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CANINE LEPTOSPIROSIS AS A ONE HEALTH SENTINEL DISEASE: ENVIRONMENTAL EXPOSURE, PATHOGEN SHEDDING, AND ZOONOTIC TRANSMISSION

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Abstract

It is well known that canine leptospirosis is a clinical disease in veterinary medicine, however, its importance as an epidemiological issue in a One Health context is only poorly investigated. This review reconsiders canine leptospirosis as not only a disease of the dog, but as a sentinel phenomenon, which represents the presence of pathogenic Leptospira in the environment, shedding by the dog, and the risk of zoonotic transmission at the human–animal–environmental interface. We combine evidence from a number of fields: biology of Leptospira and the dog's continuum of infection; the ability of owned, free-roaming, shelter, and working dogs to act as sentinels for environmental exposure; the environmental factors that promote infection, such as water, soil, flooding, temperature, and urbanization; the hidden reservoir of urinary shedding and environmental contamination; the zoonotic transmission path from dogs to humans; the dog–rodent–environment transmission network and associated factors; diagnosis and surveillance strategies; climate change's impact on disease geography; and One Health surveillance and prevention strategies. A major conceptual contribution is the three-part distinction among serological evidence of exposure, PCR-based detection of bacterial DNA and culture-based confirmation of

viable organisms, which places a three-tiered framework for surveillance. We propose that combined with human case detection, environmental sampling, climate data, and geospatial analysis, sentinel dogs can be made an important part of a leptospirosis risk early-warning system. The vision can now be realized through innovative technologies such as whole genome sequencing, environmental DNA, risk mapping using artificial intelligence and integrated climate–pathogen platforms. The review concludes that when correctly put in the One Health context, canine leptospirosis is a powerful sentinel disease, which can be used to gain insight and mitigate the transmission of environmental leptospirosis.

INTRODUCTION

Leptospirosis is a zoonotic disease worldwide, which is caused by pathogenic spirochetes belonging to the genus Leptospira. The disease illustrates the complexity of transmission of the disease at the human–animal–environment interface; infection occurs via urine of infected reservoir hosts, and contaminated water and soil are key intermediates. According to the World Health Organization, more than a million human cases are reported every year, with an estimated mortality rate of 58,900 deaths, although these figures are only approximate and the actual figures are likely to be higher because the infection is underdiagnosed. Leptospirosis epidemiology is basically ecological and depends on the rainfall pattern, flood events, land use change, rodent density, and the density and behavior of reservoir hosts. Domestic dogs have a unique role in this ecological environment: they are known to be vulnerable to infection; they are often exposed to environmental sources; they can be a source of infection (via urine); and they are closely associated with people's homes. These features suggest that canine leptospirosis could be a potent sentinel for environmental circulation of Leptospira and zoonotic risk[1].

Traditional veterinary management of canine leptospirosis has been confined to the clinical diagnosis, treatment and vaccination of individual dogs. This is a clinically relevant viewpoint, but overlooks the role of dogs as interface organisms on a larger scale. Dogs travel through the same habitats as humans do, including yards, parks, water sources, urban alleys, and rural areas, and they often travel before or with humans. Free roaming and peridomestic dogs can cover extensive territories, and come in contact with rodent urine, contaminated soil and water sources which man may have occasional contact. If infected, dogs can shed Leptospira in their urine for weeks to months, creating a risk to people as it can contaminate things they touch in their home and community[2]. This convergence was demonstrated in the 2025 Ecuadorian Amazon epidemic, where pathogenic Leptospira detected by qPCR was present in 94.7% of peridomestic, free-ranging dogs in urine with the presence of *L. noguchii, L. santarosai* and *L. interrogans,* which is a source of zoonotic risk for children who play and fetch water in a domestic setting. This discovery highlights the role of dogs as important part of the epidemiology of leptospirosis[3].

Sentinel surveillance involves using a population which is susceptible to health risks to either detect or monitor risks that could impact a larger population or environment. Companion animals, especially dogs, have been suggested as sentinels of environmental health hazards, such as those posed by lead, tick borne disease and air pollution. Dogs have several unique features that enable them to be sentinels for leptospirosis. Firstly, they can be infected with the same species and serovariants of pathogenic Leptospira affecting humans. Second, they may be impacted by contaminants in more intense ways than humans or with exposures that are more easily detected – dogs swim in contaminated water, drink from puddles and explore burrows[4]. Third, veterinary infrastructure is present in many environments, and can be made to systematically monitor. Fourth, dogs in close proximity to people provide opportunities for direct and indirect transmission; therefore, dogs may be indicators of human risk. The sentinel concept, however, should be used with care: not all canine infections represent risk to humans in the environment, and the seroprevalence data need to be interpreted considering the vaccination status of the dogs, serovar cross reactivity, and population characteristics[5].

Renal colonization and urinary shedding is the link between individual dog infection and environmental contamination. Pathogenic Leptospira enter the bloodstream and localize in the proximal renal tubules

of reservoir hosts, causing active infection that may last for months or years and with shedding of organisms in urine intermittently or continuously. Either a dog with symptoms or one that is shedding the pathogen but does not have any symptoms may become chronic renal carriers, that means that the pathogen is reintroduced into the environment with every voiding. The amount of leptospire excreted depends on the species of host, the excreted strain and individual reasons. The maximum concentration of cells per ml of urine was estimated to be shed by rats (median = 5.7 × 10 6 cells), however, larger animals can contribute more total organisms per day, depending on the daily volume of urine produced. Although smaller than cattle, dogs can add up to a lot in peridomestic environment whereby their excretions are directly exposed to humans. Leptospira can persist in soil and water for long periods (weeks to months) under favorable conditions, thus providing a long-term environmental reservoir that can infect subsequent hosts long after the infection has been shed by the original host[4].

Although it is increasingly acknowledged that the dog has an important part to play in the epidemiology of leptospirosis, much of the knowledge continues to be limited. There are few quantitative estimates of the contribution of dogs to the environmental load of Leptospira compared with that of rodents and other hosts. The extent and length of time the virus is excreted in the urine of naturally infected dogs, including dogs with subclinical infections, is poorly defined. There is a considerable lack of quantifying the risk of infection to humans from canine-shed Leptospira, aside from sharing environment. Currently, only the basics of using genomic tools that might identify transmission chains between dogs and humans, or from environment to both, for canine leptospirosis are just being used. Nor has the sentinel potential of various canine groups owned dogs, free roaming dogs, shelter dogs, and working dog groups been evaluated systematically. This review aims to fill these gaps, providing a comprehensive synthesis of the available literature in the ecological, epidemiological and genomic aspects of canine leptospirosis in a One Health approach[6].

2. Leptospira Biology and the Canine Infection Continuum

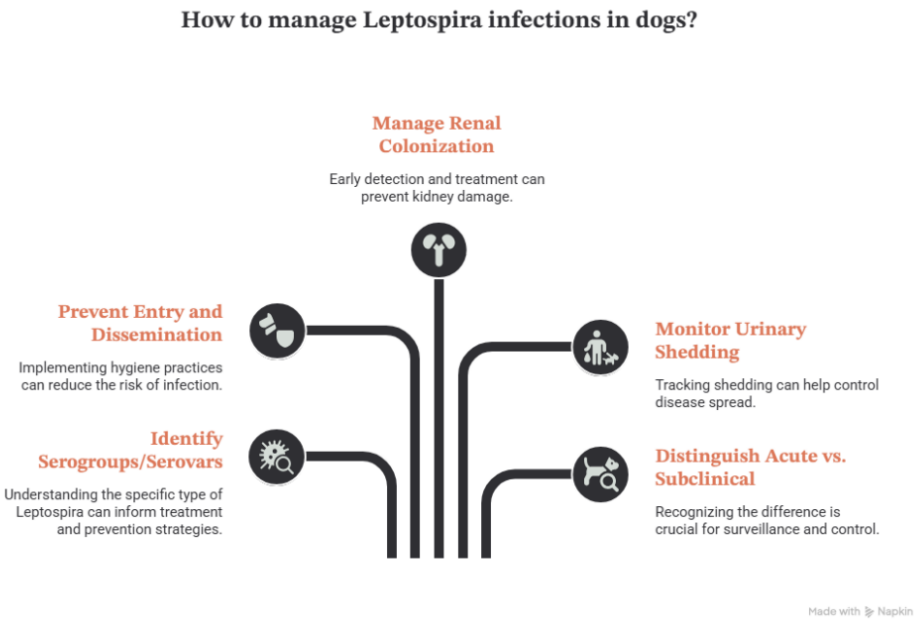


Figure 1.0 Management of Leptospira Infection Strategies

2.1. Pathogenic Leptospira and Genomic Diversity

Leptospira genus consists of antigenically and genetically diverse spirochetes. The genus has been recently revised into pathogenic, intermediate and saprophytic species and pathogenic species into P1 and P2 groups according to genetic and pathogenic characteristics. Forty-one species are recognized, about 20 of

them are pathogenic (P1) and 21 are intermediate (P2) species which are potentially pathogenic to animals and humans. This genomic diversity is very important for diagnostic, vaccine design and epidemiological tracking. Whole genome sequencing has shown that L. interrogans is the most commonly isolated pathogenic species worldwide, with other species, such as L. kirschneri, L. borgpetersenii, L. noguchii and L. santarosai being significant causes of disease. Leptospira's transmission dynamics are complex and the genomic plasticity of the organism allows adaptation to hosts and immune evasion[7].

2.2. Serogroups, Serovars, and Canine-Associated Lineages

Pathogenic species belong to group I, the species L. interrogans and L. kirschneri are responsible for disease in dogs and more than ten serovars are associated with clinical disease world-wide. Epidemiologically speaking, historically, serogroups Icterohaemorrhagiae and Canicola seemed to be most commonly involved in canine infection, where rodent reservoir (Icterohaemorrhagiae) and dog-to-dog transmission (Canicola) were most important. Since the advent of canine vaccines, though, seroconversion with other serogroups, most notably grippotyphosa and pomona in North America, and grippotyphosa and australis in Europe, has been observed widely. The apparent serovar shift might be due to more exposure of dogs to wildlife reservoir hosts, and to improvements in diagnostic panels. Dogs have always been thought to be infected with a limited number of Leptospira strains, but molecular typing has started to show the extent of the actual diversity. In Japan the predominant serovars in dogs with disease are Australis, Autumnalis and Hebdomadis, with some instances of human isolates being grouped with canine isolates instead of rodent isolates. The multi-host connectivity of Leptospira transmission networks was demonstrated by sequence types detected in dogs that are similar to those identified in rats, mice, cats, hedgehogs, horses, and even in wild boar in northeast Italy[8].

2.3. Entry, Dissemination, and Renal Colonization

Leptospira is transferred to the host through mucous membranes (conjunctiva, mouth, nose) or abraded skin, especially after prolonged exposure to contaminated water. The bacteria subsequently spread throughout the body, causing transient leptospiremia which may cause seeding of various organs such as liver, lungs and kidneys. The acute phase of the infection may be clinically manifest (fever, jaundice, renal failure and pulmonary hemorrhage) or subclinical, depending on the host immunity, strain virulence and infectious dose. Transmission ecology requires renal colonization: Leptospira localize in the proximal convoluted tubules where they avoid the host immune response and find a niche that allows them to be excreted in urine for longer periods of time. This persistence in the kidneys is the hallmark of the carrier state and the connection between the individual case and environmental contamination[9].

2.4. Persistence in the Renal Tubules

A number of mechanisms, including immune evasion, biofilm production, and metabolic adaptation, have been proposed to account for the persistence of Leptospira in renal tubules but are not fully understood. The bacteria are able to form in vitro and in vivo biofilms and cell aggregates that can shield them from environmental and host defense factors. c-Di-GMP signalling seems to be responsible for the conversion between a planktonic (motile, virulent) state and a biofilm associated state with low levels of c-di-GMP at host body temperature (37°C) and high levels at environmental temperature (28–30°C). This temperature regulation probably helps dissemination during the acute infection, but will help persistence in the colder environment of the lumen of the renal tubule. Renal carriage can persist for varying periods of time in different host species and with different Leptospira strains and serovars, recovered dogs can shed despite receiving antimicrobial therapy with serovar Canicola being associated with persistent shedding[10].

2.5. The Transition from Infection to Urinary Shedding

Urinary shedding is the shift from the individual level of infection to the level of transmission risk to the population. Shedding can occur continuously or intermittently, and the amount of Leptospira shed in the urine is variable, depending on the host, strain and stage of infection. Leptospiruria usually starts during the acute stage and can last for weeks to months in dogs. The 2021 outbreak in LA has been

reported to frequently shed leptospires in the urine of infected dogs, which is unusual since shedding by incidental hosts is usually low-level and intermittent. The high prevalence of leptospiruria was thought to be due to the adaptation of serovar Canicola to dogs, and was found to be concerning about the possibility of dog-to-dog or dog-to-human transmission. Thus the switch from infectivity to shedding does not simply reflect a biological phenomenon but rather an epidemiological threshold, as soon as shedding is reached, the infected dog can be a source of environmental contamination and pose a danger to other hosts including humans[11].

2.6. Acute Disease Versus Subclinical Carriage

Another important but overlooked part of canine Lepto is subclinical carrier state. Some dogs infected with this organism do not have symptoms, get better on their own, and are known as "cures" or "clears" while others develop a asymptomatic chronic shedding phase. There is a significant difference between acute disease and subclinical carriage that has important implications for surveillance and control. Only the tip of the epidemiological iceberg is seen in clinical case detection. Subclinically infected dogs, through shedding, may be a source of transmission risk but would not necessarily be diagnosed as infected. This silent transmission interface calls into question the traditional surveillance paradigm and supports clinical population-level screening (serosurveys and urine PCR testing in high-risk situations). This is demonstrated by the 2021 outbreak in Los Angeles, where some dogs recovered from leptospirosis continued to shed pathogenic leptospires, even after antimicrobial therapy[12].

3. Dogs as Environmental Sentinels of Leptospira Exposure

3.1. What Makes a Companion Animal a Sentinel?

The concept of sentinel surveillance is that a population under surveillance can give early warning of environmental and/or public health threats. To be a good sentinel species, a species must share the same routes of exposure as the target population (humans), be sensitive to the hazard, and be easy to observe. Dogs are considered to meet these criteria for leptospirosis in several ways. The exposure they experience to contaminated water, soil, and rodent urine is similar to human exposure especially in domestic and recreational areas. They can be infected by the same pathogenic Leptospira species that infect humans. There is potential, for systematic data collection, on veterinary infrastructure, however, restricted and not uniformly distributed. Furthermore, dogs can be "accumulators" of environmental risk because their behaviour (sniffing, licking, swimming) can lead to greater exposure to the environment than is found for humans, which may lead to greater evidence of environmental contamination[11].

3.2. Free-Roaming, Owned, Shelter, and Working Dogs as Sentinel Populations

Each type of dog population has unique sentinel benefits and drawbacks. Owned pets give access to veterinary records and association with clinical outcomes; however, pets' exposures may have been restricted due to the behaviour of owners (e.g., leash walking, limited access to waterways). Free roamers and peridomestic dogs have the largest exposure potential but they are not easily sampled in a systematic fashion and the dynamics of these populations are poorly known. Shelter animals represent a focus population with exposure history and a high turnover that are unknown. Occupational exposures may be similar to high-risk humans (farmers, outdoor workers) with working dogs (herding, hunting, search and rescue). Selection of sentinel population should be dependent on surveillance goal, as free roaming or working dogs could be better sentinels for detecting environmental contamination, while owned pets may be better sentinels for human exposure in domestic environments[13].

3.3. Serological Evidence of Historical Environmental Exposure

Widespread exposure of dogs for pathogenic Leptospira was observed in serological surveys performed by the microscopic agglutination test (MAT) in various geographic and ecological regions. In a systematic review of canine leptospirosis seroprevalence, studies from South America, Asia, Europe, Oceania, and North America have been identified and significant discrepancies in the prevalence and serovar distribution have been observed. There is serological evidence of dogs' exposure both in rural and urban areas and risk factors for exposure include close proximity to outdoor water, swimming or drinking water

from outdoor sources, and indirect contact with wildlife. Importantly, seroprevalence is a measure of past exposure not current infection – vaccination can complicate interpretation. However, serological results do give a good indication of environmental circulation of Leptospira species and can help identify populations and geographical regions which might require more surveillance[14].

3.4. Molecular Detection as Evidence of Active Infection

The molecular approach – specifically PCR for Leptospira DNA in blood or urine – helps to indicate active infection and possible shedding. Using quantitative PCR (qPCR) can provide an estimation of the pathogen load, providing a more real-time measurement of the level of risk of transmission than serology alone. In the Ecuadorian Amazon, molecular surveillance identified high level shedding of Leptospira pathogenic in free range peridomestic dog urine samples with 94.7% (n = 94) of samples testing positive. Molecular detection can also be used for the identification of Leptospira species and strains by sequencing for genomic tracking of transmission networks. PCR positivity does not differentiate between the viable and the non-viable organisms, however, and intermittent shedding might make it difficult to get a positive result. The following limitations should therefore be considered in the interpretation of molecular data in sentinel surveillance and other evidence streams should be considered in the context of molecular data[15].

3.5. Linking Canine Surveillance with Environmental Surveillance

Canine surveillance alone is however greatly enhanced with environmental sampling. Environmental DNA (eDNA) analysis is able to detect pathogenic Leptospira in water and soil and offers direct evidence of environmental contamination, which may be useful to complement data on canine infections. Using multiplex qPCR, the presence of pathogenic Leptospira P1 and P2 groups was found in 37% of the water samples and in 41% of the soil samples in a study conducted in the Paraná, Salado, and Coronda river basins in Argentina. Combining dog surveillance with environmental monitoring can identify areas with significant environmental contamination, but low dog exposure, as well as areas with high-risk environment to dogs and humans. This is a holistic approach that reflects the One Health paradigm of considering the health of humans, animals, and the environment as interrelated[16].

3.6. Limitations of the Sentinel Concept

The sentinel concept should be used with an awareness of the limitations that it has. Human Exposure is not Necessarily Reflected in Canine Exposure: canines may be exposed to environmental exposures that do not happen to humans or canines can be exposed in significantly higher intensities than people are typically exposed. However, there are ways for humans to be exposed that do not exist for dogs, such as activities that are part of their work or play. Vaccination makes serological interpretation more difficult because vaccine-induced antibody can mimic natural antibody, which may be present following vaccination. Subclinical infection occurs – clinical cases underestimate the amount of infection. Plus, in many areas, there's no systematic monitoring of canines, which makes it difficult to extrapolate from sentinel findings. These restrictions suggest multiple methods/sentinels for surveillance rather than any single one[17].

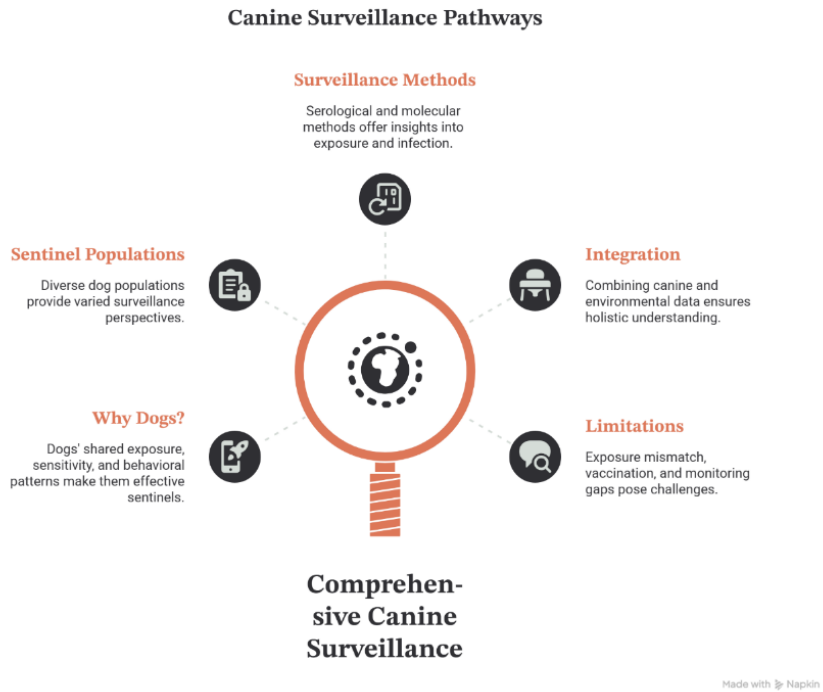


Figure 2.0 Illustration of Canine Surveillance Pathways

4. Environmental Determinants of Canine Leptospirosis

4.1. Water as a Major Interface for Transmission

Pathogenic Leptospira may be carried by water and acts as a reservoir for the pathogen. These bacteria can survive in fresh water for weeks to months especially under warm humid conditions with neutral to alkaline pH. Dogs that swim, drink water from outside sources, or wade in floodwaters are at higher risk for exposure. The proximity to outdoor water, swimming or drinking from outdoor water, and indirect exposure to wildlife were significant risk factors in a study of dogs with leptospirosis in the United States. The range of waterborne transmission includes not only natural water bodies, but also puddles, drainage ditches and standing water in urban areas if they are contaminated. The water interface is especially significant for sentinel surveillance since the identification of water contamination can offer direct evidence of environmental contamination that can precede or accompany canine and human infections[1].

4.2. Soil, Moisture, and Environmental Persistence

An important, but under acknowledged part of the environmental Leptospira reservoir is soil. Pathogenic leptospires are able to persist in moist soil for weeks or months and so, soil contamination might occur even when water sources are not visibly infected. The bacteria can be capable of forming biofilms on soil particles or in association with complex environmental microbiota increasing persistence. One of the major factors of survival is related to soil moisture levels: in dry conditions, the viability is decreased, while in water saturated soil, Leptospira can survive for a long time. Dogs being exposed to the soil, rolling around, or digging can result in exposure via mucous membranes or through abraded skin contact. The soil–dog interface is especially pertinent for peridomestic environments where dogs and humans cohabit yards and gardens, and during situations in which it is possible for the dog to be exposed to contaminated urine directly from the ground[4].

4.3. Flooding, Heavy Rainfall, and Hydrological Disturbance

Leptospirosis outbreaks in humans and animals have been consistently identified to be due to flooding and heavy rainfall. In the mathematical modelling of human leptospirosis in Thailand, flooding alone was a more significant factor for transmission than rainfall, and the best fit model was the one including

flooding and temperature. Dogs may also be exposed to leptospirosis during heavy rain and flooding, which also appear to be factors contributing to outbreaks. Bacteria can be resuspended from soil/sediment in flood waters and be moved to new areas where the dogs and humans are exposed to it. This delay (one month in the Thailand model) between rainfall and disease onset is caused by the multiple interactions between hydrological and ecological factors in pathogen mobilization and transmission. Flood events should be considered times of elevated risk and should be monitored through increased sampling and monitoring for sentinel purposes[18].

4.4. Temperature and Climate-Driven Changes in Transmission

The transmission of Leptospira is affected by temperature in many ways: survival of the bacteria in the environment, host behavior and population dynamics and human-animal contact patterns. The Thailand modeling study indicated a negative correlation between incident cases and temperature, with the model that included both flooding and temperature variables showing the best fit. This relationship may differ from region to region; warmer temperatures in temperate regions could lengthen the transmission season, and in tropical regions, high temperatures could result in lower survival in the environment. A Europe-wide spatiotemporal assessment revealed an increased risk of leptospirosis in regions with warmer mean temperature (maximum relative risk of 5.28) and future climate scenarios predicted an increase in cases, especially under higher greenhouse gas emission scenarios. The results indicate that leptospirosis may have a broader geographical distribution and seasonality due to climate change, with consequences for dogs and humans[19], [20].

4.5. Urbanization and Expansion of Peri-Urban Dog Populations

Urbanization can contribute to the transmission of leptospirosis because of related increased densities of rodents, poor sanitation, impervious surfaces that concentrate runoff, and high densities of dogs and humans living in close proximity. For canine leptospirosis, the spread of peri-urban areas (the transitional space between urban and rural areas) may be especially important, since these zones sometimes have large populations of free-roaming dogs, high populations of rodents and limited veterinary surveillance. In urban informal settlements, the environmental determinants of leptospirosis transmission in high-density areas are: flooding, vegetation land cover and rat abundance. Dogs in these areas can also act as sentinels for contamination of the environment that could cause adverse effects on people who live there, including children who play in contaminated areas[1], [21].

4.6. Waste Accumulation, Drainage Systems, and Rodent Activity

Limited drainage and waste management facilities provide environmental conditions and ecological niches for rodents and for Leptospira survival. Urban rats are important carriers of pathogenic Leptospira, which can be disseminated to different strains throughout an urban area via rat movement. In Boston, a six-year study detected the presence of Leptospira in 59 of 328 rat kidneys collected at 17 locations, and where the genetic analysis of one human case matched rat strains from the same location as the case. Dogs can come into contact with rodent urine by direct contact with rats or by touching surfaces, water or soil that are contaminated with the urine. The abundance and shedding of rats vary in space and time in urban informal settlements, being higher at valley bottoms and during seasonal rains. Environments that canines frequent may give sentinel data regarding circulation of rodent associated Leptospira on a spatially resolved basis[22], [23].

4.7. Recreational and Occupational Exposure Landscapes

In addition to domestically enclosed settings, recreational and occupational exposures result in unique dog and human exposure landscapes. In the wild, hunting dogs, search-and-rescue dogs and water sport dogs can be exposed to contaminated water and urine from animals. In the same way, people can be exposed to leptospirosis through swimming, kayaking, fishing, hunting, and other recreational activities and this can also be manifested in the sentinel data for dogs in the same recreational activities. Another interface where dogs and man share risk is occupational exposure in veterinary clinics, animal shelters

and farms. Such exposure landscapes can play a key role in sentinel surveillance as they can reveal specific geographic exposures and activities that might require more specific prevention strategies[24], [25].

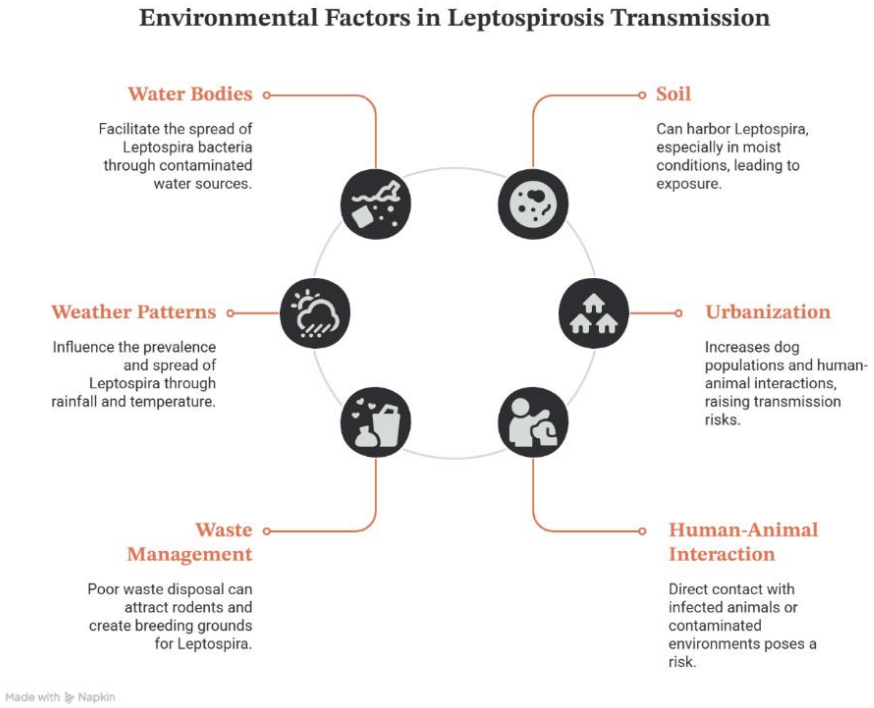


Figure 3.0 Environmental Determinants of Canine Leptospirosis

5. The Hidden Reservoir: Urinary Shedding and Environmental Contamination

5.1. Renal Persistence and Establishment of the Carrier State

Renal colonization and shedding of pathogenic Leptospira in urine is referred to as the carrier state. Acute infection results in localization of leptospires in the proximal renal tubules for which they can persist for weeks to months. Host immune responses, pathogen virulence factors and environmental factors in the tubular microenvironment all play significant roles in the establishment of renal carriage. Dogs are particularly susceptible to infection by serovar Canicola which has been linked to persistent infection following clinical recovery and antimicrobial therapy. The epidemiological importance of this adaptation: Canicola infected dogs can become long-term shedders and act as a reservoir of infection in the canine population and have the potential to be transmitted to humans[4], [26].

5.2. Dynamics of Urinary Leptospira Shedding

The main way that dogs infected with the virus shed the infection is through urine. Leptospira concentration in urine is subject to considerable variation with host, strain and stage of infection. A meta-analysis of shedding data showed that rats shed the most per mL of urine (median 5.7 × 106 cells), and the amount shed daily would be a function of both how much and how many mL of urine the animals produce. The systematic information on shedding intensity and shedding duration for dogs is still a gap that needs to be filled. The 2021 outbreak in Los Angeles reported high prevalence of shedding (leptospiruria) among affected dogs, while shedding loads were not quantified. The Ecuadorian study reported high urine positivity using qPCR (94.7%) without quantification of the bacteria. These knowledge gaps are critical to understanding the role of dogs in environmental contamination with Leptospira, and for the evaluation of zoonotic risk[10].

5.3. Intermittent Versus Persistent Shedding

Depending on dog-host/pathogen interactions, shedding can be intermittent or continuous. Because of intermittent shedding, surveillance can be problematic because one negative PCR urine dip will not rule out infection or shedding capacity. Persistent shedding is particularly the case of serovars which are

adapted to surviving in the reservoir, such as Canicola, and is a continual source of environmental contamination. Control implications are important: a persistent shedder needs closer observation and perhaps retreatment, whereas the intermittent shedder might not be detected with a once-only approach. Therefore, for surveillance purposes, molecular methods with high sensitivity that can detect Leptospira DNA are preferable to culture although PCR can not distinguish viable and non-viable organisms[27].

5.4. Factors Influencing Shedding Intensity and Duration

There are several factors that affect the amount and length of urinary shedding in dogs. Underlying renal function, age and immune status among host factors. Pathogen factors - virulence of strain and adaptation to the canine host. The timing and type of antimicrobial therapy are all factors in treatment; some dogs will shed even while treated. Environmental factors can also come into play as stress, concurrent infections and nutritional status may influence immune competence and pathogen clearance. Knowledge of these determinants is important in managing and interpreting surveillance information to develop appropriate control measures. For treatment, for instance, if the treatment does not consistently kill off the carriage, then clinical healing cannot be interpreted as shedding stopping, and perhaps post treatment monitoring should be considered[28].

5.5. Survival of Shed Leptospira in Natural Environments

However, shed into the environment in urine, Leptospira has to survive long enough to infect a new host. Temperature, moisture, pH, exposure to UV, and the presence of microbial competitors/ predators are all factors in environmental survival. Leptospires are pathogenic under appropriate conditions and have the ability to persist in water for over 20 days and in soil for over 40 days. The survival rate is up to 20 months in bottled mineral water and has been seen to be 6 months in water-saturated soil. Enhanced persistence by biofilm formation and association with complex environmental microbiota. These survival traits lead to the formation of chronic environmental foci of infection that may affect several hosts over time, if they are exposed to it. Hence, the environmental phase of Leptospira transmission is an active ecological process that is determined by the microbial community and environmental factors[29].

5.6. From Canine Urine to Contaminated Water and Soil

Environmental contamination is a multi-step process going from deposition of an animal's urine onto the soil or water to a survival of Leptospira in the environmental matrix and then to contact with a susceptible host. In peridomestic areas, it is possible that dogs urinate on ground, plants, or hard surfaces; and the bacteria get washed into water sources on rainy days. In aquatic systems, urine can be excreted directly into the water where dilution and dispersal easily take place. The Ecuadorian example of "Amazon environment sharing" depicts multiple overlapping zones of aquatic space use by people, dogs, and wildlife which produces concentrated transmission interfaces where zones of both urine deposition and human contact are shared. The same dynamics can happen in urban environments where dogs and humans coexist in parks, waterfronts and drainage areas[30].

5.7. Shedding Without Clinical Disease: The Silent Transmission Interface

Sometimes it can be difficult to find the problem with canine leptospirosis because some dogs can be subclinical shedders. Infected but non-clinically diseased dogs might not ever come to veterinary care and could still be able to excrete Leptospira in the environment and risk other animals and humans. It is important to understand that there is a difference between a “clinical case” and a “subclinical infection”: only a fraction of infected animals present clinically, and the prevalence of shedding may be significantly greater than the number of clinical cases. The silent transmission interface from this study supports the use of active surveillance measures like serosurveys, urine PCR screening, and environmental sampling, instead of passive case reporting. It also stresses the need to treat canine leptospirosis as a problem affecting a population, not just a single case[12].

6. From Dog to Environment to Human: Mapping the Zoonotic Transmission Chain

6.1. Direct Dog-to-Human Exposure

Dogs can transmit the virus directly, by touching with infected urine or tissue. People who may be at high risk of exposure to the urine or reproductive fluids of infected animals are veterinarians, veterinary technicians, shelter workers and dog breeders. Owners can also be at risk, especially if their dog is house trained or has areas where it regularly has an accident, or if the dog's owner cleans up urine without taking proper precautions. There were no human cases of the disease associated with the canine outbreak in 2021; however, the widespread leptospiruria was a concerning issue for possible zoonotic transmission. In humans, direct transmission is probably underdiagnosed due to either mild symptoms or asymptomaticity and/or misdiagnosis. Direct transmission risk is related to dog shedding duration and intensity and type of dog-human interaction and use of protection measures[31].

6.2. Indirect Transmission Through Contaminated Water

The best-known way for humans to become infected with leptospirosis is by indirect exposure from contaminated water. Humans are infected via urine from reservoir hosts (e.g. dogs) in water. The results of the mathematical modelling of human leptospirosis in Thailand revealed that the estimated transmission rates from contaminated environment to humans were always higher than those from livestock, suggesting that environmental transmission is the predominant transmission route. Some of this environmental contamination happens when dogs shed urine, especially in peridomestic areas where their urine might find its way into water sources that people use. The relative importance of dogs versus rodents and other hosts in contaminating water sources is hard to measure and probably depends on the ecology. Their contribution could be significant in areas where there are many free-roaming dogs with high prevalence of Leptospira[32].

6.3. Soil and Household Environmental Exposure

The soil and domestic surroundings can act as transmission surfaces when tainted with infected urines. Dogs may develop localized contamination in their yards, gardens and/or on indoor surfaces that lasts for weeks. Exposure can be through contaminated soil from gardening, play or home activities. Children are especially at risk because of their tendency to play in dirt, to put objects in their mouth and less frequent hygiene practices. The domestic setting provides a special converging point for exposure that is shared between the dog and human. Classic cases of occupational or recreational exposure may be episodic, whereas household dogs and people may be exposed continuously, resulting in constant transmission risk[31].

6.4. Occupational and Recreational Exposure Pathways

Canine leptospirosis exposure is occupational in veterinary practice, animal sheltering, dog breeding and research facilities. Veterinarians and support staff can be exposed by contact with urine, blood or tissues of infected dogs, especially during urinary catheterization or while whelping. Recreational exposure is associated with concurring in recreational activities with dogs: hunting, hiking, swimming, and boating. In these environments, human and dogs can be exposed to the same sources in the environment, which can make the number of cases in dogs and humans appear similar. Dogs in these situations can be considered sentinels because they alert people of contamination present in the environment that could also be a risk to humans, although the transmission may not be dog-to-dog-to-human[16].

6.5. Household Dogs as Bridges Between Outdoor and Indoor Environments

Household dogs can act as a link between the outdoor environmental reservoirs and the indoor human habitation. A dog may bring Leptospira into the house on its fur and/or paws after swimming in contaminated water or walking on contaminated soil. More importantly, if a dog becomes infected and sheds Leptospira in urine, then the dog can infect people (including children and immunocompromised people) in the domestic setting. This "bridging" type is an important part of the role of the canine sentinel: dogs can be exposed in multiple environments, such as parks, waterways, yards, and then transport this exposure to the domestic environment. Dogs vary in how much they shed and how often they have

accidents, plus the hygiene of the home will all be factors in how likely it is for a dog to transmit the disease indoors[4], [33], [34].

6.6. Distinguishing Dog-Mediated Transmission From Shared Environmental Exposure

One of the problems with assigning a human risk to leptospirosis via dogs is the difficulty of separating the risk associated with them from environmental exposure. If both the dog and its owner are affected, they may have been affected by the same contaminated water source or perhaps the dog may have infected the human. The ambiguity can be addressed through genomic epidemiology: If the Leptospira strains isolated from a dog and its owner share the same genotype, the possibility of dog-to-human transmission is more likely than that of a common exposure to a complex environmental source. Using whole-genome sequencing, human cases have been shown to be linked to rat reservoirs in urban settings; the same could be attempted for canine–human transmission investigations. Without genomic evidence, an attribution can only be made on the basis of an epidemiological inference, and as such is uncertain[35].

7. The Canine–Rodent–Environment Transmission Network

7.1. Rodents as Maintenance Hosts

Pathogenic Leptospira are best known as being maintained in rodents, especially Rattus norvegicus and Rattus rattus, and as the principal source of human infection in many situations. Rats may be in urban areas and can harbor several strains of Leptospira and may be a potential vector of the bacteria. A six-year study in Boston revealed Leptospira in 59 out of 328 samples of rat kidneys collected at 17 sites; genetic analysis identified the strain in a human case with that of rats from the same area as the case, supporting strongly the possibility of rat-to-human transmission. The abundance and shedding rates of rodents vary in space and time and are higher when there is more vegetative land cover and more rainfall during the season. It is known that the rodent–environment–human chain of transmission exists; however, the role of dogs in this chain is not well defined[4].

7.2. Dogs as Accidental and Maintenance Hosts

Depending on the Leptospira serovar, dogs maybe either accidental (incidental) or maintenance hosts. Dogs (and humans) are incidental hosts which develop acute disease but do not maintain longer transmission for serovars adapted to rodents. However, dogs are maintenance host of serovar Canicola, which can persist in the kidneys and be transmitted between dogs. This dual capacity makes interpretation of canine surveillance data challenging, as a dog with a rodent adapted serovar indicates environmental exposure to rodent urine, but a dog with Canicola indicates transmission of Canicola in the canine population level. Canine isolates can be differentiated using molecular typing techniques which will aid in targeted control measures[36].

7.3. Wildlife–Dog Interfaces

Wildlife-dog interfaces are important transmission pathways that have not yet been studied. Dogs can come into contact with Leptospira via predation of wild animals or through use of the same water sources as the wildlife, or from their urine. The prevalence of shedding of Leptospira spp. was high in free-ranging dogs from Indigenous communities in the Ecuadorian Amazon, where the predominant species were L. noguchii and L. santarosai species associated with wildlife. This indicates that dogs might act as sentinels of the presence of Leptospira infection in wildlife reservoirs and as links between wildlife reservoirs and human homes. A concentrated transmission interface is the "Amazon environment sharing", which refers to the simultaneous use of the same aquatic environment, leading to contact between humans, dogs and capybaras. The same kind of wildlife–dog–human interfaces can be found in the urban parks, peri-urban space and agricultural landscape[37].

7.4. Rodent Density, Urban Waste, and Canine Exposure

Infections may occur when dogs are exposed to the urine of rodents, in areas where their urine has contaminated the environment. Rodent numbers are important in determining how contaminated an environment is with Leptospira. In cities where waste management is insufficient, it is possible to establish

ecological niches for rodents and dogs are more likely to come into contact with them. Rats may shed Leptospira, a study in urban informal settlements had found that the shedding was related to spatial (valley bottom) and temporal (seasonal rainfall) factors and older, sexually mature rats. Dogs that live in these environments are potential sentinels for Leptospira circulation associated with rodents and can be used to provide spatially resolved data in complement to the rodent trapping surveys. The urban ecology of leptospirosis is therefore a very important relationship between the canine–rodent interface[38].

7.5. Multi-Host Environmental Amplification

Environmental Leptospira reservoir, which is increased by a variety of host species. Rats can produce the greatest amount of contamination per mL in their urine, while larger mammals such as dogs, cattle, and wildlife, because they have a higher volume of urine, can contribute significant amounts of total contamination. When the host population and prevalence of infections are taken into account, peridomestic cattle are said to be more important than rats in low-income rural communities for driving environmental cycling. However, it is probable that the dog is somewhere in between, as it is smaller than cattle, but is also likely to be more prevalent than cattle in some circumstances and more common than cattle in peridomestic environments and may also have a higher prevalence of Leptospira than cattle in some settings. Multi-host amplification is a phenomenon of environmental contamination, with control measures that are effective against only a single host species likely to be limited in effectiveness[39].

7.6. Host Switching and Ecological Connectivity

Leptospira transmission can occur between hosts and host switching can reconfigure transmission networks. Dogs can become exposed to the serovars in the environment and can become a chronic carrier and transmit these strains to other dogs or humans. However, serovars such as Canicola, adapted to the dog, can be transmitted to wildlife and establish new reservoirs. Genomic studies have shown Leptospira strains can switch between host species and geographic areas; in some areas human isolates are closer to canine or rodent isolates. Integrated genomic and ecological surveillance, monitoring Leptospira strains across host species and environments, is needed to understand host switching[40].

8. Diagnostic Surveillance: From Exposure Detection to Pathogen Shedding

A helpful conceptual framework for considering surveillance is to distinguish between three types of diagnosis: serology which detects evidence of past exposure; PCR which detects the presence of detectable DNA; and culture which detects the presence of viable bacteria. There are various implications of surveillance and control, depending on the type of modality. Serology (mainly MAT) will detect antibodies raised in response to infection with Leptospira. Positive Serology results mean the animal has been exposed to Leptospira at some time but not necessarily at the time of the test and not necessarily shedding. Serology is helpful for retrospective diagnosis when combined with an acute titer and a convalescent titer as well as for population-level surveillance to estimate the proportion of dogs in a population that have been exposed. Vaccination, however, will complicate the serological interpretation, and MAT does not allow the determination of the serovar of the infecting organism because of crossreactivity. The serovar panel as well as the cutoff titer also influence sensitivity and specificity and the protocols used differ from study-to-study[4], [41], [42].

Urine for shedding detection and blood for acute infection are most commonly used for PCR based detection of Leptospira DNA in clinical samples. The presence of Leptospira DNA in the urine gives a good indication of renal carriage and transmission risk, as a negative urine PCR does not rule it out. A more nuanced estimate of transmission potential is quantitative PCR which can be used to estimate pathogen load. But PCR does not differentiate between dead and living microorganisms: the presence of PCR-positive bacteria may be due to recently killed bacteria, which are not a risk of transmission. PCR is also not very sensitive for intermittent shedders or to rule out infection. PCR is most useful in high risk populations for shedding for surveillance and should be used along with clinical and epidemiologic information[43].

Culture is still the "gold standard" for the confirmation of viable Leptospira organisms. Leptospira can be isolated from urine or tissues, and this would constitute definitive evidence of infection and can be used

to characterize the strain by whole genome sequencing. Technically demanding however, culture is slow (weeks-months), and insensitive, especially for samples stored or transported. The fastidious nature of Leptospira, with regards to its needs for temperature, pH and nutrients, renders the use of culture impractical for routine surveillance. Recent methodologies such as Leptospira culture from frozen rodent kidney have been made, but culture is likely to remain a research tool and not a tool in surveillance[27].

9. Climate Change and the Emerging Geography of Canine Leptospirosis

9.1. Extreme Rainfall and Flood-Associated Transmission

Leptospirosis outbreaks are always linked to heavy rain and floods in human and animal populations. The Thailand modelling study revealed that flooding had a greater impact on transmission than rainfall alone, and that there was a one month time lag between flooding and the maximum incidence. Leptospira is mobilized from soil and sediments by floodwaters, which can spread the bacteria to new areas that were not previously contaminated, and provide new exposure to dogs and humans. In many regions, extreme rainfall events are expected to increase in frequency and intensity due to climate change, which could potentially increase the risk of transmission that is associated with flooding. In the case of canine leptospirosis, this would imply that low-risk areas could have an outbreak during extreme weather events and surveillance systems need to be in place to identify the signs[44].

9.2. Climate-Driven Expansion of Environmental Suitability

Climate change could increase the geographical area under conditions that support Leptospira survival and transmission. A Europe-wide assessment identified the presence of high-risk areas for leptospirosis in regions with high mean temperature and future climate scenarios suggested increase in the incidence of leptospirosis, especially under high GHG emission scenarios. In temperate areas, the transmission season could be longer if the weather gets warmer, and Leptospira could maintain itself in colder regions when they warm up. For leptospirosis in dogs, this may include further risks in areas where the disease is not yet common like northern Europe and North America. There is a need to improve veterinary surveillance systems in these areas to catch new detections[45].

9.3. Urban Flooding and Companion Animal Exposure

Companion animals and their owners are exposed to unique risks in urban flooding situations. The impervious surfaces in urban areas concentrate run-off and a poorly-designed drainage network can cause urban flooding even with moderate rainfalls. Flooded areas pose a potential risk of exposure to contaminated water and contaminated soil and standing water can be a risk to dogs with yard or street access. Low-income neighborhoods with substandard infrastructure may suffer from urban flooding, and have more free roaming dog populations than other communities. Urban flooding, rodent infestations and high dog density promote amplified transmission which can be identified by the presence of canine sentinel dogs[1], [46].

9.4. Changing Dog–Wildlife–Rodent Interactions

Climate change could change relationships between dogs, wildlife and rodents which impact Leptospira transmission. Rodent dynamics can be influenced by changes in rainfall and temperature, and greater numbers of rodents are associated with greater food abundance. Due to climate change, wildlife species may change their geographic distribution; this could lead to new Leptospira strains being introduced into areas that dogs and humans have not been exposed to in the past. Dogs can be sentinels of these evolving relationships: when prevalence of Leptospira changes in dogs, it may indicate shifts in the reservoir of the rodents or wildlife. Therefore, it may be more useful to keep an eye on exposure patterns in the dog, as this could give an early indication that there is a change in the transmission ecology because of climate change[47].

9.5. Geographic Re-Emergence of Canine Leptospirosis

Evidence of re-emergence of canine leptospirosis in some areas where it was once well controlled exists. The 2021 outbreak in Los Angeles came in a time when canine leptospirosis was thought to be not a

problem in urban areas, and vaccination was not routinely recommended by veterinarians. This outbreak spread to dogs at risk as in previous pre-vaccine outbreaks, male, young adult, medium-to-large breed outdoor dogs, indicating that change in the environment and/or change in the dynamics of the dog population may be a factor in increasing the exposure. Other areas are seeing similar re-emergence that may be related to climatic changes, urbanization, and rodents. Canine surveillance can monitor these re-emergence trends and guide vaccination and prevention[48].

9.6. Climate-Responsive Sentinel Surveillance

Climate sensitivity of leptospirosis provides opportunities for climate responsive sentinel surveillance. Since the burden of canine leptospirosis is likely to be associated with rainfall, flooding and temperature as is the case for human leptospirosis, climatic data can be used to inform a prediction of when the incidence is likely to be greatest and thereby help to inform heightened surveillance efforts. The Thailand model showed how human cases can be predicted based on the environmental factor variables that can be added into the transmission models. The same system may be used for dog-watching, for instance, with data on vet cases and climate factors creating an early-warning system. Climate-responsive surveillance would be a more frequent sampling in high-risk areas (flood prone areas, rat infested areas, or areas with high free roaming dog populations) and at high-risk times (post heavy rainfalls or flooding)[49].

10. One Health Surveillance and Prevention: From Sentinel Dogs to Early-Warning Systems

10.1. Integrating Veterinary and Human Surveillance

One Health means merging veterinary and human surveillance data as the basis for an approach to leptospirosis. Human and canine leptospirosis monitoring is currently largely independent of one another, with cases of leptospirosis being reported to animal health authorities and to public health authorities. This separation reduces the understanding of epidemiological links between canine and human infection and decreases the sentinel value of the canine data. Integrated surveillance would include common case definitions, sharing of data platforms, and joint investigations of clusters. When human cases are detected, veterinary authorities should be alerted to investigate canine exposure in the same area. On the other hand, if canine cases are detected, it is important for public health authorities to be notified in order to evaluate the human risk and targeted interventions[50].

10.2. Environmental Sampling as a Complement to Canine Surveillance

Environmental samples for pathogenic Leptospira can be used as a source of direct evidence of contamination that can augment canine surveillance data. Environmental (water and soil) sampling with molecular approaches e.g. qPCR, eDNA metabarcoding can help define environmental hotspots and monitor the progression of contamination over time. In a study in Argentina, it was possible to show that in different environments, water and soil samples can be analyzed and pathogenic strains of Leptospira groups P1 and P2 were recovered in 37% and 41%, respectively. Canine surveillance along with environmental sampling subsequent to, if positive, can be used to determine if the area is contaminated, and what exposure points (e.g., particular water bodies, drainage areas) need to be taken action. On the other hand, detection of Leptospira in the environment can be a signal to initiate surveillance for canine and human cases in areas where clinical cases are not yet known[51].

10.3. Geospatial Mapping of Canine and Human Cases

Spatial analysis can be used to uncover spatial patterns in canine and human leptospirosis that can provide guidance for targeted prevention efforts. Geographical mapping of cases to their place of residence, place of exposure and environmental risk factors can help in the identification of hotspots and risk corridors. Spatial epidemiology has helped investigate associations between the abundance of rats and shedding of Leptospira bacteria and the risk of human infection in urban informal settlements. These similar approaches can be adapted to combine canine case data, human case data, rodent surveillance data and environmental data to generate risk maps to inform resource allocation. Geospatial analysis can also be used to monitor how Leptospira strains are dispersing among the population as was done in a Boston rat

study, where computer-based analysis of genetic and spatial data showed association between the human and rat isolates[52].

10.4. Climate and Environmental Early-Warning Indicators

Climate and environmental data can be used as early-warning indicators of risk of leptospirosis. There are measurable variables that precede human and canine cases such as rainfall, flooding, temperature and rodent abundance. In Thailand model, it was found that the human incidence of leptospirosis could be predicted with one month delay from flooding and temperature. Precipitation, temperature and forest–human nexus were found as risk factors that could be used in early-warning systems in a Europe-wide assessment. Climate data might also be used to guide increased monitoring around climate risk periods, and to inform the interpretation of the trends in the case data, for canine sentinel surveillance. Meteorological, environmental, and health data can be integrated to create climate–pathogen surveillance platforms which may show promise in the future of leptospirosis early warning[53].

10.5. Vaccination and Reduction of Canine Infection Risk

Vaccination is an important measure for lowering the number of cases of canine leptospirosis and possibly the amount of contamination in the environment. Vaccines are available for only a small number of serovars (usually Icterohaemorrhagiae, Canicola, Grippotyphosa and Pomona) and vaccine-induced immunity is thought to be serogroup-specific. The apparent shift in serovars infecting dogs towards Grippotyphosa and Australis in some areas indicates that some serovars may be missed in some areas due to incomplete vaccine coverage for serovars that are circulating. Better characterisation of serovars infecting dogs in various geographic regions could lead the future vaccine design to create more protective vaccines. Vaccination of dogs could be beneficial from a One Health approach as vaccinated dogs are less likely to become infected and shed, therefore reducing the environmental load of Leptospira. But there's no known measurement for how much impact on human risk canine vaccines have at the population level[2].

10.6. Rodent and Environmental Management

Leptospira contamination can be managed by controlling rodents and the environment. IPM to reduce the population of rodents can reduce contamination of the environment and exposure of canines. Waste management and drainage system improvements can also help in decreasing the sources of water habitation, such as the presence of rodents and standing water which act as reservoirs for Leptospira. Environmental interventions in situations where flooding and rat abundance are important risk factors may have more impact than focusing on individual hosts (urban informal settlements). Canine surveillance can be used to help inform these interventions and to determine where dogs are coming into contact with rodent-associated Leptospira and therefore where rodent control is needed[46].

10.7. Community and Veterinary Awareness

Awareness and education is a part of prevention. Leptospirosis risk factors should be known to a veterinarian and the possibility of leptospirosis should be considered in dogs with compatible clinical signs despite the disease being considered “uncommon” in urban areas. Dog owners should be aware of potential exposures (water, wildlife/wild waterfowl, puddling) and preventive measures: vaccinations, avoiding risky water sources. Utilize human leptospirosis risk for public health authorities, based on the canine sentinel surveillance data and any indication of environmental contamination. Community-based surveillance with the involvement of the local community and health promoters to support data collection and reporting can improve detection in underserved areas[54].

A robust One Health model would consist of a package that brings together dog surveillance, human surveillance, environmental surveillance, climate, and geospatial. This holistic perspective emphasizes that leptospirosis is not only a zoonotic disease from animals to humans, but an ecological disease influenced by environmental factors and host-pathogen dynamics. Canine sentinel data can be used in conjunction with and improves other surveillance data streams[1].

11. Emerging Technologies for Sentinel-Based Leptospirosis Surveillance

11.1. Whole-Genome Sequencing of Canine Leptospira

Whole genome sequencing (WGS) revolutionized investigation of Leptospira epidemiology with its high-resolution phylogenetic analysis and strain tracking. The core genome MLST (cgMLST) which data 545 conserved loci, enables global comparisons and prediction of serogroups. Genotyping for single nucleotide variant (SNV) can be used for the inference of evolutionary relatedness and population dynamics. WGS can be used with the canine Leptospira strains to investigate and understand transmission networks, sources of infection and how strains are transmitted among dogs, wildlife and people. WGS was used to analyze L. interrogans strains of human, dog and wildlife origin in Japan and found geographic distributions and genotype–host associations with some human strains grouping with canine strains. The same method could be applied in other situations to better understand the risk of dogs in human infections[55].

11.2. Genomic Tracking of Transmission Networks

Through the process of genomic epidemiology, it is possible to distinguish whether the transmission was dog-to-dog or a shared exposure to a common environment by comparing the genome of Leptospira strains found in dogs, humans, and the environment. If a human case is caused by a strain which is genetically identical to a dog isolate from the same household, then dog-to-human transmission is likely. If human and dog isolates are different, a shared environmental exposure to different strains of these is more likely. The Boston rat study provided proof of the efficacy of this method: a human case was correlated, via genomic analysis, with strains of rats from the same area. Broader genomic surveillance of dogs would increase the resolution of transmission network reconstruction and provide for more precise interventions[56].

11.3. Spatial Epidemiology and GIS-Based Risk Mapping

Geographic information systems (GIS) allow for the combination of spatially mapped information on canine cases, human cases, environmental contamination, rodent densities, and climate factors. Environmental and hydrological factors have been identified by spatial epidemiology as being more important than factors related to rats in leptospirosis spillover in urban informal settlements. GIS-based risk mapping can help identify potential "hotspots" in which the exposure of humans and dogs overlap, inform environmental sampling, and focus prevention efforts. Spatial models can predict future risk areas, when coupled with climate projections, under varying climate scenarios[57].

11.4. Environmental DNA and Molecular Surveillance

Environmental DNA (eDNA) can be used to detect the presence of Leptospira in water and soil without the use of culture. Multiplex qPCR allows simultaneous detection and identification of pathogenic Leptospira groups and metabarcoding allows identification of organisms associated with environmental persistence that can harbor Leptospira. eDNA surveillance can supplement the canine sentinel data, as it provides direct evidence of environmental contamination at given locations. It is especially useful to make positive water source identification for both people and dogs to determine if there is contamination in the water source, rivers, lakes and urban drainage systems[58].

11.5. Artificial Intelligence for Predictive Risk Mapping

AI and ML technologies could combine various data streams, including climate, environmental, veterinary, and human surveillance to predict the risk of leptospirosis. They can be used to discern nonlinear, complex relationships that conventional statistical models are lacking. In the context of sentinel-based surveillance, AI could be applied to provide predictions of the highest risk canine populations to monitor based on environmental and demographic factors, predictions of expected outbreak timing from climate data, or identification of spatial patterns in case information that may be of interest. The AI-based early-warning system for leptospirosis is a new field that has great promise[53].

11.6. Integrated Climate–Pathogen Surveillance Platforms

The new generation of platforms is represented by integrated platforms, which combine environmental sampling, climate monitoring and health surveillance. These platforms would gather real-time information on cane toad populations, flooding, soil and water contamination with Leptospira, temperature, and human and canine Leptospira infections. These data streams might be analysed using machine learning algorithms to produce risk forecasts and set alerts during circumstances that are favourable to transmission. The Europe-wide leptospirosis risk assessment, incorporating epidemiological, environmental and climate data, showed a way forward to this integrated surveillance. Collaboration between meteorological, environmental, veterinary and public health agencies would be necessary to operationalize these platforms, a quintessential One Health endeavour[59].

Conclusions

From a One Health perspective, canine leptospirosis transcends the veterinary clinical disease. It is a sentinel phenomenon that reflects the ecology of the circulation of these pathogenic Leptospira, the shedding of the bacteria in the urine of infected animals, and the environmental contamination and risk of zoonotic transmission when humans, dogs, and environmental reservoirs overlap. Leptospira exposure and infection occurs in a wide variety of environments, and exposure trends in dogs frequently reflect or predict exposure trends of people. Thus, serological and molecular surveillance of canine environment can yield the 'spatially and temporally resolved' data on environmental circulation of Leptospira not obtainable by other means. Infection of dogs, including subclinical dogs, results in shedding in the urine and environmental contamination as well as transmission interfaces in domestic and community environments. Leptospira are known to survive in soil and water, meaning that the impact of shedding can be long-lasting. Environment, behavior, and social-economic factors influence the zoonotic transmission to humans from dogs to humans which is multifactorial (direct dog to human contact as well as contaminated water, household environment, and shared outdoor areas).

Climate change is affecting the geographical distribution and intensity of transmission of leptospirosis, as extreme rainfall, flooding and warming temperatures are causing a new risk landscape for dogs and humans. They can be detected early by canine sentinel surveillance in conjunction with climate and environmental information. New technologies, such as whole genome sequencing, eDNA, spatial epidemiology and AI-based risk mapping, provide opportunities to operationalize sentinel-based surveillance and help turn the canine data into actionable public health intelligence. From a practical point of view, canine leptospirosis needs to be incorporated into One Health early-warning systems, which would include veterinary, human, environmental and climate data. A conceptual framework for developing an appropriate surveillance program to meet different objectives can be found in the difference between serological evidence of exposure, PCR evidence of shedding, and culture evidence of viable organisms. In conclusion, dogs can provide insight into the ecology of leptospirosis, which is useful in prevention, surveillance and for protecting animal and human health.

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