

Research Article

RNA in-situ hybridization for pathology-based diagnosis of feline infectious peritonitis (FIP): current diagnostics for FIP and comparison to the current gold standard

Arjun Sweet¹, Nicole Andre¹, Gary Whittaker²

1. Department of Microbiology & Immunology, College of Veterinary Medicine, Cornell University, United States; 2. Cornell University, United States

Feline infectious peritonitis (FIP) is a systemic disease of cats caused by a highly pathogenic variant of feline coronavirus, or FCoV (termed FIPV). Two serotypes of FCoV exist: type 1 viruses constitute 85% to 95% of FIP cases, while type 2 viruses are responsible for the remaining 5% to 15% of infections. Immunohistochemistry (IHC) currently serves as the gold standard for diagnosis of FIPV; however, IHC is limited by its wide variations in sensitivity. RNA in situ hybridization (RNA ISH) has an established foothold in infectious disease diagnostics and presents a potentially improved method for detection of FIPV. This study evaluated the efficacy of RNA ISH probes targeted to FIPV, as compared to IHC using monoclonal antibody FIP 3-70. Formalin-fixed paraffin-embedded tissues from FIP-positive cats were used for ISH, with RNA presence determined chromogenically. ISH tissue slides were then compared to their IHC counterparts, with efficacy determined based on metrics including staining intensity and abundance. Positive ISH staining on tissue was found to be both more intense and abundant than for IHC—suggesting that ISH serves as a highly sensitive method for the detection of FCoV/FIPV, in comparison to IHC.

Arjun N. Sweet and Nicole M. André contributed equally.

Corresponding author: Gary Whittaker, gary.whittaker@cornell.edu

Introduction

Feline infectious peritonitis (FIP) is a leading cause of mortality in young cats. The clinical nature of the disease was characterized in the 1960's and the etiologic agent was subsequently identified as a coronavirus, specifically feline coronavirus (FCoV) ^{[1][2]}. FCoV can be classified in several ways. Two distinct biotypes of FCoV exist. The first biotype, feline enteric coronavirus (FECV) infection, is characterized as a self-limiting gastrointestinal disease with an enterocyte tropism with either asymptomatic presentation or mild clinical signs such as diarrhea. FECV is highly prevalent in multi-cat environments and many domestic cats demonstrate evidence of prior infection through serology ^[3]. The other biotype, feline infectious peritonitis virus (FIPV), results from a small subset of FECV-infected cats through mutation of FECV through a combination of host and viral factors. The biotype switch from FECV to FIPV results in an increased tropism for macrophages, resulting in a systemic infection ^[4]. On the basis of serotype, type I FCoV is considered to be feline in origin while type II FCoV is believed to have resulted from recombination events between FCoV type I and canine coronavirus (CCoV) ^[5]. Importantly, both serotypes have been characterized in FECV and FIPV forms.

The presentation of FIP is on a clinical spectrum. The effusive/wet form of the disease is more common and is characterized by a rapid disease progression with accumulation of a proteinaceous exudate in the abdominal and thoracic cavities, as well as less specific clinical signs including, fever, malaise, anorexia, weakness, and shortness of breath ^[1]. The non-effusive/dry form of the disease generally has a more protracted disease course and is frequently characterized by neurological and ocular signs as well as granulomatous lesions in the abdominal organs ^[6]. Given the spectral nature of the disease, mixed forms of FIP—with an overlap of both wet and dry presentations—are also a possible presentation ^[4]. The progression of FIP is always fatal without treatment, and while experimental therapies exist, there are no approved treatments. Consequently, FIP is a serious disease and is a leading infectious cause of mortality in cats.

Despite the well-characterized clinical nature of FIP, the diagnosis of FIP remains a considerable challenge for clinicians. FIP often remains a diagnosis of exclusion, whereby other conditions are ruled out on the basis of clinical presentation and various laboratory tests. Given the fatal nature of FIP and a lack of licensed treatments that extend beyond a supportive measure, euthanasia is common. Ideally, a definitive diagnosis is reached before opting for euthanasia or treatment, but this is rarely achieved ^[7]. Several diagnostic methods have been used in clinical and laboratory settings and involve limitations in

the ante-mortem (versus post-mortem) application as well as an overall trade-off in sensitivity and specificity. The balance between sensitivity and specificity has been a consistent issue with FIP diagnostics.

Review of diagnostic options

Clinical evaluation

The presentation of FIP is diverse with effusive, non-effusive, and mixed forms of the disease, and transition between the wet and dry forms is possible [6]. Preliminary diagnosis involves obtaining a high index of suspicion for FIP while ruling out other conditions. Signs that are common to both effusive and non-effusive forms (fever, anorexia, and lethargy) are non-specific to FIP. The hallmark presentation of wet FIP is effusion which, while more descript than the aforementioned signs, is also not entirely specific to FIP [8]. Similarly, in dry FIP, while the neurologic and ophthalmologic signs may be more specific of the disease state, they are not exclusive to FIP. Although signs may be suggestive of FIP—and other conditions may be ruled out with their own diagnostic testing to support an FIP diagnosis—they are of limited utility to arrive at the diagnosis on their own.

Serum biochemistry

Attempts at interpreting acute phase protein levels in the diagnosis of FIP have are associated with low specificity. Alpha-1-acid glycoprotein (AGP) is an acute phase protein whose levels are upregulated in the serum of cats with FIP, and has the potential to be used as a diagnostic indicator of FIP. Importantly, AGP can also be upregulated in other conditions, thereby limiting its diagnostic specificity [9]. In similar fashion, serum amyloid A (SAA) is another acute phase protein whose levels are upregulated in FIP. SAA is able to distinguish between infection of the two FCoV biotypes (FECV vs FIPV); however, as is the case with AGP, SAA can be upregulated in other disease processes, including other effusive conditions [10][11]. In tandem with other clinical signs, the use of SAA in the diagnosis of FIP may not reach the needed positive predictive value to arrive at a definitive conclusion. In summary, use of acute phase proteins in the diagnosis of FIP, while advantageous in allowing for an antemortem evaluation, is limited by upregulation of such proteins in other disease states—some of which also involve effusion and/or systemic inflammation, and is not routinely performed.

Other serum biochemistry abnormalities have also been associated with FIP. Reports of jaundice in cats with effusive FIP led to investigation of bilirubin levels in the clinical evaluation of FIP. Bilirubin as an indicator of FIP is most powerful when high serum levels are not accompanied by substantially increased liver enzymes, as a marked elevation of both may be reflective of liver disease as opposed to FIP [11]. Hyperbilirubinemia is prevalent in FIP cases and its prevalence can increase throughout disease progression, with first assessment of cats with FIP in one study showing 36.1% prevalence which later increased to 89.3% before death [12]. While hyperbilirubinemia presents a viable antemortem option to raise suspicion of FIP, its use as a diagnostic tool is limited by several factors. First, since the development of FIP is not always accompanied by hyperbilirubinemia, the sensitivity of it as an indicator is limited. This further extends to the different clinical presentations of the disease. While hyperbilirubinemia can be demonstrated in both effusive and non-effusive forms of the disease, the presentation is more frequent in effusive FIP, somewhat limiting its utility as a diagnostic indicator from the dry forms of the disease. Lastly, while the suspicion of FIP is heightened with elevated serum bilirubin without an accompanying increase in liver enzymes, other conditions such as sepsis and pancreatitis can present similarly, thereby limiting specificity [8]. The increase in serum bilirubin that often occurs late in the disease course also presents a limitation in terms of early diagnosis and treatment.

Hyperglobulinemia, alongside hypoalbuminemia, is frequently observed in FIP. Use of the albumin to globulin (A:G) ratio has been used as a diagnostic marker for FIP, with a lower ratio (<0.6) more indicative of the disease [13]. Importantly, A:G ratios do not significantly differ between cats presenting with or without effusion. The positive predictive value—the probability that an animal with a positive test has the disease of interest—is highly dependent on the prevalence of the disease in the population. The low prevalence of FIP limits the ability for a low A:G ratio to confirm the disease. Conversely, the negative predictive value—probability that a negative test result is truly indicative of an individual not having the disease—is more favorable. Therefore, while a A:G ratio that exceeds the threshold of suspicion for FIP is beneficial for ruling out FIP, but a low A:G ratio is not always indicative of the disease [14].

Rivalta's test.

The presence of a proteinaceous exudate, characteristic of the effusive forms of the disease, has been used to develop an easily accessible, non-invasive diagnostic test for FIP. This test, Rivalta's test, is an inexpensive crude assay in which a small portion of the effusion is added to an aliquot of acetic acid. With a high protein content sample, as is the case with FIP effusion, a precipitate is produced from the addition

of the clinical sample. Such a simple, cost-effective diagnostic test presents advantages for private practices and animal shelters, where financial resources may be limited and a clinician may not have access to the latest diagnostic technology. Rivalta's test has demonstrated moderately encouraging results when it is used for the diagnosis of FIP, with a sensitivity and specificity of 91.3% and 65.5%, respectively, and a positive predictive value of 58.4% [15]. Importantly, while a positive Rivalta's test may increase the suspicion for FIP, it does not definitively support a diagnosis. Rivalta's test relies on the high protein content of the effusion of cats, rather than a specific detection of FIPV. Consequently, a positive Rivalta's test only demonstrates that the effusion is an exudate—containing large plasma proteins—as opposed to a transudate, which does not contain as much protein.

Serology

While it seems intuitive that use of FCoV serology may be of diagnostic utility for FIPV, a fundamental problem lies in the pathogenesis of the disease. FIP results from a prior infection of the FECV biotype that, through a combination of viral and host factors, mutates into the FIPV biotype. The close relationship between the two biotypes leads to considerable limitations in the diagnostic value of FCoV serology as the two biotypes are virtually identical to each other antigenically, resulting in the production of highly similar antibody responses. Given the extensive prevalence of current or prior FECV infection among domestic cat populations, as well as the comparatively low prevalence of FIP, the return of a positive serology result does little to confirm the diagnosis of FIP. Rather, serology can only be used to determine if a cat has evidence of prior FCoV infection.

While the detection of FCoV antibodies does not offer much specificity in differentiating between the two biotypes, antibody titers have been investigated as a diagnostic marker between FECV and FIPV infection. Many healthy cats with FECV infection have antibody titers ranging from 1:100 to 1:400 [16]. While these ranges do not necessarily exclude FIP, as cats with FIP can have titers within this range or even be seronegative, the upper extremes of FCoV antibody titers have some diagnostic value. Among cats with titers of 1:1600, 94% had FIP in one study [17]. The clinical suspicion of FIP increases as titers further increase to 1:3200 [18]. Importantly, cats with high antibody titers constitute the minority of FIP cases. Despite the strong positive predictive value of high FCoV antibody titers, the inconsistent prevalence of these high titer values among cats with FIP limits their utility in the clinical setting.

Molecular Diagnostic Tests

Achieving a timely clinical suspicion or diagnosis is crucial with FIP given the severe, rapid progression of the disease and the frequent decision to perform euthanasia in response. Several diagnostic methods, each with varying levels of success, have been applied to the clinical setting with the aim of detecting FIPV in order to achieve a diagnosis. Here these molecular methods, along with their limitations, are discussed

RT-PCR

Polymerase chain reaction (PCR) has been investigated for the diagnosis of FIP given the technique's well-established foothold in infectious disease diagnostics. Reverse transcription (RT) has been the primarily used form of the reaction given the potential for laboratory contamination with DNA or other PCR products ^[18]. Nested PCR, which involves amplification of a small viral cDNA sequence from a larger, previously purified cDNA segment, has also been employed in FIP diagnostics. One study using such a method on the ascites of FIP-suspected cats, using a targeted approach that focused on sequence differences in the E2 gene (spike protein) between FECV and FIPV showed a sensitivity and specificity of 91.6% and 94%, respectively ^[19]. However, the authors do stipulate that since cross-reactivity was only tested against one FECV strain, other FECVs with greater genetic similarity to the targeted FIPV strains may limit the specificity of the technique.

One of the major considerations with the application of PCR to the diagnosis of FIP is the collection site of the sample. FECV infection is generally self-limiting to the intestines while FIPV, resulting from efficient monocyte/macrophage tropism, is systemic. A common method of sample collection in cats is a fecal swab. However, given the tropism of FECV for enterocytes, use of a fecal swab PCR for FCoV is of little utility in providing a definitive FIP diagnosis.

The tropism of FECV for enterocytes does not limit the detection of viral RNA to the intestine. Regardless of the development of FIP, a large portion of FCoV infected cats demonstrate viremia ^[20]; however, it has been suggested that cats with FIP demonstrate a higher viral load in haemolymphatic tissues compared to FCoV-infected cats without severe disease ^[21]. The detection of FCoV RNA systemically undermines the ability to distinguish FIP from another similarly presenting disease in a cat that also has a persistent FECV infection. As is the case with PCR tests for the diagnosis of other infectious diseases, a negative

result does not necessarily preclude that a cat is infected with FCoV or has FIP—as false negatives are a known shortcoming of diagnostic PCR tests.

Design of current PCR tests, in and of themselves, frequently fall short in distinguishing between the two FCoV biotypes due to the close genetic relationship. Current PCR tests, in order to achieve the necessary sensitivity to detect all FIPV variants, target conserved portions of the viral genome such as the membrane (M) gene or the nucleocapsid (N) gene [22][23]. Attempting to design a PCR test that exploits the genetic differences between FECV and FIPV would allow for a greater diagnostic specificity. Initially, it was believed that a truncated Orf3c gene may be responsible for the biotype switch from FECV to FIPV—presenting as an area for differentiation for PCR based tests. However, this truncation is not present across all FIPV variants, thereby limiting sensitivity [24]. Additional investigation was also conducted with Orf7b as a possible differentiating genetic element between the two biotypes, with FIPVs showing an intact Orf7b which was believed to be necessary for the macrophage tropism of the virus. However, with FECVs also demonstrating an intact Orf7b, this genetic difference does not distinguish between the two biotypes and cannot be used to definitively diagnose FIP [25].

The interest in finding distinct genetic and antigenic differences between the two FCoV biotypes has led to consideration of the viral spike glycoprotein—the major protein involved in infectivity and cell tropism—to distinguish between FECV and FIPV given their different tropism. While key genetic differences do exist within the spike glycoprotein between the two biotypes, specifically in the S1/S2 cleavage site, which is cleaved by host proteases to facilitate viral entry and membrane fusion, these mutations are not constant across all FIPV variants [26][27][28]. Furthermore, the S1/S2 cleavage site is only present in serotype I FCoVs, which effectively limits use of it as a suitable target for molecular-based diagnostics by excluding type II FCoVs. Other amino acid substitutions, M1058L and S1060A, have also been explored as potential distinguishers but again, are not present across all FIPV variants [27][29][30]. In summary, while current PCR tests fall short in differentiating between FECV and FIPV, development of a more specific PCR that exploits differences between the two biotypes sees a noticeable decline in sensitivity due to an increased risk of false negative results. It is hoped that more extensive genomic, next-generation sequencing of the virus variants will overcome the shortcoming of the more traditional and restrictive PCR-based techniques.

Immunostaining

Immunostaining presents one of the most specific methods of FIP diagnosis, and is where the current diagnostic gold standard lies. Immunostaining uses monoclonal or polyclonal antibodies that target FCoV antigen to deliver a colored or fluorescent label to the infected tissue. Importantly, given the close antigenic relationship between FECV and FIPV, detection of FCoV antigen itself does not necessarily indicate the presence of the FIPV biotype. Instead, the specificity of the technique comes through the detection of significant antigen in monocytes and macrophages.

Immunostaining as a diagnostic technique can be broadly classified into two methods. Immunocytochemistry (ICC) uses a fluorescent secondary antibody targeted against the FCoV-specific primary antibody to allow for evaluation of effusion and/or fine needle aspirates via fluorescent microscopy. ICC presents a relatively non-invasive option for a specific diagnosis. A study examining the use of ICC for FIP diagnosis placed its specificity at 91% and its sensitivity at 53%, indicating that while a positive result often indicates an accurate FIP diagnosis—albeit with the possibility of false positives—there is ample opportunity for false negative results ^[31]. Importantly, this study was performed with fine needle aspirates of mesenteric lymph nodes, which tend to have a high viral load. For effusion samples, the ability to achieve a positive result may be further limited by the poor cell count of the fluid, which is a characteristic of FIP-related effusions.

The other method of immunostaining, immunohistochemistry (IHC), utilizes the detection of FCoV antigen in fixed tissue, typically in macrophages. IHC is considered the current diagnostic gold standard and has demonstrated a 100% specificity, meaning a positive result is always indicative of the cat having FIP ^[31]. IHC is performed by the sampling of tissue which, due to its invasive nature, generally limits the technique to the post-mortem setting. Therefore, rather than using the technique to guide clinical judgement, IHC is mainly performed in a confirmatory manner to offer closure to clinicians and family of the pet as well as guide their actions to delay acquisition of another cat, as it may be at risk for contracting FCoV and (possibly) developing FIP.

Despite the confirmatory nature of IHC, as with the ICC the major drawback is sensitivity. FCoV immunostaining often uses the monoclonal antibody FIPV 3-70, targeting the FIPV 3-70 epitope of the viral nucleocapsid. Large variation in sensitivity of the technique with the antibody has been observed. A 2008 study examined the performance of FIPV 3-70 mAb compared to CCV2-2 (canine coronavirus nucleocapsid) and found that a substantial portion of FIP-confirmed cats (via CCV2-2 IHC) had cells that

expressed the FIPV 3-70 epitope—resulting in a 37% sensitivity [32]. While such low sensitivity is not always the case with IHC for FIP diagnosis, the opportunity for certain viral populations to evade detection by the technique presents a significant limitation in what is considered the current gold standard of FIP diagnostics.

Investigation of RNA ISH

The shortcomings of IHC present an obvious area to address in the diagnosis of FIP. Developing a new diagnostic method that reduces the quantity of false negative results while still preserving the specificity of the immunohistochemical gold standard—not seeing an observed increase in false positive results—is the optimal outcome.

Instead of investigating a new antigenic target for IHC, we reasoned that RNA in situ hybridization (ISH) presents an excellent alternative for the laboratory diagnosis of FIP. RNA ISH has an established foothold in infectious disease diagnostics and can be particularly useful when there is no known or available antibody epitope with the adequate sensitivity and specificity to allow for consistent detection of a pathogen via immunohistochemical methods. As opposed to the use of antibody to detect a specific antigen, RNA ISH functions through the detection of specific RNA sequences through oligonucleotide probes—effectively allowing for the detection and microscopic visualization of pathogen-specific RNA sequences in tissue. In the case of FIPV, the technique may provide a key advantage. By targeting RNA, as opposed to protein with IHC, the aforementioned antigenic heterogeneity is bypassed—as there is no direct need for the presence of the FIPV 3-70 epitope. Rather, there must just be sufficient viral RNA to allow for visualization. Should a given tissue be suitable for productive infection, viral RNA should be present in sufficient quantities to allow for detection.

Traditional RNA ISH techniques have struggled in sensitivity, requiring significant expression of the desired transcripts, and also required a considerable amount of individual labor—thereby limiting its utility in the clinical setting [33][34]. However, in recent years in situ technology that offers a greater diagnostic sensitivity has emerged. One such option is RNAScope™, which uses custom-designed probes that are targeted to 18-25 base pair regions of the desired RNA sequence and a series of amplifiers and chromogenic labeling to allow for proper visualization. Here, we investigate the performance of this RNA ISH technique in the histological diagnosis of FIP, evaluating its comparison to the current diagnostic gold standard of IHC.

Methods

Selection of probe target region

A preliminary evaluation of target genes was performed using a review of the existing literature. A previous study successfully developed a pancoronavirus RT-PCR assay for the detection of all known coronaviruses based on a conserved portion of the Orflab gene that encodes the viral RNA polymerase [35]. Therefore, in order to capture all FIPV variants and limit the decline in sensitivity that would be observed by choosing a less conserved region, the Orflab gene presented as the optimal target site for the RNA ISH probes. A set of thirteen Orflab FIPV sequences (accession numbers: FJ938052.1, FJ938059.1, FJ938055.1, KX722529.1, KY566211.1, KY566210.1, KY566209.1, KY292377.1, MG893511.1, KF530123.1, KX722531.1, KX722530.1, EU186072.1) was shared with Advanced Cell Diagnostics (Hayward, CA) for development of a custom probe. A probe based on serotype II FIPV Orflab sequences was identified in preliminary investigation to have the greatest sensitivity across both serotypes. The probe had a target area from base pairs 12380 to 13396 with 84.4% pairwise identity (average percent of exact matches over the aligned sequences) and a T_m of 83.5°C.

IHC and selection of FIP samples for ISH

Immunohistochemistry was performed by the Section of Anatomic Pathology, Department of Biomedical Sciences at Cornell University College of Veterinary Medicine. Unstained slides containing sections of tissue 5 µm thick were baked in an oven at 80°C for thirty minutes. On a Leica BOND-MAX Stainer, slides were de-waxed with Bond Dewax Solution (Leica-cat#AR9222). Epitope retrieval was then performed using Bond Epitope Retrieval Solution 1 (Leica-cat#AR9961), with the solution applied for thirty minutes. Monoclonal antibody FIPV 3-70 (Custom Monoclonals-Cat#MCA2194) was diluted at 1:1000 and applied to the slide for sixty minutes, after which PV-AP-Anti-Mouse IgG Reagent (Leica-cat#PV6110) was applied to the slide for thirty minutes. Leica Bond Polymer Red Detection (Leica-cat#DS9390) was applied for fifteen minutes and then followed by hematoxylin for five minutes (Leica-cat#DS9390). Slides were then removed from the stainer and allowed to air dry. When dry, slides were dipped in xylene and cover-slipped.

A collection of immunohistochemical slides of feline tissues with suspected FIP collected prior to the COVID-19 pandemic were obtained from a previous study and evaluated by light microscopy for the presence of FIPV antigen. Tissues included brain, liver, kidney, lung, spleen, intestine, and mesenteric

lymph node. Slides that demonstrated immunoreactivity were further assessed for the abundance of FIPV-containing lesions. Slides which demonstrated larger, more intensely stained lesions were cross-referenced to formalin-fixed paraffin embedded (FFPE) tissue blocks from which the slides originated and selected for examination with RNA ISH. Tissue samples from a unique thirty cats were selected for evaluation with RNA ISH.

RNA in situ hybridization

FFPE blocks corresponding to the selected IHC slides were cut into 5 µm sections and placed onto slides by the Section of Anatomic Pathology at Cornell University College of Veterinary Medicine. RNA ISH was performed using the RNAscope™ 2.5 HD Reagent Kit RED provided by Advanced Cell Diagnostics (Hayward, CA). After obtaining the slides from the diagnostic laboratory, slides were first deparaffinized on a slide warmer at 60°C for 20 min, followed by two changes in xylene for 5 min and two changes in 100% ethanol for 3 min each. After drying, slides were treated with hydrogen peroxide for 10 min at room temperature, washed twice with water, and boiled in a target retrieval solution for 15 min. After two additional washes in water followed by an additional wash in ethanol and air drying, slides were then treated with the kit-included protease (Cat. #322330) and incubated at 40°C for 30 min.

The target probe (Cat. #462091) was applied to each of the target slides except one select duplicate, to which a negative control probe was applied. Probes were allowed to hybridize and incubate at 40°C for two hours, followed by two washes in wash buffer (Cat. #310091) for 2 min each. A series of six amplification steps, each followed by two 2 min washes in wash buffer were performed. Amplifiers one through four were incubated at 40°C, alternating between 30 min and 15 min durations. Amplifiers five and six were incubated at room temperature for 30 min and 15 min. Slides were then treated with RED chromogenic reagent for 10 min and then washed with water. Slides were then counter-stained in hematoxylin, after which they were rinsed under tap water for 5 min. After dehydrating, slides were cover-slipped and examined by light microscopy.

Microscopy

All slides were evaluated by light microscopy using a histology microscope. Pictures were taken using an ECHO Revolve microscope (San Diego, CA) using the brightfield configuration. Microscope settings were: brightness; 32, contrast; 75, color balance; 75, LED; 67%. Magnification for pictures was set at 4x.

Results

FIPV IHC-RNA ISH Comparison

RNA ISH using the Orf1ab FIPV probe was performed on the tissues of thirty unique cats. All thirty RNA ISH slides returned positive results that were either comparable to or exceeded the gold standard of IHC. Tissues stained with RNA ISH often showed to be more robust than their IHC counterparts and was more diffuse throughout the examined organ sections. RNA ISH staining was not limited by tissue type and was well corroborated by the IHC slides, with staining across both slides being associated with well-defined lesions. Negative controls were adequate, upholding the specificity of the technique compared to the IHC gold standard.

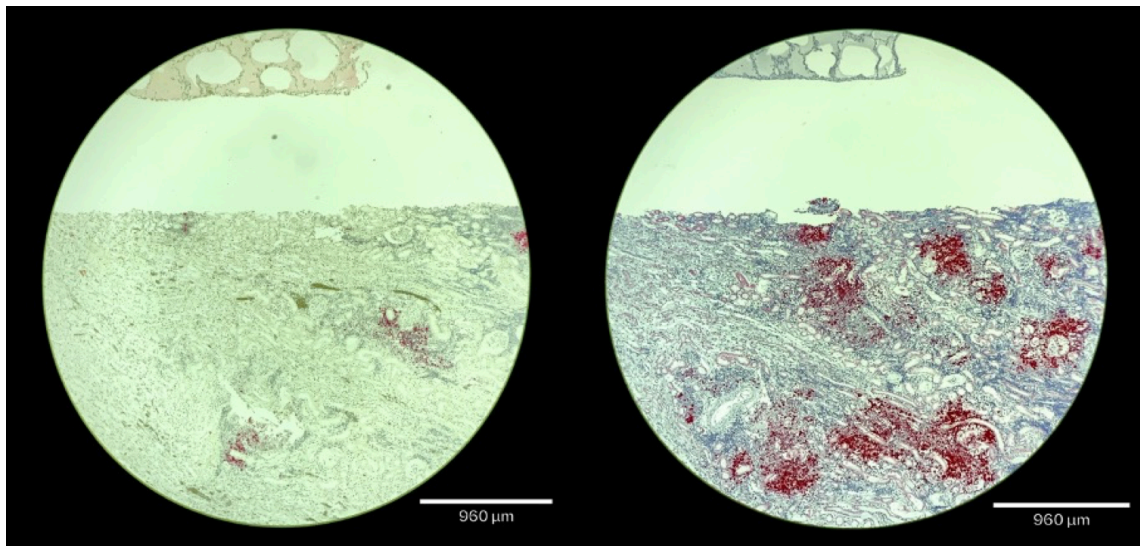


Figure 1. Cat A. Comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 4x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown are kidney (large tissue) and lung (small tissue).

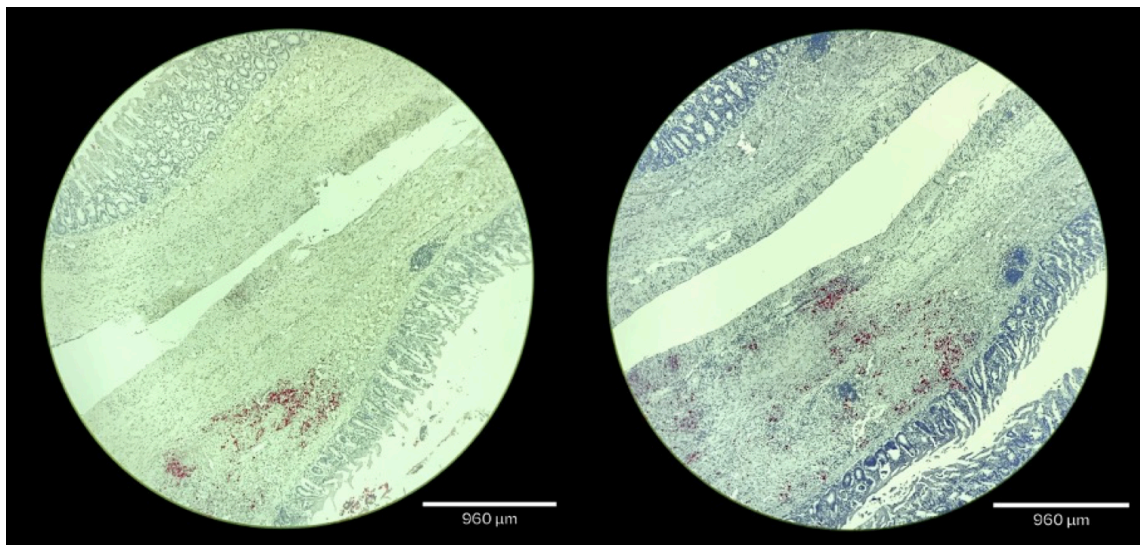


Figure 2. Cat B. Comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 4x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown are intestine.

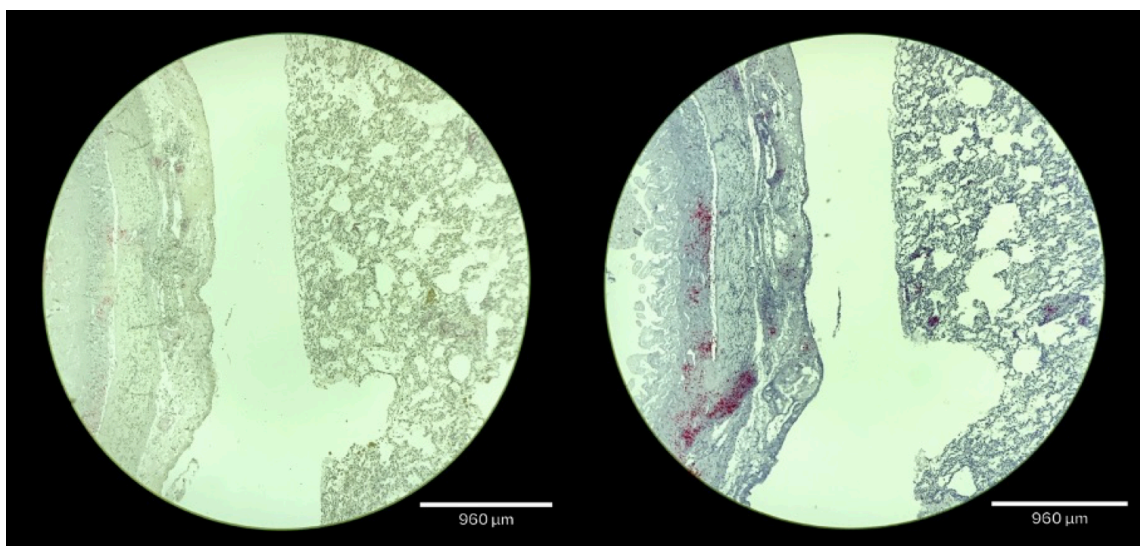


Figure 3. Cat C. Comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 4x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown are intestine and lung (left and right tissues of the image, respectively).

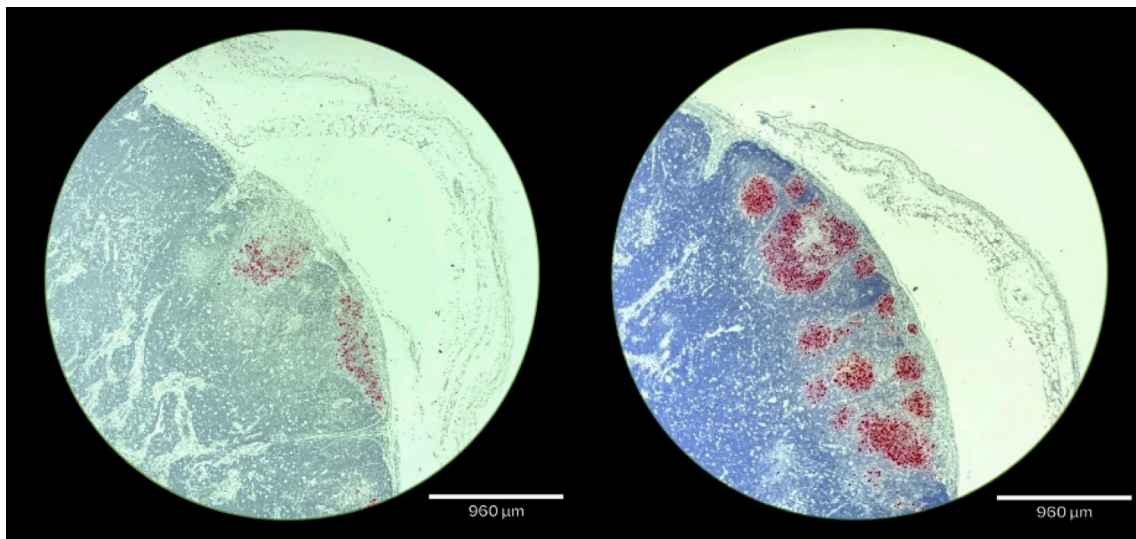


Figure 4. Cat D. Comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 4x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown are mesenteric lymph node.

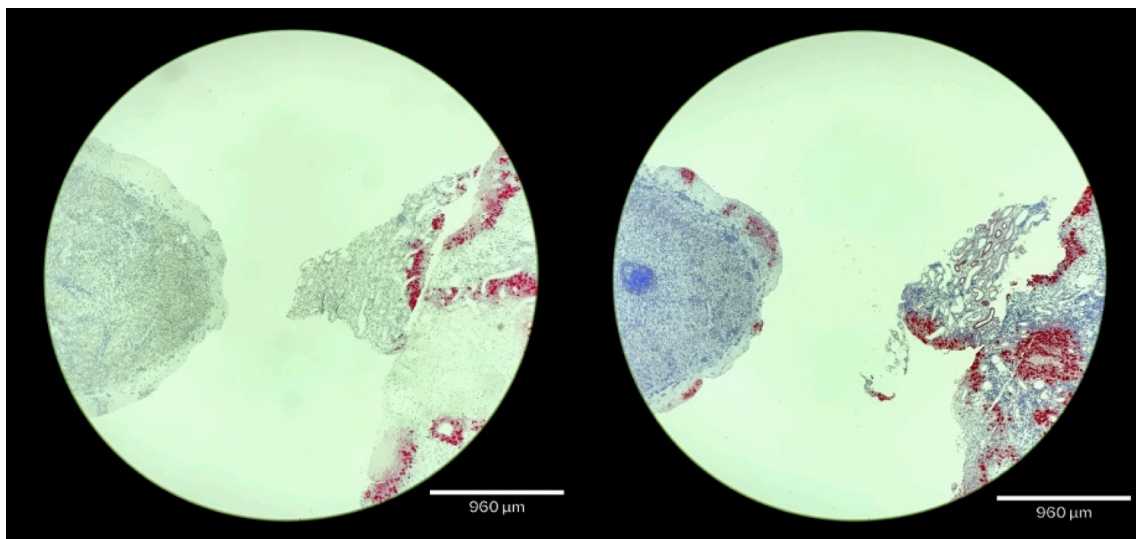


Figure 5. Cat E. Comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 4x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown are spleen (left tissue) and kidney (right).

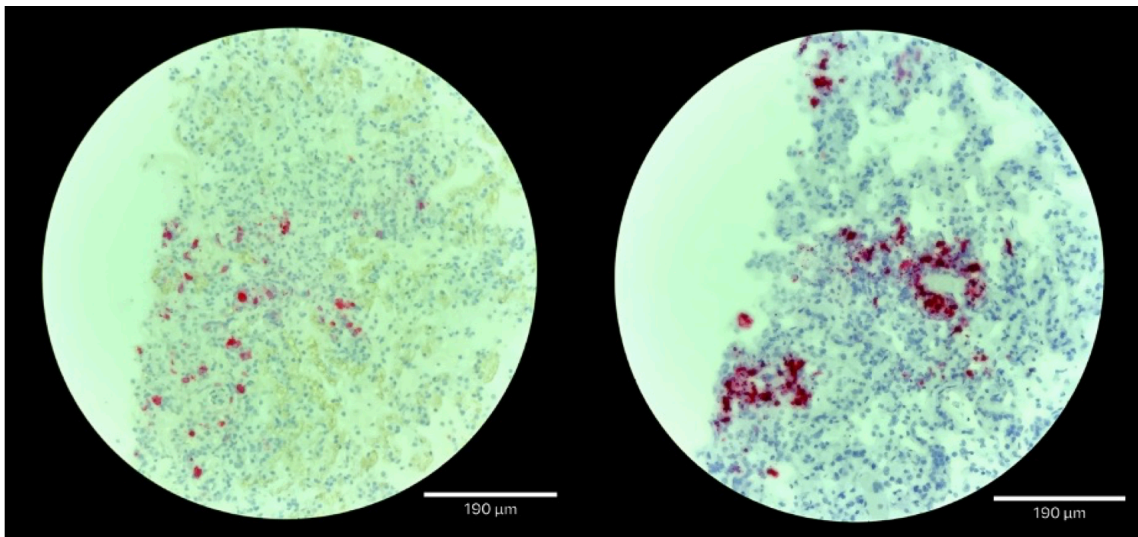


Figure 6. Cat C. Higher magnification comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 20x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown here are intestine. Red dots represent detection of FIPV nucleocapsid (for IHC) or detection of FIPV ORF1ab gene (for RNA ISH).

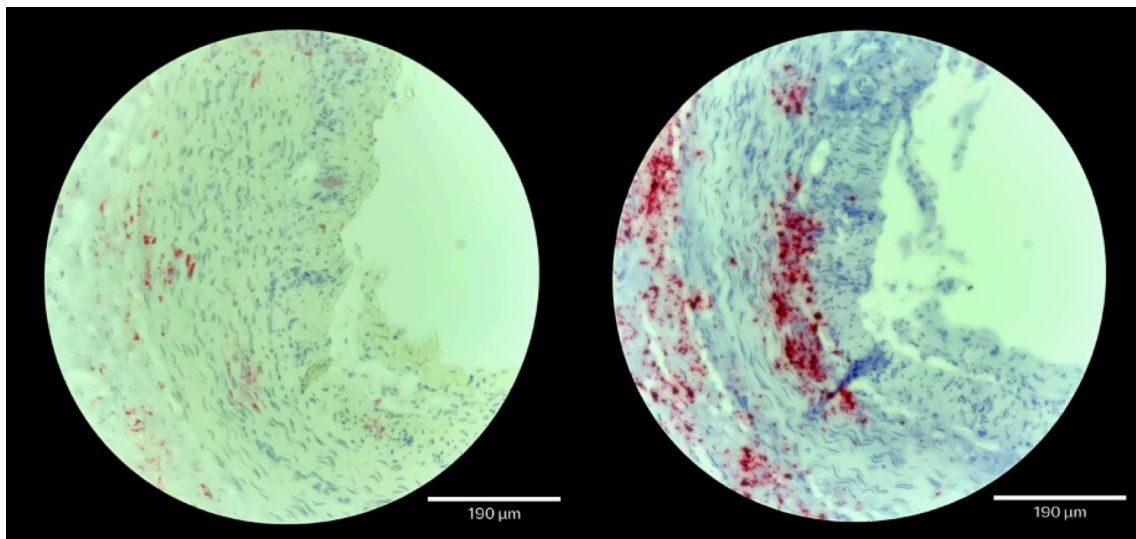


Figure 7. Cat F. Higher magnification comparison of FIPV 3-70 IHC and RNA ISH using the FIPV ORF1ab probe. Images were taken of matching areas of tissue sections under a 20x magnification lens. Immunohistochemistry is shown on the left while RNA ISH is shown on the right. Tissues shown here are lung. Red dots represent detection of FIPV nucleocapsid (for IHC) or detection of FIPV ORF1ab gene (for RNA ISH).

Discussion

The present study serves as a preliminary investigation of an FIPV RNA ISH probe for the diagnosis of FIP in performing a side-by-side comparison of the RNA ISH probe with the current FIP diagnostic gold standard of immunohistochemistry. The comparison between the current gold standard of IHC and our RNA ISH probe demonstrates evidence that use of RNA ISH, with the conserved genetic target of ORF1ab, allows for an improved performance in FIPV detection compared to IHC with FIPV mAb 3-70. While only tissues from cats with IHC-confirmed FIP were used in this study, several samples showing RNA ISH positivity were much stronger in their positive staining as well as not solely limited to a few individual cells, as they were in IHC, but present in large lesions. FIPV MAb detection was occasionally very faint in these cases where it would be limited to a few individual cells—leaving considerable possibility for these cases to be incorrectly classified as a negative result.

The specificity value of 100% for IHC presents as a critical component of the diagnostic technique. As this study did not investigate tissues from FIPV-negative cats, it was not possible to ascertain the specificity of the technique. Given that FIPV staining from RNA ISH tended to match a similar distribution to that of

IHC when there was abundant staining for both techniques, it supports RNA ISH closely following the specificity of the gold standard and not leading to aberrant positive staining. Again, as specificity is calculated using the proportion of test-negative cases over the sum of test-negative and false positive individuals, the use of only true positive cases in this study prevents a true validation of specificity with the samples we have examined here. Furthermore, in using a third-party RNA ISH assay, the technology and its detailed workings remain largely proprietary information. Not being directly involved in probe design hinders the ability to refine the probes and their targeted genetic areas that may have important implications for the sensitivity and specificity of the technique. The corroboration of this RNA ISH technique by immunohistochemical staining, however, allows for confidence in the technique and the suitability of the genetic target.

We consider that RNA ISH offers significant benefits to support its further investigation and adoption in the clinical setting. The improvements in sensitivity of FIP diagnosis that RNA ISH provides can support those working with FIP in both the clinical and research spheres. On the clinical side, achieving an adequate diagnosis allows for an improved diagnostic ability of veterinary clinicians. A devastating disease such as FIP can leave pet owners distraught and, when false negatives arise, leaves them without answers. The ability to produce a diagnosis and provide it to families allows for closure in the grieving process. Current clinical advice also suggests that owners of a cat with FIP should abstain from obtaining a new cat for a period of several months in order to limit the risk of contracting FCoV and possibly developing FIP. Improved diagnostics may also play an important role in the public health aspect of FIP, lowering the incidence of disease and mortality. While further studies must be carried out to ascertain the true sensitivity and specificity of the technique, the preliminary investigation conducted here supports its use for the confirmation of FIP.

An improved ability to detect FIPV also presents benefits on the research front, allowing for retrospective investigation of cats that were suspected to have FIP but whose tissues yielded negative IHC results. In having a broader scope of detection among these cases, examining FIP cases that return positive RNA ISH results but negative IHC results presents exciting research questions—particularly, investigating what antigenic or genomic differences may exist between viruses that can be detected by IHC versus those that are able to subvert the technique. Further studying the virological properties of these IHC-undetected FIPV variants and any potential differences with the detectable population may uncover insights that allow for a better understanding and characterization of FIPV and its circulating variants. An improved

detection ability may uncover important viral clues and characteristics that allow for a more complete understanding of FIPV.

Acknowledgements

We thank Dr. Andrew Miller for assistance in FIP case selection and pathological evaluation. Additional thanks to Beth Licitra and Ximena Olarte-Castillo for careful reading of this manuscript, and all the members of the Whittaker Lab for helpful discussions and support. GW is supported by the Michael Zemsky Fund for Feline Disease and the Feline Health Center at the College of Veterinary Medicine, Cornell University.

References

1. ^aL. G. Wolfe, R. A. Griesemer. (1966). *Feline infectious peritonitis*. *Pathol Vet*. 3(3):255-270. doi:10.1177/030098586600300309. PubMed PMID: 5958991.
2. ^ΔJ. M. Ward. (1970). *Morphogenesis of a virus in cats with experimental feline infectious peritonitis*. *Virology*. 41(1):191-194. doi:10.1016/0042-6822(70)90070-x. PubMed PMID: 4986314; PubMed Central PMCID: PMC7131342.
3. ^ΔM. Kummrow, M. L. Meli, M. Haessig, E. Goenczi, A. Poland et al. (2005). *Feline coronavirus serotypes 1 and 2: seroprevalence and association with disease in Switzerland*. *Clin Diagn Lab Immunol*. 12(10):1209-1215. doi:10.1128/CDLI.12.10.1209-1215.2005. PubMed PMID: 16210485; PubMed Central PMCID: PMC1247821.
4. ^aK. Hartmann. (2005). *Feline infectious peritonitis*. *Vet Clin North Am Small Anim Pract*. 35(1):39-79, vi. doi:10.1016/j.cvsm.2004.10.011. PubMed PMID: 15627627; PubMed Central PMCID: PMC7114919.
5. ^ΔJ. A. Jaimes, J. K. Millet, A. E. Stout, N. M. Andre, G. R. Whittaker. (2020). *A Tale of Two Viruses: The Distinct Spike Glycoproteins of Feline Coronaviruses*. *Viruses*. 12(1). doi:10.3390/v12010083. PubMed PMID: 31936749; PubMed Central PMCID: PMC7019228.
6. ^aN. C. Pedersen. (2009). *A review of feline infectious peritonitis virus infection: 1963-2008*. *J Feline Med Surg*. 11(4):225-258. doi:10.1016/j.jfms.2008.09.008. PubMed PMID: 19254859; PubMed Central PMCID: PMC7129802.
7. ^aD. Addie, S. Belak, C. Boucraut-Baralon, H. Egberink, T. Frymus et al. (2009). *Feline infectious peritonitis. ABCD guidelines on prevention and management*. *J Feline Med Surg*. 11(7):594-604. doi:10.1016/j.jfms.2009.05.008. PubMed PMID: 19481039; PubMed Central PMCID: PMC7129471.

8. ^a S. Tasker. (2018). Diagnosis of feline infectious peritonitis: Update on evidence supporting available tests. *J Feline Med Surg.* 20(3):228-243. doi:10.1177/1098612X18758592. PubMed PMID: 29478397.
9. ^a S. Paltrinieri, A. Giordano, V. Tranquillo, S. Guazzetti. (2007). Critical assessment of the diagnostic value of feline alpha1-acid glycoprotein for feline infectious peritonitis using the likelihood ratios approach. *J Vet Diagn Invest.* 19(3):266-272. doi:10.1177/104063870701900306. PubMed PMID: 17459855.
10. ^a A. Giordano, V. Spagnolo, A. Colombo, S. Paltrinieri. (2004). Changes in some acute phase protein and immunoglobulin concentrations in cats affected by feline infectious peritonitis or exposed to feline coronavirus infection. *Vet J.* 167(1):38-44. doi:10.1016/s1090-0233(03)00055-8. PubMed PMID: 14623149; PubMed Central PMCID: PMC7128346.
11. ^a A. N. Sweet, N. M. Andre, A. E. Stout, B. N. Licitra, G. R. Whittaker. (2022). Clinical and Molecular Relationships between COVID-19 and Feline Infectious Peritonitis (FIP). *Viruses.* 14(3). doi:10.3390/v14030481. PubMed PMID: 35336888; PubMed Central PMCID: PMC8954060.
12. ^a H. Y. Tsai, L. L. Chueh, C. N. Lin, B. L. Su. (2011). Clinicopathological findings and disease staging of feline infectious peritonitis: 51 cases from 2003 to 2009 in Taiwan. *J Feline Med Surg.* 13(2):74-80. doi:10.1016/j.jfms.2010.09.014. PubMed PMID: 21216644; PubMed Central PMCID: PMC7129202.
13. ^a F. Riemer, K. A. Kuehner, S. Ritz, C. Sauter-Louis, K. Hartmann. (2016). Clinical and laboratory features of cats with feline infectious peritonitis--a retrospective study of 231 confirmed cases (2000-2010). *J Feline Med Surg.* 18(4):348-356. doi:10.1177/1098612X15586209. PubMed PMID: 26185109.
14. ^a U. Jeffery, K. Deitz, S. Hostetter. (2012). Positive predictive value of albumin: globulin ratio for feline infectious peritonitis in a mid-western referral hospital population. *J Feline Med Surg.* 14(12):903-905. doi:10.1177/1098612X12454862. PubMed PMID: 22811479.
15. ^a Y. Fischer, C. Sauter-Louis, K. Hartmann. (2012). Diagnostic accuracy of the Rivalta test for feline infectious peritonitis. *Vet Clin Pathol.* 41(4):558-567. doi:10.1111/j.1939-165X.2012.00464.x. PubMed PMID: 22913882; PubMed Central PMCID: PMC7169324.
16. ^a N. C. Pedersen, C. E. Allen, L. A. Lyons. (2008). Pathogenesis of feline enteric coronavirus infection. *J Feline Med Surg.* 10(6):529-541. doi:10.1016/j.jfms.2008.02.006. PubMed PMID: 18538604; PubMed Central PMCID: PMC7130060.
17. ^a K. Hartmann, C. Binder, J. Hirschberger, D. Cole, M. Reinacher et al. (2003). Comparison of different tests to diagnose feline infectious peritonitis. *J Vet Intern Med.* 17(6):781-790. doi:10.1111/j.1939-1676.2003.tb02515.x. PubMed PMID: 14658713; PubMed Central PMCID: PMC7197515.

18. ^aN. C. Pedersen. (2014). An update on feline infectious peritonitis: diagnostics and therapeutics. *Vet J.* 201 (2):133-141. doi:10.1016/j.tvjl.2014.04.016. PubMed PMID: 24857253; PubMed Central PMCID: PMC7110619.
19. ^ΔD. A. Gamble, A. Lobbiani, M. Gramegna, L. E. Moore, G. Colucci. (1997). Development of a nested PCR assay for detection of feline infectious peritonitis virus in clinical specimens. *J Clin Microbiol.* 35(3):673-675. doi:10.1128/jcm.35.3.673-675.1997. PubMed PMID: 9041410; PubMed Central PMCID: PMC7129648.
20. ^ΔR. Sherding. (2006). Feline Infectious Peritonitis (Feline Coronavirus). *Saunders Manual of Small Animal Practice.* 132-143. doi:10.1016/B0-72-160422-6/50012-7. PubMed Central PMCID: PMC7150141.
21. ^ΔA. Kipar, K. Baptiste, A. Barth, M. Reinacher. (2006). Natural FCoV infection: cats with FIP exhibit significantly higher viral loads than healthy infected cats. *J Feline Med Surg.* 8(1):69-72. doi:10.1016/j.jfms.2005.07.002. PubMed PMID: 16213766; PubMed Central PMCID: PMC7129897.
22. ^ΔF. A. Simons, H. Vennema, J. E. Rofina, J. M. Pol, M. C. Horzinek et al. (2005). A mRNA PCR for the diagnosis of feline infectious peritonitis. *J Virol Methods.* 124(1-2):111-116. doi:10.1016/j.jviromet.2004.11.012. PubMed PMID: 15664058; PubMed Central PMCID: PMC7112896.
23. ^ΔC. Dye, C. R. Helps, S. G. Siddell. (2008). Evaluation of real-time RT-PCR for the quantification of FCoV shedding in the faeces of domestic cats. *J Feline Med Surg.* 10(2):167-174. doi:10.1016/j.jfms.2007.10.010. PubMed PMID: 18243744; PubMed Central PMCID: PMC712582154.
24. ^ΔB. R. Bank-Wolf, I. Stallkamp, S. Wiese, A. Moritz, G. Tekes et al. (2014). Mutations of 3c and spike protein genes correlate with the occurrence of feline infectious peritonitis. *Vet Microbiol.* 173(3-4):177-188. doi:10.1016/j.vetmic.2014.07.020. PubMed PMID: 25150756; PubMed Central PMCID: PMC7117521.
25. ^ΔN. C. Pedersen. (2014). An update on feline infectious peritonitis: virology and immunopathogenesis. *Vet J.* 201(2):123-132. doi:10.1016/j.tvjl.2014.04.017. PubMed PMID: 24837550; PubMed Central PMCID: PMC7110662.
26. ^ΔB. N. Licitra, J. K. Millet, A. D. Regan, B. S. Hamilton, V. D. Rinaldi et al. (2013). Mutation in spike protein cleavage site and pathogenesis of feline coronavirus. *Emerg Infect Dis.* 19(7):1066-1073. doi:10.3201/eid1907.121094. PubMed PMID: 23763835; PubMed Central PMCID: PMC713968.
27. ^aE. A. Healey, N. M. Andre, A. D. Miller, G. R. Whitaker, E. A. Berliner. (2022). Outbreak of feline infectious peritonitis (FIP) in shelter-housed cats: molecular analysis of the feline coronavirus S1/S2 cleavage site consistent with a 'circulating virulent-avirulent theory' of FIP pathogenesis. *JFMS Open Rep.* 8(1):20551169221074226. doi:10.1177/20551169221074226. PubMed PMID: 35173971; PubMed Central PMCID: PMC7138841931.

28. [△]N. M. Andre, B. Cossic, E. Davies, A. D. Miller, G. R. Whittaker. (2019). Distinct mutation in the feline coronavirus spike protein cleavage activation site in a cat with feline infectious peritonitis-associated meningoencephalomyelitis. *JFMS Open Rep.* 5(1):2055116919856103. doi:10.1177/2055116919856103. PubMed PMID: 31534775; PubMed Central PMCID: PMC6739741.
29. [△]L. A. McKay, M. Meachem, E. Snead, T. Brannen, N. Mutlow et al. (2020). Prevalence and mutation analysis of the spike protein in feline enteric coronavirus and feline infectious peritonitis detected in household and shelter cats in western Canada. *Can J Vet Res.* 84(1):18-23. Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/31949325>. PubMed PMID: 31949325; PubMed Central PMCID: PMC6921991.
30. [△]H. W. Chang, H. F. Egberink, R. Halpin, D. J. Spiro, P. J. Rottier. (2012). Spike protein fusion peptide and feline coronavirus virulence. *Emerg Infect Dis.* 18(7):1089-1095. doi:10.3201/eid1807.120143. PubMed PMID: 22709821; PubMed Central PMCID: PMC3376813.
31. [△]S. Felten, K. Hartmann, S. Doerfelt, L. Sangl, J. Hirschberger et al. (2019). Immunocytochemistry of mesenteric lymph node fine-needle aspirates in the diagnosis of feline infectious peritonitis. *J Vet Diagn Invest.* 31(2):210-216. doi:10.1177/1040638718825280. PubMed PMID: 30694113; PubMed Central PMCID: PMC6838827.
32. [△]L. Poncelet, A. Coppens, D. Peeters, E. Bianchi, C. K. Grant et al. (2008). Detection of antigenic heterogeneity in feline coronavirus nucleocapsid in feline pyogranulomatous meningoencephalitis. *Vet Pathol.* 45(2):140-153. doi:10.1354/vp.45-2-140. PubMed PMID: 18424826.
33. [△]R. F. Ambinder, R. B. Mann. (1994). Detection and characterization of Epstein-Barr virus in clinical specimens. *Am J Pathol.* 145(2):239-252. Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/8053485>. PubMed PMID: 8053485; PubMed Central PMCID: PMC1887400.
34. [△]E. J. Speel, A. H. Hopman, P. Komminoth. (1999). Amplification methods to increase the sensitivity of in situ hybridization: play card(s). *J Histochem Cytochem.* 47(3):281-288. doi:10.1177/002215549904700302. PubMed PMID: 10026231.
35. [△]L. Vijgen, E. Moes, E. Keyaerts, S. Li, M. Van Ranst. (2008). A pancoronavirus RT-PCR assay for detection of all known coronaviruses. *Methods Mol Biol.* 454:3-12. doi:10.1007/978-1-59745-181-9_1. PubMed PMID: 19057882; PubMed Central PMCID: PMC67120317.

Declarations

Funding: The author(s) received no specific funding for this work.

Potential competing interests: The author(s) declared that no potential competing interests exist.