and haplotype associations with disease were performed using logistical regression to correct for the confounding variables using PLINK. The strength of the associations was again checked with a multiple permutation test, using 10 000 permutations.

Estimates of statistical power were performed using the PS Power and Sample Size program (Dupont and Plummer 1998). When SNPs with a MAF ranging from 5% to 50% are used this study was powered to detected risk alleles with Odds Ratios (OR) ranges of 1.64–2.43 (Labrador Retrievers, ED) to 2.10–3.46 (Golden Retrievers, CCLR) and protective alleles with OR ranges of 0.61–0.13 (Labrador Retrievers, ED) to 0.48—undetectable (Golden Retrievers, CCLR) if the allele is protective, at 80% power (P < 0.05).

Results

A total of 113 SNPs were analyzed; in Labrador Retrievers, 44% (n = 54) of SNPs were informative (MAF >1%), 14% (n = 16) of SNPs demonstrated low heterozygosity (MAF <1%), 15% (n = 17) were monomorphic, and 27% (n = 30) were not in HWE; in Golden Retrievers, 61% (n = 69) were informative, 27% (n = 31) were monomorphic, and 12% (n = 13) were not in HWE. The average genotyping rate for the Labrador Retrievers was 94.5% (range 81.3–99.6%), and 96.6% for the Golden Retrievers samples (range 84.9–100%). The concordance of the internal genotyping control between plates was 100%.

Case-control comparison of genotypes identified 10 SNPs whose minor alleles were significantly associated with risk (n = 5) or protection (n = 5) of orthopedic disease independent of confounding using the additive model (Table 2). The case-control comparison of haplotype frequencies identified 8 haplotypes that were associated with the risk (n = 5) or protection (n = 3) of orthopedic disease independent of confounding using the additive model (Table 3). One haplotype of IL12β (CCTAACGG) was associated with the risk of developing ED and HD in Labrador Retrievers. Multiple permutation tests revealed statistical significance to be lost for all SNPs and haplotypes evaluated.

Discussion

A common genomic risk for joint disease and OA was not identified between 2 different breeds for the same disease or within the same breed for different diseases. Thus, our hypothesis that the genomic basis for the development of canine joint disease would be identified was not supported, although many other plausible candidate genes were not evaluated. Successful candidate gene studies of association identifying positive associations between a canine phenotype and genotype have been reported for diseases, such as diabetes mellitus (Short 2006). However, the overall success of such studies in identifying a mutation associated with a trait is extremely low in dogs when compared with linkage analysis (Aguirre-Hernandez and Sargan 2005). Although the collection of data for mapping studies is challenging from a client-owned dog population, whole-genome association have the power to identify the genomic regions which are associated with complex traits in dogs and thus which harbor candidate genes suitable for further evaluation (Karlsson and Lindblad-Toh 2008).

The analysis of multiple SNPs or haplotypes for association with a phenotype requires appropriate statistical correction to minimize the Type-1 statistical error (Balding...
SNPs separated by breed (GR, Golden Retriever; LR, Labrador Retriever), disease (CCLR, cruciate disease; ED; HD), gene, SNP position, minor allele, minor frequency in controls (%C), major allele, the OR for the MAFs in the disease population with 95% confidence intervals (95% CIs) and statistical significance (P value) when compared by logistical regression, and the corrected P value determined by multiple permutation testing.

Conversely, it should be noted that the phenotype quality of the disease cohorts is extremely high, as all cases were at the extreme end of the phenotype. First, each case required surgery for their underlying condition and second, each case was diagnosed by a veterinary orthopedic specialist. Difficulties in obtaining appropriate numbers of samples to accurately determine differences in allele and genotype frequencies for case-control study of canine disease with dog populations are a recognized issue (Short et al. 2007).

The majority of SNPs we evaluated were in the intronic (n = 33) or promotor (n = 28) regions, in contrast to the predominantly exonic SNPs evaluated in successful human candidate gene association studies of OA (Valdes et al. 2004;...
Valdes, Van-Oene, et al. 2006). Ideally, exonic SNPs would have been evaluated for all genes, but few or none were identified in the genes screened. Although open-access canine SNP databases are available, detail is presently lacking for individual genes and was not always able to detect exonic SNPs in each candidate gene evaluated using our methodology.

Conclusions

A common genetic risk for the development of canine joint disease and OA was not identified between different diseases within a single breed, or for the same disease in two different breeds in this study of association with polymorphisms in 20 candidate genes. Spurious association of candidate gene allele frequencies is ready identified in candidate genes if data are not appropriately corrected for multiple testing.

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References


for whole-genome association and population-based linkage analyses. Am J Hum Genet. 81:559–575.


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