Diagnosis of Canine Leptospirosis by a Highly Sensitive FRET-PCR Targeting the \textit{lig} Genes

Chuanling Xu$^{1*}$, Amanda Loftis$^{2\dagger}$, Sudhir K. Aaluwalia$^1$, Dongya Gao$^1$, Ashutosh Verma$^2$, Chengming Wang$^{1*}$, Bernhard Kaltenboeck$^{1*}$

$^1$Department of Pathobiology, College of Veterinary Medicine, Auburn University, Auburn, Alabama, United States of America, $^2$Department of Biomedical Sciences, Ross University School of Veterinary Medicine, St. Kitts, West Indies

Abstract

Canine leptospirosis is underdiagnosed due to its wide spectrum of clinical presentations and the lack of a rapid and sensitive test for the accurate diagnosis of acute and chronic infections. In this study, we developed a highly sensitive and specific fluorescence resonance energy transfer (FRET)-PCR to detect common pathogenic leptospires in dogs, including \textit{Leptospira interrogans} serovars Autumnalis, Canicola, Copenhageni (Icterohaemorrhagiae serogroup) and Pomona, and \textit{Leptospira kirschneri} serovar Grippotyphosa. This PCR targets the \textit{lig} genes, exclusively found in the pathogenic \textit{Leptospira} species but not in saprophytic species (\textit{L. biflexa}). A robust, high-stringency step-down real-time platform was coupled to the highly specific detection of leptospiral DNA by fluorescently labeled FRET probes. This enabled the detection of a single copy of the \textit{lig} gene in a PCR containing DNA from up to 50 μL canine blood or 400 μL urine. Sensitivity determination by use of limiting serial dilutions of extracted leptospiral DNA indicated that the \textit{lig} FRET-PCR we established was almost 100-fold more sensitive than the widely accepted lipL32 SYBR assay and 10-fold more sensitive than a 16S rRNA TaqMan assay. Application of this method to 207 dogs with potential leptospliral infection enabled us to diagnose three cases of canine leptospirosis characterized by low amounts of leptospiral DNA in body fluids. Detection of canine leptospirosis with the \textit{lig} FRET-PCR was more sensitive with the \textit{lig} FRET-PCR than with the 16S rRNA TaqMan PCR, which detected only 2 of the 3 cases, and the lipL32 SYBR PCR, which detected none of the 3 dogs with leptospirosis.

Introduction

Leptospirosis is a zoonotic disease caused by pathogenic leptospires that infect a wide range of animals around the world [1–3]. The clinical diagnosis of canine leptospirosis is difficult because multiple factors, including the virulence of the infecting leptospires, environmental factors affecting the organisms, and the age and immune status of the dog, result in a broad spectrum of clinical manifestations and laboratory findings [1–3]. Antibody-based assays can be used for diagnosis, but they have limited sensitivity in the early stage of illness, and antibodies elicited by vaccination cannot be discriminated from natural infection. Since 1986, molecular techniques such as southern blotting, dot-blotting [4], \textit{in situ} hybridization [5], and nucleic acid amplification techniques such as real-time PCR assays [6–10] have been applied to detect the presence of leptospiral nucleic acids. Quantitative real-time PCR assays targeting the genes \textit{secY}, \textit{lipB}, \textit{lipL32}, \textit{lig}, and \textit{lipC} with either SYBR green or hydrolysis probes (such as TaqMan) for detection, have been widely used for the diagnosis of leptospirosis [6–13].

Before 1989, the genus \textit{Leptospira} was divided into two species, \textit{L. interrogans}, including all pathogenic leptospires, and \textit{L. biflexa}, including all saprophytic leptospires. Currently, based on genetic relatedness, the genus \textit{Leptospira} has been reclassified into 22 species (11 pathogenic), about 38 antigenically related serogroups (31 pathogenic) and more than 250 serovars [1–3]. Unfortunately, the leptospiral genomes are highly fluid and contain a high number of transposases to mediate multiple genome rearrangements [2], which makes it challenging to design highly sensitive and specific real-time PCR assays to accurately quantitate and differentiate all pathogenic and saprophytic leptospiral strains.

The most common pathogenic leptospires in dogs are \textit{L. interrogans} serovars Canicola, Icterohaemorrhagiae, and Pomona, and \textit{L. kirschneri} Grippotyphosa [1–3,14]. Serovars Canicola and Icterohaemorrhagiae are the primary pathogenic strains associated with canine leptospirosis disease [1].

The leptospiral immunoglobulin-like (\textit{lig}) gene produces Lig proteins that are key virulence determinants in pathogenic \textit{Leptospira} species [15]. These \textit{lig} genes are only present in pathogenic, but not saprophytic, \textit{Leptospira} species [10,15]. Three \textit{lig} genes, designated \textit{ligA}, \textit{ligB}, and \textit{ligC} (pseudogene in many species), have been identified. The amino terminal domains of the \textit{LigA} and \textit{LigB} paralogs are essentially identical, showing 98.5% similarity. In this report, we describe the development and
application of a highly sensitive FRET-PCR targeting a region of the lig gene which is identical for ligA and ligB genes.

Materials and Methods

Dogs
All work in this study was approved by the Institutional Animal Care and Use Committee of Ross University School of Veterinary Medicine (RUSVM). Written or verbal consent from the owners of the dogs was received to use blood and urine in this study. Whole blood collected in ethylenediaminetetraacetic acid (EDTA) was used for complete blood count (CBC) and comprehensive biochemical profiles using the VetScan HM5 and VetScan VS2 platforms (Abaxis, Union City, CA). Urine samples were tested using a VetLab UA Analyzer (IDEXX, Westbrook, ME) and proteinuria was further confirmed by the use of sulfosalicylic acid (SSA) precipitation. For PCR testing, urine (up to 4 mL) was centrifuged for 5 minutes at 10,000 g and the resulting pellet was resuspended in 200 μL of phosphate-buffered saline. Aliquots of 200 μL of whole blood or 200 μL of urine sediment were frozen at −20°C until DNA extraction was performed.

DNA Extraction
The High-Pure PCR Template Preparation Kit (Roche Molecular Biochemicals, Indianapolis, IN) was used to extract total nucleic acids from blood and urine samples as previously described [16]. The blood or urine sample was mixed with an equal volume of binding buffer [6 M guanidine-HCl, 10 mM urea, 20% (v/v) Triton X-100, 10 mM Tris-HCl, pH 4.4], and the DNA samples were eluted in 40 μL of elution buffer for blood and 100 μL for urine.

Real-time PCRs
The widely used lipL32 SYBR and 16S rRNA TaqMan assays to detect leptospiral DNA were performed on an Applied Biosystems 7500 Real-time PCR System (Applied Biosystems, Foster City, CA, USA) as published [7,9]. FRET-PCR assays for Anaplasma 16S rRNA and Babesia 18S rRNA were performed on a Roche LightCycler 2.0 PCR Instrument (Roche Applied Science, Indianapolis, IN, USA) as previously described [17]. The hydrolysis-probe based PCR for Ehrlichia canis 16S rRNA was performed on an Applied Biosystems 7500 Real-time PCR System (Applied Biosystem, Foster City, CA) as described previously [18]. In this study, we designed a FRET-PCR to target the leptospiral lig genes [15]. The nucleotide sequences of the lig genes of the pathogenic leptospires for dogs were obtained from GenBank. The primers and probes for the lig FRET-PCR were designed by use of Vector NTI software (Invitrogen Corporation, Carlsbad, CA) and synthesized by Integrated DNA Technologies (Coralville, IA). The lig FRET-PCR amplifies a 176-bp target, and the positions of primers and probes are shown in Fig. 1. The forward and reverse primers and the anchor and reporter probes have 1, 2, 1, and 1 degenerate nucleotides, respectively: forward primer: 5'-GCTACWGGGATCTACCTCGA-3'; reverse primer: 5'-GGACTACTTACYTTTCCGAATGTGGCT-3'; anchor probe: 5'-ATTTCAACCGCCAAAACAAAATCAAG-3'; reporter probe: 5'-Bodipy630/650-GGAGCAGCTACGGAGGATTAT-(Phosphate)-3'. The fluorescein probe was 3'-labeled with carboxyfluorescein (6-FAM) and acts as the FRET donor probe, excited by 488 nm light. The Bodipy630/650 probe was HPLC-purified and is used as the FRET acceptor probe, emitting ~640 nm fluorescence following excitation by 6-FAM in close physical proximity. To ensure the specificity of the lig FRET-PCR, all four
oligonucleotides were analyzed for similarity with other sequences by nucleotide megablast (optimized for highly similar sequences) versus all accessioned sequences in GenBank.

FRET-PCR was performed on a LightCycler 2.0 real-time PCR platform (Roche Molecular Biochemicals, Indianapolis, IN) using a previously described thermal protocol and PCR conditions [16]. Each reaction was performed in a 20 μL final volume, using 10 μL of extracted DNA. Thermal cycling consisted of 15 high-stringency step-down cycles followed by 25 relaxed-stringency fluorescence acquisition cycles. The 15 high-stringency step-down thermal cycles were 60–0 sec @ 95°C, 12 sec @ 64°C, 8 sec @ 72°C; 90 sec @ 95°C, 12 sec @ 62°C, 8 sec @ 72°C; 30–0 sec @ 95°C, 12 sec @ 60°C, 8 sec @ 72°C. The relaxed-stringency fluorescence acquisition cycling consisted of 30–0 sec @ 95°C, followed by fluorescence acquisition of 12 sec @ 58°C, and 10 sec @ 72°C. Following the completion of FRET-PCR, the melting curve analysis for probes annealing to the PCR products was determined by monitoring the fluorescence from 37°C to 85°C, and the first derivatives of F4/F1 were evaluated to determine the probe melting temperature (\(T_m\)) [16].

DNA from a pure culture of a wild-type isolate of \textit{Leptospira interrogans} serovar Pomona (a gift from Frank Austin of Mississippi State University to Auburn University) was extracted and quantitated. The extracted and quantitated DNA was diluted in a background of 20 μg/mL salmon sperm DNA in TE buffer. This genomic DNA standard was used to determine the sensitivity of the lip\(\text{g}\) FRET-PCR method that is capable of saturation amplifying single target molecules (Fig. 2). The resistance to PCR inhibition is indicated by the conditions of the PCR with very high background of unrelated DNA, resulting in amplification of single target molecules at a more than trillion-fold excess of unrelated DNA (2\(\times\)10\(^{12}\)) g background DNA/1.93 pg salmon sperm DNA per 20 μL PCR.

Results

Development and Laboratory Validation of the Canine Pathogenic \textit{Leptospira} spp. FRET-PCR

We obtained all available lip\(\text{g}\) gene sequences for canine pathogenic leptospires in GenBank for alignment and identified a target region that is highly conserved among these taxa (Fig. 1), but does not exist in saprophytic leptospires. By nucleotide megablast similarity search, each of the four oligonucleotides showed 18 hits with pathogenic leptospires, with 0–1 nucleotide mismatch, but no hits with other pathogens, non-pathogenic leptospires, or the host genome. The \textit{Leptospira} species identified by nucleotide BLAST and gene accession numbers are shown in Table 1 [15,20–24].

The lip\(\text{g}\) FRET-PCR amplified genomic DNA extracted from \textit{L. interrogans} Pomona with high sensitivity and specificity. \textit{L. interrogans} Pomona DNA was diluted on a high background salmon sperm DNA, resulting in 0.2 μg salmon sperm DNA per 20 μL PCR. Negative controls of PCRs with background salmon sperm DNA never resulted in positive amplifications. Two-fold serial dilutions of leptosomal genomic DNA yielded either fully positive PCRs equivalent to PCRs with high target copy input, or negative amplification reactions (Fig. 2). At higher dilutions, not all of the 5 PCR reactions with equal dilution of the leptosomal DNA tested positive, indicating a Poisson distribution of the targets, with the positive PCRs containing 1 or more targets while the negative PCRs contained no copies of the target DNA (Fig. 2). This conclusion is justified based on the unambiguously positive or negative PCR amplification curves, indicating a robust PCR method that is capable of saturation amplifying single target molecules (Fig. 2). The resistance to PCR inhibition is indicated by the conditions of the PCR with very high background of unrelated DNA, resulting in amplification of single target molecules at a more than trillion-fold excess of unrelated DNA (2\(\times\)10\(^{-7}\) g background DNA/1.93\times10\(^{-19}\) g mass of 176 bp target DNA = 1.04\times10\(^{13}\)). The absence of any PCR inhibition is also evident in the equal slope of the amplification curve of low-copy samples as compared to high-copy samples (Fig. 2).

Logistic regression analysis of the amplification data in Figure 2 indicated a 50% probability of a positive PCR at a PCR input of 0.0476 genomes. Thus, we calculated from the mean of 0.3 targets per 0.0476 genomes an approximate number of 10.5 targets per leptosomal genome. The positive amplification of leptosomal DNA is associated with the presence of a specific melting curve (\(T_m = 62.5\)°C), which was the same for all 5 \textit{Leptospira} strains tested, but does not exist in the samples free of leptosomal DNA (Fig. 2, insert), indicating 100% specificity. The tripartite melting curve results from different melting temperatures of the oligonucleotide species among the degenerate FRET probes.

Comparison of Sensitivity between lip\(\text{g}\) FRET, 16S rRNA TaqMan and lipL32 SYBR PCRs

Sensitivity of the lipL32 SYBR assay, 16S rRNA TaqMan assay and lip\(\text{g}\) FRET PCR was compared using 10-fold serial dilutions of genomic DNAs from five different pathogenic leptospires. All were tested in triplicate, and no difference in sensitivity between strains was seen for the FRET-PCR or TaqMan PCR assays. The lip\(\text{g}\) FRET-PCR showed 100% sensitivity when 0.008 pg DNA (approximately 1.6 genomes; equivalent to 3 lip\(\text{g}\) gene copies per
Detection of Canine Leptospirosis by FRET-PCR

Table 1. Pathogenic canine leptospiral strains detectable by the *Leptospira* spp. lig FRET-PCR as indicated by sequence matches of primers and probes.

<table>
<thead>
<tr>
<th>Species</th>
<th>Serogroup</th>
<th>Serovar</th>
<th>Strain</th>
<th>Gene accession</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>L. interrogans</em></td>
<td>Icterohaemorrhagiae</td>
<td>Copenhageni</td>
<td>Fio cruz L1-130</td>
<td>AE016823.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>Icterohaemorrhagiae</td>
<td>Lai</td>
<td>56601</td>
<td>AE013000.2</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>Icterohaemorrhagiae</td>
<td>Lai</td>
<td>IPAV</td>
<td>CP001221.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>Pomona</td>
<td>Pomona</td>
<td>Kennewicki PO-06047</td>
<td>EU700267.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
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<td>Pomona</td>
<td>Kennewicki PO-06047</td>
<td>EU700268.1</td>
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<td><em>L. interrogans</em></td>
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<td>Pomona</td>
<td>Kennewicki Cornell</td>
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<td>Pomona</td>
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<td>FJ030916.1</td>
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<tr>
<td><em>L. interrogans</em></td>
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<td>pLPLIG8</td>
<td>FJ030617.1</td>
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<td><em>L. interrogans</em></td>
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<td>Kito</td>
<td>EU700267.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>Canicola</td>
<td>Canicola</td>
<td>Kito</td>
<td>EU700268.1</td>
</tr>
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<td><em>L. interrogans</em></td>
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<td>Canicola</td>
<td>Hond Ultrecht IV</td>
<td>EU289225.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>ND</td>
<td>ND</td>
<td>FPW1039</td>
<td>AKWR02000178.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>ND</td>
<td>Manilae</td>
<td>UP-MMC-NID</td>
<td>AB098516.1</td>
</tr>
<tr>
<td><em>L. interrogans</em></td>
<td>ND</td>
<td>Manilae</td>
<td>UP-MMC-NID</td>
<td>AB098517.1</td>
</tr>
<tr>
<td><em>L. kirschneri</em></td>
<td>Grippotyphosa</td>
<td>Grippotyphosa</td>
<td>RM52</td>
<td>EFS17920.1</td>
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<tr>
<td><em>L. kirschneri</em></td>
<td>Grippotyphosa</td>
<td>Grippotyphosa</td>
<td>Moskva V</td>
<td>AY190126.2</td>
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</table>

*Each of the four oligonucleotides in the lig FRET-PCR was used in nucleotide megablast searches (optimized for highly similar sequences) against all accessioned sequences in GenBank, and all matched to these 18 strains of pathogenic leptospires with 0–1 nucleotide mismatch.

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Figure 2. Detection limit of the Leptospira spp. lig FRET-PCR. For use as quantitative standard in the lig PCR, DNA from a wild-type isolate of Leptospira interrogans serovar Pomona was extracted and quantified by PicoGreen DNA fluorescence assay (Invitrogen, Karlsbad, CA, USA). The number of genomes was calculated assuming a Leptospira spp. genome size of 4.63 Mb (MW = 3.06 x 10^9 Dalton), which was further used to determine the sensitivity of the lig FRET-PCR by amplification of logarithmic dilutions of this standard. To calculate the actual number of lig gene targets per leptospiral genome, the 10-copy standard DNA was further serially diluted from 1:100-fold (0.1 genomes/PCR) to 1:500-fold (0.02 genomes/PCR), and 5 aliquots of each dilution step were subjected to PCR detection. This approach yielded a Poisson distribution of positive and negative amplification reactions, with fewer of the 5 aliquots positive at higher dilutions. Logistic regression analysis indicated a 50% probability of a positive PCR at a PCR input of 0.0476 genomes. The complete separation between positive and negative reactions indicates a robust PCR methodology that reliably amplifies single target copies. Thus, we calculated from the mean of 0.5 targets per 0.0476 genomes an approximate number of 10.5 targets per leptospiral genome. The insert of the melting curves shows that positive amplification of leptospiral DNA is associated with the presence of a specific melting point (T_m = 62.5°C) which does not exist in the samples free of leptospiral DNA.

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Table 2. Diagnosis of leptospirosis in survival canine cases.

<table>
<thead>
<tr>
<th>Age and sex</th>
<th>Type of Case</th>
<th>Blood PCR: FRET/Taqman</th>
<th>Urine PCR: FRET/Taqman</th>
<th>Post-Treatment PCR</th>
<th>Acute serology: MAT</th>
<th>Convalescent serology: MAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case #1: April 2012</td>
<td>2 yr Neutered Male</td>
<td>Chronic</td>
<td>--/--</td>
<td>--/--</td>
<td>Not Done</td>
<td>Negative</td>
</tr>
<tr>
<td>Case #2: April 2013</td>
<td>7 mo Intact Male</td>
<td>Chronic</td>
<td>--/--</td>
<td>+/+</td>
<td>Negative</td>
<td>Canicola 1:100</td>
</tr>
<tr>
<td>Case #3: May 2013</td>
<td>1.5 yr Intact Male</td>
<td>Acute</td>
<td>+/+</td>
<td>+/+</td>
<td>Canicola 1:100</td>
<td></td>
</tr>
</tbody>
</table>

aC_t for FRET assay 34.7, C_t for TaqMan assay 37.1.
bC_t for FRET assay 31.7, C_t for TaqMan assay 34.5.
doi:10.1371/journal.pone.0089507.t002
negative, consistent with chronic infection. Both blood and urine samples were negative using the lipL32 SYBR assay.

Treatment with doxycycline (5 mg/kg q12hr for 21 days) was initiated on June 14, 2012, and a re-check examination was performed on July 6, 2012. At this time, blood and urine samples both tested negative by PCR, but proteinuria was still present. Serology, using MAT and representatives of eight Leptospira serogroups (Australis, Autumnalis, Ballum, Canicola, Copenhageni, Grippotyphosa, Hebdomadis, and Pomona), revealed no reactive antibodies. At a final re-check on November 1, 2012, the proteinuria had resolved (56 mg/dL).

Case #2: On April 16, 2013, a 7-month-old male Bull mastiff puppy was presented for acute onset of limping. It was afebrile and lameness was attributed to effusion in both stifles, possibly from osteochondrosis dissecans. During the course of testing, slightly elevated bilirubin (0.8 mg/dL, reference range 0.1–0.6) was noted, along with isostenuria (USG 0.015), slight hematuria, and renal and squamous epithelial cells seen in urine sediment. CBC was unremarkable. Antibodies against E. canis or Anaplasma phagocytophilum/plays were not detected (4DX SNAP test; IDEXX, Westbrook, ME), and blood bacteriological cultures were negative.

Urine and blood samples were subjected to pathogenic Leptospira spp. PCRs (Table 2); urine was positive by lig FRET-PCR, but not by 16S rRNA TaqMan or lipL32 SYBR PCRs, and blood tested negative in all assays. Following treatment with doxycycline, repeat PCR testing was negative for both blood and urine samples. The convalescent sample collected on May 14 was tested using MAT and did not contain antibodies to Leptospira interrogans serovar Canicola (Table 2).

Case #3: On May 13, 2013, a 1.5 year old, intact, male island mix dog presented for lethargy, inappetence, vomiting, and diarrhea of acute onset. The dog was parasitized by intestinal nematodes (Trichuris spp., Ancylostoma spp., and Toxocara spp.), and elevated eosinophils were noted on CBC (1×10^3/μL), range 0.1–0.75. Mild monocytosis (1.5×10^3/μL, range 0.15–1.35) was also seen. Biochemistry revealed several abnormalities, including hyperbilirubinemia (2.6 mg/dL), hypercalcaemia (13.0 mg/dL, range 8.6–11.8) with hyperphosphatemia (16.5 mg/dL, range 2.9–6.6), and elevated creatinine (13 mg/dL, range 0.3–1.4). On urine analysis, hypothenuria (USG 1.013) with proteinuria had resolved (56 mg/dL), was noted, with both red and white blood cells seen in urine sediment. A 4DX SNAP test was performed and no antibodies against E. canis or Anaplasma phagocytophilum/plays were detected. Serology was performed for Leptospira, using MAT; this acute serum reacted only with the Leptospira interrogans serovar Canicola strain (Table 2). Urine and blood tested positive in the lig FRET-PCR, only urine in the 16S rRNA TaqMan PCR, and blood and urine samples were negative in the lipL32 SYBR assay (Table 2). The dog was hospitalized for 6 days with intravenous fluids, after which oral doxycycline therapy was initiated. A re-check appointment was performed on May 28, at which time convalescent samples were PCR negative and the owner reported the dog was in good health. MAT results from convalescent serum collected May 28 revealed antibodies reactive to serovars Pomona, Autumnalis and Grippotyphosa (Table 2).

Discussion

Canine leptospirosis is often difficult to diagnose, as it has a wide spectrum of clinical presentations, ranging from lethargy, depression, anorexia, and fever to diarrhea and icterus, which mimic the clinical findings of many other diseases including ehrlichiosis, babesiosis, canine distemper virus infection and canine brucellosis. Definitive diagnosis by culture and isolation of the organisms requires weeks, and seroconversion often does not occur until acute infection has resolved [25,26]. Further, chronic seronegative carrier states have been reported [25], and the microscopic agglutination tests used for serology do not discriminate between infection and vaccination. PCR assays that enable the reliable detection of Leptospira DNA would be very useful for the detection of both acute and chronic infections. However, due to the minute amount of Leptospira DNA in the blood and urine specimens of infected dogs, a highly sensitive PCR platform is required for accurate diagnosis.

Choice of an appropriate PCR target gene and optimized design of primers and probes is absolutely critical to ensure the sensitivity and specificity of quantitative PCR [27]. Here, we developed a rapid and sensitive PCR assay targeting the lig genes, which exist only in pathogenic canine leptospires and not in saprophytic strains. Comparison of leptospiral genome numbers determined by DNA quantification and of lig gene copy numbers determined by lig FRET-PCR indicated variable numbers of lig gene copies per genome, with approximately 10 lig copies in our Pomona quantitative standard strain (Fig. 2), and approximately 3 lig copies in other pathogenic leptospiral field isolates (Table 2). The high numbers of 553 LigA protein and 914 LigB protein molecules per leptospiral cell [28] support a potential evolutionary benefit of lig gene duplication for pathogenic leptospirae.

The lig FRET-PCR assay was highly sensitive and enabled the specific detection of a single target gene copy, less than one genome of Leptospira spp. The multiple lig gene target copies per leptospiral genome may explain in part the high sensitivity of the lig FRET-PCR established in this study, aside from the robustness of the step-down amplification thermal protocol. Additionally, the lig FRET-PCR uses 10 μL of highly concentrated template DNA in each reaction, five times as much as has been validated for previous TaqMan or SYBR assays. Combining concentrated DNA extraction, increased template volume, and the sensitivity of the lig FRET-PCR, we could detect as few as 20 copies of the pathogenic leptospiral lig gene per one mL of blood or 10 copies per 3–4 mL of urine, translating into detection of single leptospiral bacteria per 0.17–0.5 mL of blood or 1 mL of urine. The whole process, from DNA extraction to completion and interpretation of PCR results, requires about 3 hours of time.

When we compared sensitivities using equal amounts of genomic DNA in each reaction, the lig FRET-PCR was almost 100-fold more sensitive than the widely accepted lipL32 SYBR assay and 10-fold more sensitive than a 16S rRNA TaqMan. The FRET-PCR successfully identified all five strains of Leptospira spp. tested, representing five different serogroups which cause canine leptospirosis. However, due to the minute amount of Leptospira DNA in the blood and urine specimens of infected dogs, a highly sensitive PCR platform is required for accurate diagnosis.
confirmed that these dogs were negative for leptospiral DNA post-treatment. Thus, overall detection of canine leptospirosis was more sensitive with the lig FRET-PCR than with the 16S rRNA TaqMan PCR, which detected only 2 of the 3 cases, and the lipL32 SYBR PCR, which detected none of the 3 dogs with leptospirosis. Furthermore, analysis of urine specimens, despite greater difficulty obtaining these from frequently oliguric dogs with acute leptospirosis, is preferable over the analysis of the more easily obtainable blood specimens.

Our findings also underscore the limitations of serological testing for leptospirosis in dogs. Two of the three cases described here were confirmed, serologically, based upon convalescent serum; the third case was chronically infected but seronegative. Harkin et al [25] identified canine leptospirosis by PCR, but antibody against leptospirosis was not detected in the serum of the infected dog. Our findings confirm that serology is a poor predictor of urinary shedding of leptospires.

While we detected urinary shedding of leptospiral DNA in 3 dogs by the most sensitive lig FRET-PCR and are confident that these dogs represent true positive results, it is difficult to evaluate test accuracy by estimating the number of false negative PCR results in this study, or for that matter in any study, given the very high number of true negatives. One approach to estimate false negatives would be pattern matching in clinical appearance, biochemical parameters, and serology between dogs with confirmed leptospirosis and those that have remained negative by PCR. Another approach would be to maximize sample DNA input in the PCR by increasing the volume of urine for DNA extraction. This could be achieved by high-speed sedimentation of, e.g. 4 mL or more urine, and DNA extraction from the complete sediment. Such PCRs may have a DNA input equivalent to 1 mL or more urine as compared to the 0.1 mL equivalent used after standard direct extraction performed in this study. Such approaches will be required to not only evaluate PCR performance, but to estimate overall accuracy of diagnosis of canine leptospirosis, with the caveat that dogs with symptomatic leptospirosis may present with oliguria.

In conclusion, our study shows that the lig FRET-PCR established in this study is a reliable, rapid, and highly sensitive assay for the diagnosis of the most common pathogenic canine leptospires. To our knowledge, this is the first report of using FRET-PCR technology for the diagnosis of canine leptospirosis. The test shows better specificity than the widely used lipL32 SYBR, and higher sensitivity than the 16S rRNA TaqMan, and in particular the lipL32 SYBR assay, and can detect clinical cases of canine leptospirosis that could be overlooked using a less sensitive method. These data establish the lig FRET-PCR as best suited for PCR detection of canine leptospirosis, when used in combination with an optimized sample DNA extraction procedure. Further validation will require larger comparative studies with higher numbers of Leptospira spp.-positive animals that will allow firm establishment of negative as well as positive predictive values of this assay.

Acknowledgments

The authors thank Dr. Fred Austín from Mississippi State University for providing leptospirotal cultures from which Pomona DNA was extracted for use as a standard for the lig FRET-PCR in this investigation. We also thank the RUSVM Veterinary Teaching Hospital clinicians who helped to identify the dogs in this study: Drs. Bart Gillespie, Susan FitzHarris, Christa Gallagher, and Susan Porter.

Author Contributions

Conceived and designed the experiments: BK AL CW SA. Performed the experiments: CX AL AV DG SA. Analyzed the data: AL CW BK. Contributed reagents/materials/analysis tools: AL AV CW BK. Wrote the paper: AL CW BK.

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