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Neoplasms and novel gammaherpesviruses in critically endangered captive European minks (*Mustela lutreola*)

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Abstract

The European mink (*Mustela lutreola*) is a riparian mustelid, considered one of the most endangered carnivores in the world. Alpha, beta and gammaherpesviruses described in mustelids have been occasionally associated with different pathological processes. However, there is no information about the herpesviruses species infecting European minks. In this study, 141 samples of swabs (oral, conjunctival, anal), faeces and tissues from 23 animals were analysed for herpesvirus (HV) using a pan-HV-PCR assay. Two different, potentially novel, gammaherpesvirus species were identified in 12 samples from four animals (17.3%), and tentatively named Mustelid gammaherpesvirus-2 (MUGHV-2) and MuGHV-3. Gross examination was performed on dead minks ($n = 11$), while histopathology was performed using available samples from HV-positive individuals ($n = 2$), identifying several neoplasms, including B-cell lymphoma (identified by immunohistochemistry) with intralesional syncytia and intranuclear inclusion bodies characteristic of HV ($n = 1$), pulmonary adenocarcinoma ($n = 1$), and biliary ($n = 1$) and preputial ($n = 1$) cystadenomas, as well as other lesions (e.g., axonal vacuolar degeneration [$n = 2$] and neuritis [$n = 1$]). Viral particles, consistent with HVs, were observed by electron microscopy in the mink with neural lymphoma and inclusion bodies. This is the first description of neoplasms and concurrent gammaherpesvirus infection in European minks. The pathological, ultrastructural and PCR findings (MuGHV-2) in the European mink with lymphoma strongly suggest a potential role for this novel gammaherpesvirus in its pathogenesis, as it has been reported in other HV-infected species with lymphoma. The occurrence of neural lymphoma with intralesional syncytia and herpesviral inclusions is, however, unique among mammals. Further research is warranted to elucidate the potential oncogenic properties of gammaherpesviruses in European mink and their epidemiology in the wild population.

KEYWORDS

biliary cystadenoma, herpesvirus, lung adenocarcinoma, lymphoma, mustelid, preputial cystadenoma

1 | INTRODUCTION

The European mink (*Mustela lutreola*) is a critically endangered riparian mustelid with populations in eastern (Ukraine, Russia, Estonia and Romania) and western (south-western France and northern Spain) Europe (Maran et al., 2016). The main factors causing its decline are interspecies competition with the non-native American mink (*Neovison vison*), habitat loss and degradation (pollution), over-hunting and infectious diseases (e.g. Aleutian mink disease and canine distemper; Lodé, Cormier, & Le Jacques, 2001; Mañas, Gómez, Asensio, Palazón, Pŏdra, et al., 2016; Maran et al., 2016). Without the implementation of more effective conservation measures, the European mink will very likely soon become extinct in Spain (Ferrer, 2014).

To date, the exposure to, and infection by, several viruses have been studied in wild European minks: *Aleutian mink disease virus* (Fournier-Chambrillon et al., 2004; Guzmán et al., 2008; Mañas, Gómez, Asensio, Palazón, Podra, et al., 2016; Mañas et al., 2001), *Canine morbillivirus* (syn. canine distemper virus) (Guzmán et al., 2008; Mañas et al., 2001; Philippa et al., 2008), canine parainfluenza virus (syn. parainfluenza virus type 5 or *Mammalian rubulavirus 5*), canine adenovirus (syn. *Canine mastadenovirus A*) and viruses belonging to the families *Astroviridae*, *Picobirnaviridae* and *Parvoviridae* subfamily *Parvovirinae* (Bodewes et al., 2014). Nevertheless, in spite of the numerous members of the family *Herpesviridae* of veterinary and public health significance (Huff & Barry, 2003; Widén et al., 2012), to the authors' knowledge, there is no information about herpesviruses (HVs) in European minks. The HVs infecting vertebrates (family *Herpesviridae*) are further subdivided into three subfamilies: *Alphaherpesvirinae*, *Betaherpesvirinae* and *Gammaherpesvirinae* (ICTV, 2017). In other mustelid species, for example the sea otter (*Enhydra lutris*), HV-like intranuclear inclusion bodies along with HV-compatible virions and exposure to herpesvirus have been described (Goldstein et al., 2011; Reimer & Lipscomb, 1998). Alpha-, beta- and gammaherpesviruses (α-HVs, β-HVs, γ-HVs) were identified in American martens (*Martes Americana*) with no mention to associated disease (Dalton et al., 2017). Only γ-HV infection has been reported in other mustelids: in oral ulcerations and plaques, and nasal secretions of sea otters (Tseng et al., 2012); in ulcerative skin lesions of a captive fisher (*Martes pennanti*) (Gagnon, Tremblay, Larochelle, Music, & Tremblay, 2011); and in free-living European badgers (*Meles meles*) (Banks, King, & Daniells, 2002; Dandár, Szabó, & Heltai, 2010; Sin et al., 2014), in which a γ-HV has not yet been associated with lesions or clinical disease (King et al., 2004). Finally, the susceptibility to α-HV *Suid alphaherpesvirus 1*, the aetiological agent of Aujesky' disease/pseudorabies (Gorham, Hartsough, & Burger, 1998; Liu et al., 2017; Quiroga, López-Peña, Vázquez, & Nieto, 1997; Wang et al., 2018) and the replication of α-HV *Canine herpesvirus-1* in foetal lung cells (Reading & Field, 1999) have been reported in American mink.

The goals of this study were to: (a) survey if HVs are present in a European mink captive population and (b) describe the clinical and pathological findings with a particular focus on morphological evidence of an association with herpesviral infection.

2 | MATERIALS AND METHODS

2.1 | Study population and samples

This study was performed on the captive European mink population of the Pont de Suert Captive Breeding Center (Pont de Suert, Lleida, northeastern Spain) which is part of the Spanish Breeding Program.

The European mink samples were obtained from the live animal collection of the Pont de Suert captive collection in September 2017 (identified as LM = live mink) and from the dead minks stored at that centre until October 2017 (identified as PM = post-mortem mink). All these minks were either originated from Spanish captive breeding centres or captured in the wild, also in Spain. Individual sex, last weight, date and place of birth (when available), origin, and arrival date to Pont de Suert, and date of death or euthanasia are summarized in Appendix S1. All European minks in Pont de Suert tested negative for *Aleutian mink disease virus* and *Canine morbillivirus* antibodies upon their admission to the captive breeding programme.

In September 2017, all live adult European minks in the breeding centre were anesthetized for routine health check with a combination of intramuscular ketamine (5 mg/kg, Imalgene 100 mg/ml, Merial Laboratorios SA, Barcelona, Spain) and medetomidine (0.1 mg/kg, Domtor, Ecuphar Veterinaria SLU, Barcelona, Spain). Intramuscular atipamezole (0.1 mg/kg, Antisedan, Zoetis SLU, Madrid, Spain) was used to reverse the effects of medetomidine a minimum of 20 min after anaesthesia had been induced. All animals were individually placed back into their cages after sampling and full recovery. During anaesthesia, all minks received a full clinical examination by an experienced veterinarian, which included body condition assessment, skin and hair inspection for ectoparasites, abdominal palpation and general examination of the mucosae, oral cavity, ears, anal-genital region and feet, and cardiac and pulmonary auscultation. Approximately 2 ml of blood was withdrawn by venipuncture from the cranial vena cava using 21-gauge 3.8-cm needles for haematology, biochemistry (data not shown) and molecular analysis (0.5 ml in a sterile eppendorf). Aside from 0.5 ml of whole blood, sterile oropharyngeal, conjunctival and anal swabs was also collected for molecular analysis and preserved frozen at −20°C. Fresh faecal samples were taken from the cages using a sterile tube and refrigerated for direct observation and egg flotation techniques with zinc sulphate (33%) for endoparasite detection (data not shown) or frozen (−20°C) to perform viral DNA detection.

2.2 | Molecular diagnostics

A total of 141 frozen tissue samples from 23 European minks were analysed by PCR for HV detection. Anal and conjunctival swabs, blood and faeces from live minks (n = 12) and representative tissue samples from carcasses (n = 10; Appendix S2) were submitted for PCR analysis. One additional animal was sampled while alive and after its death (codes LM-9 and PM-9), thus included in both categories (live animal and carcasses, Appendix S2). After a lysis step

with lysis buffer (Cell Signaling Technology, MA, USA), DNA extraction was performed by pressure filtration (QuickGene DNA tissue kit S, FujiFilm Life Science, Tokyo, Japan). Initially, a mediastinal neoplastic tissue mass from PM-1 (index case) was analysed by a nested pan-PCR that amplified a fragment of ~215–315 bp of the HV DNA polymerase gene (VanDevanter et al., 1996). A second PCR was performed to amplify a 500 bp fragment of the HV glycoprotein B gene for gammaherpesviruses (Ehlers et al., 2008). In order to explore the presence of the novel HV sequence obtained from the neoplastic tissue, a comprehensive HV screening in tissues and samples from the captive breeding centre (both live and dead animals) was performed using the PCR described by Ehlers et al. (2008). All glycoprotein B gene-positive samples were also tested for herpesviral DNA polymerase gene (VanDevanter et al., 1996).

The PCR products of DNA polymerase and glycoprotein B were visualized in 1.5% agarose gel stained with Red Safe® (Ecogen, Spain), and the amplicons of expected size were directly sequenced with sequencing primers TGVseq and IYGseq (DNA polymerase), and 2760s and 2761as (glycoprotein B), respectively, described by VanDevanter et al. (1996) and Ehlers et al. (2008). The obtained sequences were compared to those previously published in GenBank using a Blast search, and nucleotide (nt) and deduced amino acid (aa) p-distances were calculated with MEGA Software 7.0 after editing out the primers (Kumar, Stecher, & Tamura, 2016). After ClustalW alignment of glycoprotein B gene nucleotide sequences by MEGA software 7.0 (Kumar et al., 2016), nt and aa maximum likelihood phylogenetic trees were generated with 1,000 bootstrap replicates, including the newly identified HV sequences and 39 other α-, β-, and γ-HVs sequences. *Ictalurid herpesvirus 1* was selected as an outgroup. Sequence information for members of the *Herpesviridae* family was obtained from GenBank.

2.3 | Gross and microscopic examination

Complete post-mortem gross examination was performed in eleven European minks (identified with codes PM-1 through PM-11). Eight of them (PM-2–PM-8, and PM-10) were prominently autolyzed. Microscopic evaluation was performed on HV-PCR-positive animals with adequate tissue preservation (PM-1 and PM-9), using 10% formalin-fixed tissues embedded in paraffin, sectioned at 5 μm thick, and stained with haematoxylin and eosin.

2.4 | Immunohistochemistry

Immunohistochemical analyses were performed in 4 μm-thick paraffin wax-embedded tissue samples of PM-1 using antibodies against CD20 and CD3. Briefly, slides were transferred to a PT-Link Automatic System of DAKO for deparaffinization, rehydration and epitope retrieval. For this last step, slides were treated with acid buffer at pH 6 for 20 min. at 98°C and then transferred to distilled water. Endogenous peroxidase was then inhibited with Peroxidase-Blocking Solution (from Dako, Ref.: S2023). Immunostaining was performed on a Dako Autostainer Plus, using procedures, buffers and solutions provided by the fabricant. Briefly, as first antibody, a polyclonal Rabbit Anti-Human CD3 antibody (DAKO. Ref: A0452) and a polyclonal Rabbit Anti-Human CD20 antibody (CULTEK. Ref: PA5-32313) were both incubated for 40 min. at room temperature, diluted 1:100 (CD3) and 1:200 (CD20) in EnVision™ FLEX buffer. After washing, the Rabbit/Mouse EnVision Detection System (Dako Ref.: K5007) was incubated at room temperature for 40 min. at the dilution recommended by the supplier. After washing, slides were incubated for 5 min. in DAB-Chromogen–hydrogen peroxide (Dako K3468), to reveal binding. After washing, slides were counterstained in Mayer's haematoxylin for 10 s, washed in running tap water, and then automatically dehydrated, cleared and mounted.

2.5 | Electron microscopy

Transmission electron microscopy (TEM) was performed in a paraffin-embedded sample of a perineural mass found in PM-1. The tissue sample was deparaffinized with histoclear, dehydrated with 100% ethanol, infiltrated with LRWhite, sectioned into 60 nm sections and contrasted with uranylacetate. Micrographs were obtained using a FEI Morgagni 268 transmission electron microscope, and images were recorded by a side-mounted Olympus Veleta CCD charge-coupled device camera.

3 | RESULTS

3.1 | Molecular study

Herpesvirus DNA was detected in four (PM-1, PM-4, PM-8 and LM/PM-9) out of the 23 evaluated European minks. Positive HV amplification was observed in 8.5% (12/141) of the analysed samples, including 11 from post-mortem tissue samples and one from an antemortem oral swab (LM/PM-9) (Appendix S2).

Two different glycoprotein B gene sequences were detected in the four HV-positive European minks; one sequence was amplified from PM-1 (mediastinal mass) and PM-8 (lung), and a different one from PM-4 (liver, kidney, brain), and LM/PM-9 (an antemortem oral swab, brain, spinal cord, peripheral nerve [sciatic nerve and brachial plexus], spleen and bone marrow). The nt and aa identities between both novel glycoprotein B sequences were 79.9% and 86.0%, respectively. The first sequence, found in PM-1 and PM-8, was more similar to the sequence detected in a European badger (MuGHV-1, GenBank Accession number: ABF15169) with, correspondingly, nt and aa identities of 87.2% and 97.8%. The second sequence, found in PM-4 and LM/PM-9, was more related to *Lynx rufus* gammaherpesvirus-2 (ABF15169), with nt identity of 78.4%, and had the highest aa identity (86.0%) with a γ-HV identified in a harp seal (*Pagophilus groenlandicus*, KP136799). A phylogenetic tree based on glycoprotein B amino acid deduced sequences

correctly classified the two obtained novel sequences within the cluster of terrestrial mammal γ-HVs, genus *Percavirus*, with bootstrap values above 70% (Figure 1).

A DNA polymerase sequence was amplified in one of the four HV-positive animals (PM-1), while no amplification for that gene was observed in the remaining glycoprotein B gene-positive cases. The highest nt (86.5%) and aa (92.2%) identities of this sequence were to the fisher gammaherpesvirus (HM579931) obtained in another mustelid species, the fisher. The DNA polymerase sequence of PM-1 was submitted to GenBank database under accession number MN082678, while the glycoprotein B sequences obtained from PM-1 and PM-9 were submitted under accession numbers MN082679 and MN082680, respectively. Since there was a previous report using the terms 'Mustelid gammaherpesvirus' (Mustelid gammaherpesvirus-1 or MuGHV-1, Kent et al., 2018), we have tentatively named the two novel sequences as MuGHV-2 (PM-1 and PM-8) and MuGHV-3 (PM-4 and LM/PM-9). A summary of the γ-HVs detected in mustelids is provided in Table 1.

3.2 | Retrieval of information prior to death or euthanasia of HV-positive minks

Prior to death, PM-1 presented with corneal opacity in the left eye, protrusion of the right eye, severe incoordination and rear limb weakness, leading to traumatic lesions and inability to eat. PM-4 presented with poor fur quality and compromised vision. PM-8 was uncoordinated and eventually recumbent, which lead to a skin ulcer on its right hip. LM/PM-9 presented with corneal opacity in the left eye and bilateral impaired vision, mild incoordination, rear limbs weakness and hyporexia that progressed to anorexia. In order to prevent suffering and based on a full clinical examination and complementary examinations (haematology and biochemistry, data not shown), two old animals (over nine years of age; PM-1 and LM/PM-9) were humanely euthanized due to the rapid worsening of clinical signs.

3.3 | Gross and microscopic findings

The gross and histopathologic findings of the HV-positive minks (PM-1, PM-4, PM-8 and LM/PM-9) are summarized in Appendix S3. The main gross and microscopic findings and suspected cause of death in PM-1 and LM/PM-9 are described below.

PM-1 was a 647-g male with moderate to severe atrophy of adipose tissue. Protrusion of the right eye due to the presence of a grayish to greenish retrobulbar mass involving the eyelid and periocular skin was observed (Figure 2). The left eye had corneal opacity. Nerves in the left brachial plexus and left elbow joint nerves were surrounded by whitish masses up to 1 cm in greatest dimension (Figure 2). A similar but smaller lesion surrounded the right sciatic nerve distal to the coxofemoral joint. A 5.5 × 2.8 × 2.2-cm whitish mass was also found in the caudal mediastinum (Figure 2). The left adrenal gland was partly effaced by a grayish mass of 1 cm in diameter (Figure 2).

Microscopically, all masses consisted of a malignant neoplastic proliferation of round cells characterized by a round, oval or more rarely irregular, indented or reniform nucleus with 1–2 nucleoli and diverse chromatin patterns, and a low amount of eosinophilic to amphophilic cytoplasm. Anisocytosis, anisokaryosis and anaplasia were moderate to high, while pleomorphism was moderate. Up to 6 mitoses per 40x power field were observed. Neoplastic cells invaded the perineurium and endoneurium of nerves within the masses (Figures 2 and 3). Affected nerves contained large areas of necrosis with dilatation, vacuolation and fragmentation of myelin sheaths as well as spheroids, deposits of fibrin, infiltrates of neutrophils and lymphocytes, and foci of acute haemorrhage. Neural necrosis extended into the perineural neoplastic tissue, where it was accompanied by prominent infiltration of degenerate neutrophils. Neoplastic cells were present in the perineurium and endoneurium as well. Intralesional within the endoneurium and neoplastic tissue, particularly in areas of necrosis, were syncytia and intranuclear inclusion bodies. These inclusions were predominantly basophilic and filled the nucleus, but eosinophilic inclusions surrounded by a clear halo were noted as well (Figure 3). They were found within syncytia and, presumably, neoplastic cells. Similar infiltrates of neoplastic cells along with fewer well-differentiated lymphocytes and plasma cells were present in the spinal cord and root nerves, involving the meninges with a diffuse pattern and neural tissue with a perivascular and multifocal distribution. In the spinal cord, both the white and grey matter were affected (Figure 3). Cerebral meninges were also mildly infiltrated, but predominantly with well-differentiated lymphocytes and plasma cells; neoplastic round cells were rare in this location. Neoplastic infiltrates in the retrobulbar mass and adrenal gland caused loss of architecture (Figure 2) and invaded adjacent soft tissues including the skin, adipose tissue and skeletal muscle. Thrombosis was observed in the right eyelid. Other microscopic findings were cataracts in the left eye, axonal degeneration in a peripheral skeletal muscle nerve, nodular acinar pancreatic hyperplasia, prostatic hyperplasia and moderate glomerulosclerosis. Additional gross and microscopic findings are summarized in Appendix S3.

PM-9 was a 696-grams male in a good body condition. This mink presented corneal opacity in the left eye and mild thickening of the nictitating membrane. A marked bilateral hemothorax was present, and both lungs were multifocally reddish in colour. A mass of 0.5 cm in diameter was observed in the diaphragmatic lobe of the left lung. This mink had mild to moderate splenomegaly, with a red splenic mass of 0.5 cm in diameter. A cystic mass of 1.5 cm in diameter was also noted in the left liver lobe. A subcutaneous preputial mass measuring 1 × 0.5 × 0.3 cm and mild generalized lymphadenomegaly were also observed. The adrenal glands contained pale foci <1 mm in diameter.

Microscopically, the main disease processes and lesions included pulmonary adenocarcinoma, severe membranous glomerulonephritis, severe chronic diffuse granulomatous lymphadenitis, biliary cystadenoma, and preputial gland cell hyperplasia and cystadenomas with focal malignant transformation and purulent preputial adenitis. Other potential relevant lesions included moderate to

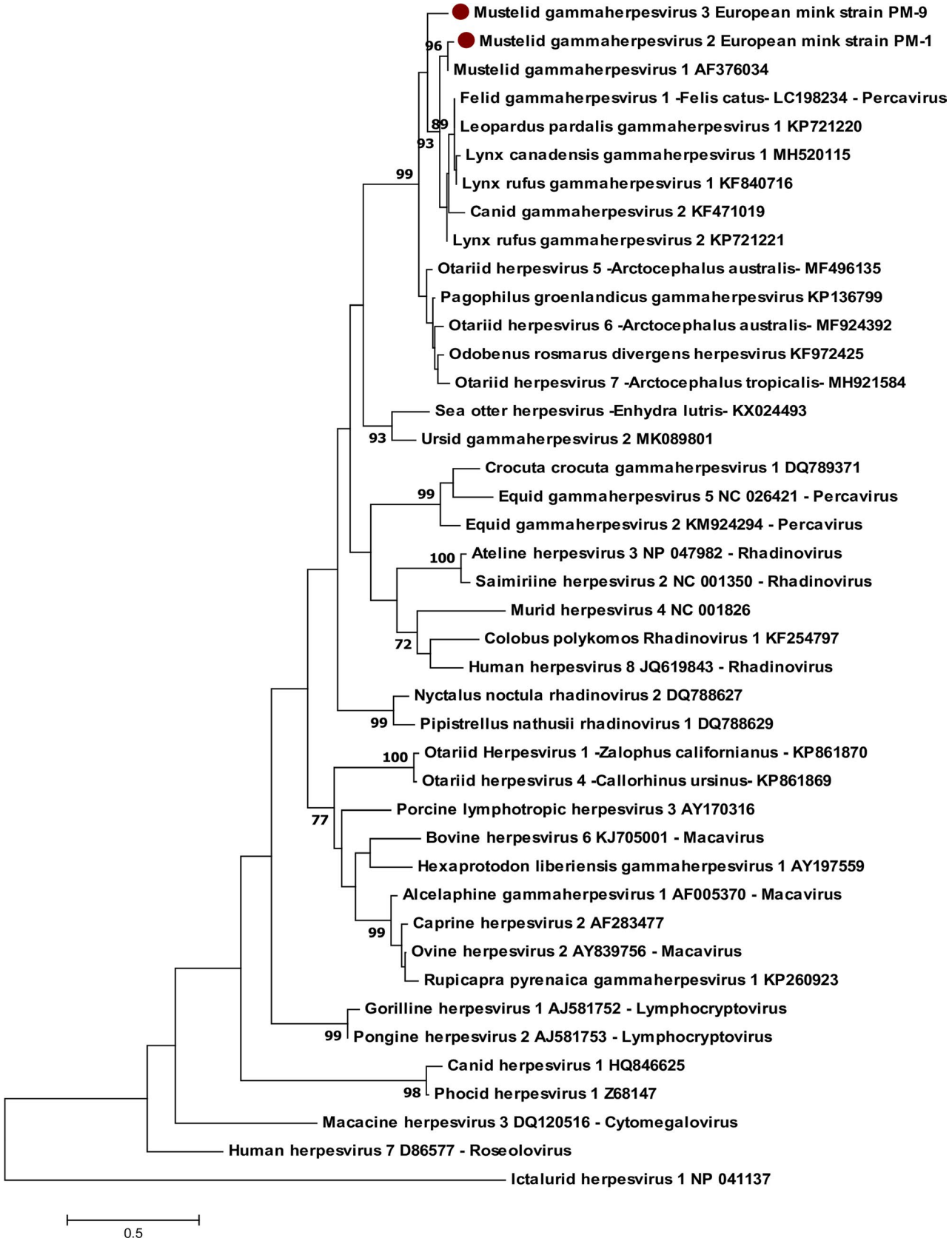

FIGURE 1 Maximum likelihood phylogram of the alignment of the obtained deduced amino acid gammaherpesvirus sequences (marked with red dots) and other herpesvirus sequences retrieved from GenBank. *Ictalurid herpesvirus 1* was selected as outgroup. The reliability of the tree was tested by bootstrap analysis with 1,000 replicates, and those bootstrap values lower than 70 were omitted

TABLE 1 Herpesviruses infections described in the family Mustelidae

Species	HV name in the article	GenBank access nº.	Lesions attributable to herpesvirus	PCR prevalence	Tissue	Country	Author
European badger (*Meles meles*)	Mustelid herpesvirus 1 (MusHV-1, γ-HV)	AF376034 AY050215 AF275656	Cytopathic effect on badger' pulmonary fibroblasts	Single case	Pulmonary fibroblasts	UK	Banks et al. (2002)
	Mustelid herpesvirus-1 (MusHV-1, γ-HV)	Not provided	Not described	95% (18/19)	Blood	UK	King et al. (2004)
				100% (10/10)	Blood	Ireland	
	Mustelid herpesvirus-1 (MusHV-1, γ-HV)	GU799569	Not reported (detected in a road-kill animal)	Single case		Hungary	Dandár et al. (2010)
	Mustelid herpesvirus-1 (MusHV-1, γ-HV)	Not provided	Not described	98.1% (354/361)	Blood	UK	Sin et al. (2014)
	Mustelid gammaherpesvirus 1	AF275657	Not described	Single case	Lung	Not described	Unpublished
	Mustelid alphaherpesvirus 1	MF042164	Not described	Single case	Mediastinal lymph node	France	Unpublished
	Mustelid gammaherpesvirus-1 (MusGHV-1)	Not provided	Not detected	55% (54/98)	Genital swabs	UK	Kent et al. (2018)
Northern sea otter (*Enhydra lutris kenyoni*)	Mustelid herpesvirus-2 (MusHV-2, γ-HV)	GU979535	Presence of ulcers or pale raised plaques on the lingual, gingival, oral, oesophageal and labial mucosa: epithelial hyperplasia and hyperkeratosis, often with epithelial cell degeneration and ulceration, and presence of eosinophilic intranuclear inclusion bodies)	46% (13/28)	Skin biopsies	United States	Tseng et al. (2012)
			Apparently healthy animal	34% (21/62)	nasal swabs	United States	
Oriental small-clawed otter (*Aonyx cinerea*)	Oriental small-clawed otter gammaherpesvirus (γ-HV)	FJ797657	Not described	Single case	Not described	Hungary	Unpublished

(Continues)

TABLE 1 (Continued)

Species	HV name in the article	GenBank access nº.	Lesions attributable to herpesvirus	PCR prevalence	Tissue	Country	Author
Captive fisher (*Martes pennanti*)	Fisher herpesvirus (FiHV, γ-HV)	HM579931	Multiple skin ulcers on the muzzle and plantar pads (thickened epidermis with increased numbers of koilocytes, perinuclear vacuolation, nuclear hypertrophy, pale amphophilic intranuclear inclusion bodies and basophilic pseudoinclusions)	Single case	Skin ulcers	Born in captivity in the Unites States and sent to Canada	Gagnon et al. (2011)
American marten (*Martes americana*)	Marten alphaherpesvirus	KX062131 KX062132 KX062133	Not described	3 cases	Not described	Canada	Dalton et al. (2017)
	Marten betaherpesvirus	KX062129 KX062134 KX062135 KX062136	Not described	4 cases	Not described		
	Marten gammaherpesvirus 1 Marten gammaherpesvirus 2	KX062128 KX062130	Not described	2 cases	Not described		
European mink (*Mustela lutreola*)	Mustelid gammaherpesvirus-2	MN082678 MN082679	Basophilic (or eosinophilic, rarely found) inclusion bodies, and syncytia in a multifocal neural and perineural lymphoma.	8.7% (2/23)	Mediastinal B-cell lymphoma and lung	Spain	This work
	Mustelid gammaherpesvirus-3	MN082680	Not detected	8.7% (2/23)	Oral swab, kidney, liver, spleen, bone marrow, brain, spinal cord, sciatic nerve and brachial plexus		

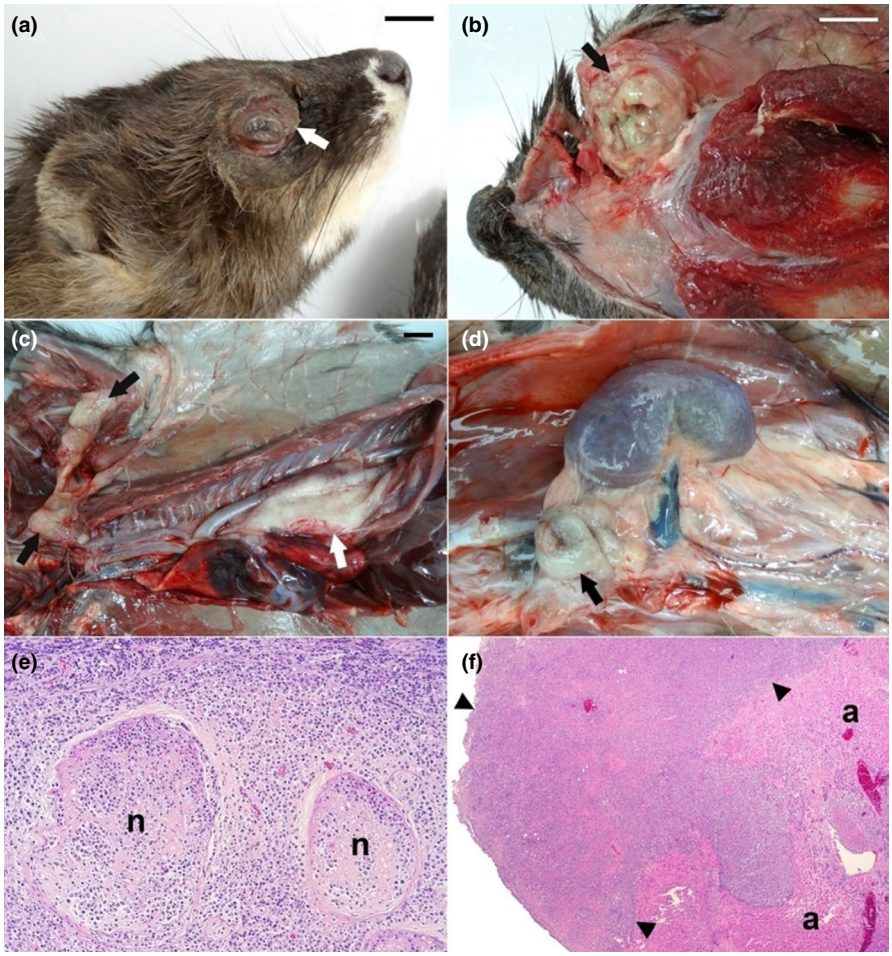

FIGURE 2 Gross and microscopic findings in European mink (*Mustela lutreola*) PM-1: (a) Periocular mass (white arrow). Scale bar = 1 centimetre. (b) Retrobulbar mass (right eye, black arrow). Scale bar = 1 centimetre. (c) Perineural mass along the brachial plexus (black arrows) and mediastinal mass (white arrow). Scale bar = 1 centimetre. (d) Mass effacing the left adrenal gland (black arrow). (e) Note diffuse infiltration of neoplastic lymphocytes in the perineural tissues and endoneurium of the brachial plexus mass; *n* = nerves (haematoxylin and eosin). (f) Adrenal gland (a) is invaded by lymphoma (delimited with arrowheads) (haematoxylin and eosin)

marked meningeal mineralization in the lumbar and thoracic spinal cord, mild multifocal spongiosis in the brain, axonal vacuolar degeneration in the thoracic spinal cord and sciatic nerve, as well as nodular hyperplasia of adrenocortical cells, pancreatic acinar and ductal cells and splenic tissue, mild multifocal fibrosis and/or interstitial lymphoplasmacytic nephritis and glomerulosclerosis. Other gross and microscopic findings are summarized in Appendix S3.

3.4 | Immunohistochemical findings

Positive immunolabelling for the B-cell marker CD20 was consistently observed in neoplastic cells in the perineural masses and endoneurium of intratumoral nerves (Figure 3). Labelling most notably involved the membrane. No labelling of neoplastic cells was observed for CD3 (Figure 3). Therefore, the lymphoma was classified as a B-cell lymphoma.

3.5 | Transmission electron microscopy (TEM)

Transmission electron microscopy detected particles of approximately 150 nm in diameter in the perineural lymphoma identified in PM-1 (Figure 4). Some of these were similar to empty nucleocapsids while others resembled nucleocapsids containing packaged DNA, and both were compatible with herpesviral particles (Ryner, Strömberg, Söderberg-Nauclér, & Homman-Loudiyi, 2006).

4 | DISCUSSION

Two different novel γ-HV sequences were identified in 12 samples from four unrelated adult captive European minks (17.3%, 4/23) that, based on amino acid identities and phylogeny, could be considered novel HV species (MuGHV-2 and MuGHV-3). The prevalence rate should be interpreted with care, once no housekeeping genes were amplified to test the integrity of the DNA present in the samples. This is, to the authors' knowledge, the first report of HV in European mink, expanding the host range of HV infections in mustelids. Other γ-HV species have been previously described in mustelids (Dalton et al., 2017; King et al., 2004; Tseng et al., 2012), occasionally identified in lesions such as oral ulcerations and plaques (Tseng et al., 2012), and skin ulcers (Gagnon et al., 2011). Nevertheless, this is the first description of γ-HV potentially associated with neoplasms in mustelids.

The two γ-HV-infected European minks with available tissues for histopathology (PM-1 and LM/PM-9) had several neoplasms, including B-cell lymphoma (*n* = 1), pulmonary adenocarcinoma

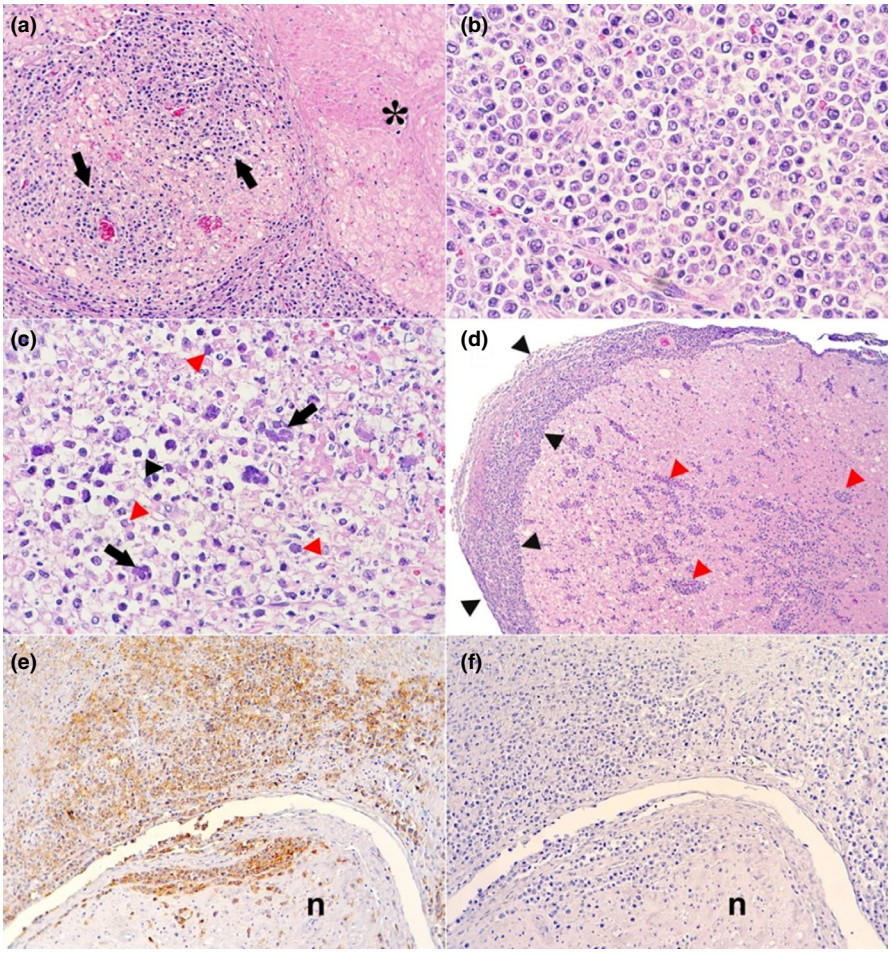

FIGURE 3 Microscopic and immunohistochemical findings in European mink (*Mustela lutreola*) PM-1: (a) Higher magnification of endoneural (arrows) and perineural lymphoid infiltrates in the brachial plexus mass. Note necrosis of neural tissue (asterisk). (b) A higher magnification of neoplastic infiltrates demonstrates neoplastic lymphoblasts (haematoxylin and eosin). (c) Note numerous basophilic intranuclear inclusion bodies (red arrowheads) in unidentified cells and syncytia (black arrows) and few eosinophilic intranuclear inclusion bodies surrounded by a clear halo (black arrowhead) in an area of necrosis involving a nerve in the brachial plexus with perineural and neural lymphoma (haematoxylin and eosin). (d) Lymphoma involving the spinal cord, particularly the pachymeninges (delimited with black arrowheads) but also the white and grey matter (red arrowheads) (haematoxylin and eosin). (e) Note positive immunolabelling for CD20 in perineural and endoneural neoplastic lymphocytes in the brachial plexus mass. (f) Neoplastic lymphocytes are not labelled with CD3 antibodies

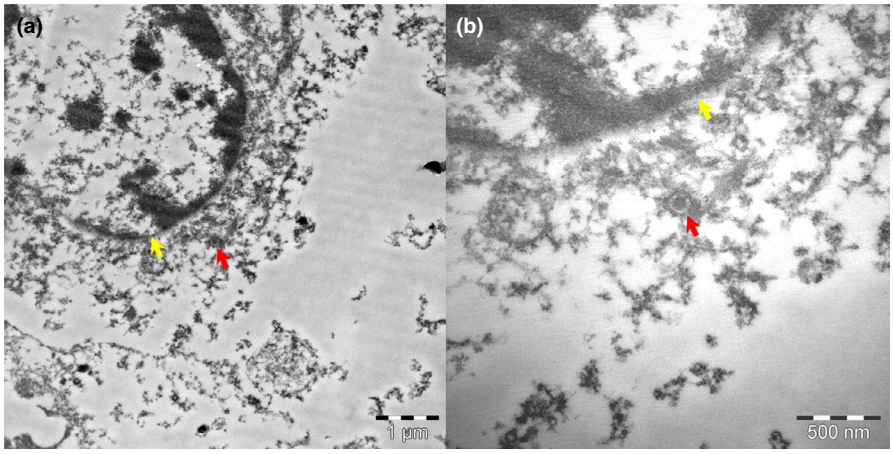

FIGURE 4 Transmission electron microscopy (TEM) of the perineural lymphoma found in European mink (*Mustela lutreola*) PM-1: (a) Intracytoplasmic herpesvirus-like particle (red arrow) after nuclear egression but prior to acquiring the secondary envelopment in the cytoplasm (which leads to the well-known enveloped herpesvirus particles seen on mature virions) and nuclear membrane (yellow arrow), and (b) detailed view of the same particle (red arrow) and nuclear membrane (yellow arrow)

(n = 1), biliary cystadenoma (n = 1) and preputial cystadenoma (n = 1). To the authors' knowledge, these are the first neoplasms described in this species. Age and infectious diseases may have played a role in the development of neoplasm. The influence of other factors that may also be implicated, such as environmental contamination or inbreeding, was not assessed. In other carnivore species, for instance the California sea lion (*Zalophus californianus*), collaborative studies showed that certain neoplasms (urogenital carcinoma) were associated with genotype, but also with HV and persistent organic pollutants (Browning, Gulland, & Hammond, 2015; King et al., 2002).

In regard to age, both animals with neoplasms and HV infection (PM-1 and LM/PM-9) were considered to be of advanced age for the species (over nine years old). The oldest recorded free-ranging European mink was five years old; however, captive animals can reach ten years of age (Mañas, Gómez, Asensio, Palazón, Pŏdra, et al., 2016). The nodular acinar pancreatic hyperplasia, prostatic hyperplasia and glomerulosclerosis observed in PM-1, as well as nodular

acinar and ductal pancreatic hyperplasia, and nodular splenic hyperplasia in LM/PM-9 were possibly related to ageing. Ageing should be considered an immunosuppression factor per se (Marchioni & Berzero, 2015), capable of facilitating neoplasm development.

The European mink with neoplasms—PM-1 and LM/PM-9—were infected with gammaherpesviruses MuGHV-2 and MuGHV-3, respectively. HV-compatible particles were observed by TEM in a B-cell lymphoma with neural tissue tropism of PM-1, in which intratumoral syncytia and intranuclear inclusion bodies characteristic of herpesviruses were noted. Noteworthy, viruses have been associated with approximately 15% to 20% of human cancers worldwide (Boccardo & Villa, 2007; Parkin, 2006). Several γ-HV are oncogenic viruses. For instance, Epstein–Barr virus (*Human gammaherpesvirus 4*) has been aetiologically associated with a broad range of lymphoproliferative lesions and B-, T- and NK-cell malignant lymphomas in humans (Shannon-Lowe, Rickinson, & Bell, 2017), including B-cell lymphoma in elderly populations, possibly associated with immunosuppression due to ageing (El Jamal, 2014; Castillo et al., 2016). Kaposi sarcoma-associated HV (syn. *Human gammaherpesvirus 8*) is associated with Kaposi's sarcoma and lymphoproliferative disorders in humans (Du, Bacon, & Isaacson, 2007). In wild mammals, γ-HVs have been implicated in the pathogenesis of several neoplastic diseases, including urogenital carcinoma or multicentric B-cell lymphoblastic lymphoma in California sea lion (Browning et al., 2015; Lipscomb et al., 2000; Venn-Watson et al., 2012). Gammaherpesvirus-associated lymphoproliferative disease has been observed in captive non-human primates of the family Callitrichidae (Ramer et al., 2000). The experimental inoculation of γ-HV saimiri herpesvirus in three-striped night monkeys (*Aotus trivirgatus*) induced acute lymphocytic leukaemia (Melendez, Hunt, Daniel, Blake, & Garcia, 1971), while Epstein–Barr virus inoculation caused lymphoma in cotton-top tamarins (*Saguinus oedipus*) (Miller et al., 1977). The herpesviruses identified in both minks, particularly in PM-1, may have been involved in the etiopathogenesis of the neoplasms found. Conversely, the detection of γ-HVs in several tissues from infected animals presenting neoplasms could have been caused by viral reactivation from latency, triggered by, among other causes, immunosuppression (which could be associated with the presence of neoplasms), given that γ-HVs become latent in lymphoid cells (Roizmann et al., 1992).

In the domestic ferret, a species closely related to the European mink, lymphomas are common spontaneous malignancies. Healthy ferrets experimentally inoculated with non-cellular extracts from ferrets with lymphoma also developed this neoplasm, which reinforces the potential role of infectious agents in the horizontal transmission of lymphomas in this species (Erdman et al., 1995). The role of *Aleutian mink disease virus* and retrovirus infection has been suggested (Erdman, Moore, Rose, & Fox, 1992). Unfortunately, due to economic constraints, the potential role of retroviruses in European minks has not been assessed yet.

Inbreeding is another factor that could partially explain the observed neoplasms. The French and Spanish European minks appear to be highly inbred (Maran et al., 2016), and it would be interesting to know if these highly genetically uniform populations are more prone to neoplasia. For instance, the loss or lack of major histocompatibility complex (MHC) diversity, known to reduce immune response effectiveness, is postulated to contribute to the successful spread of the devil facial tumour disease of Tasmanian devils (*Sarcophilus harrisii*) (Siddle et al., 2007). The association between neoplasm (urogenital carcinoma) and inbreeding has also been identified in California sea lion (Acevedo-Whitehouse, Gulland, Greig, & Amos, 2003).

The neurological clinical signs—mainly incoordination and rear limb weakness, presented by three of the four HV-positive animals (PM-1, PM-8, LM/PM-9, all over 9 years of age) were initially considered typical signs of weakness or ageing-related degenerative disorders. The microscopic lesions described in the peripheral and central nervous systems of two of the examined animals potentially explain the observed neurological signs: peripheral and central nervous system B-cell lymphomas, axonal degeneration, and peripheral skeletal muscle nerves axonal degeneration (PM-1), and brain spongiosis, and spinal cord and sciatic nerve axonal vacuolar degeneration (LM/PM-9). The spongiosis and axonal degeneration observed in LM/PM-9 could be associated with metabolic (e.g. renal encephalopathy) and/or toxic disorders. Noteworthy, LM/PM-9 had severe glomerulonephritis, mild interstitial lymphoplasmacytic nephritis, glomerulosclerosis and azotemia, with high urea (410 mg/dl) and creatinine levels (1.44 mg/dl). These were elevated when compared with the reference values described in other mustelid, the ferret: 11–42 mg/dl and 0.2–1 mg/dl, respectively, (Carpenter & Marion, 2017) and the remaining European minks analysed in this study (data not shown), which could explain the incoordination signs. No reference values are available for European mink.

Interestingly, the MuGHV-2 found in case PM-1 presented neural tissue tropism, with HV particles observed in a perineural mass, and similarly, LM/PM-9 samples of brain, spinal cord and peripheral nerve (sciatic nerve and brachial plexus) were positive to MuGHV-3. Both animals had incoordination. The aetiology of the neuritis in the B-cell lymphoma of PM-1 is unclear; it could have been due to secondary inflammation associated with the local necrosis or a direct response against herpesviral infection. Some γ-HVs have marked neurotropism, such as *Human herpesvirus 4*/ Epstein–Barr virus and *Human herpesvirus 4*/Kaposi's sarcoma-associated HV (El Jamal et al., 2014; Tso et al., 2016). For instance, Epstein–Barr virus has been suggested to cause CNS damage by parainfectious and direct virus-related mechanisms in humans (e.g. meningitis, encephalitis and lymphoma; El Jamal et al., 2014). Thus, it is not possible to exclude HVs as the potential causative agents of the nervous clinical signs observed in these infected minks. Cataracts, corneal melanosis, focal granulomatous conjunctivitis in the left eye, and protrusion of and periocular mass around the right eye observed in PM-1 may have contributed to its impaired vision. All minks were seronegative to two other viral agents that could also cause neurological clinical signs and/or impaired vision: *Aleutian mink disease virus* (Dyer, Ching, & Bloom, 2000; Hadlow, 1982) and canine distemper (Summers, Greisen, & Appel, 1984). Histopathologic evidence of infection with *Toxoplasma gondii*, *Encephalitozoon* spp. or *Sarcocystis neurona* was not observed.

One of the novel European mink γ-HVs (Mu-GHV3) was detected in an antemortem oral swab (LM-9), suggesting that viral

shedding occurs in infected European minks and, therefore, that horizontal HV transmission through oral secretions could be possible. Such characteristic has been previously identified in γ-HV viruses; Epstein–Barr virus is commonly transmitted via saliva (Marchioni & Berzero, 2015), and other γ-HVs have been detected in sea otter oral mucosal ulcers and plaques (Tseng 2012), and in oral tissue and swabs samples from northern elephant seals (*Mirounga angustirostris*) (Goldstein et al., 2006). None of the minks in this study had oral ulcers. Transmission can be enhanced in captivity as close confinement leads to a higher contact rate between animals and stress-related immunosuppression (Tseng et al., 2012). Interestingly, one of the infected European minks (LM/PM-9) had lesions compatible with chronic stress (bilateral nodular hyperplasia of adrenocortical cells), which could have reactivated latent γ-HV in the lymphoid tissue (Lam, Garner, & Miller, 2013; Roizmann et al., 1992).

Three of the HV-infected European minks were captured in the Ebro River basin (PM-4, PM-8 and LM/PM-9). The fourth one (PM-1) was born in Pont de Suert in 2006. Herpesvirus can cause lifelong infections (Roizmann et al., 1992); therefore, it was not possible to establish if these animals became infected during their stay in the captive breeding centre (the virus was detected when they had already been in captivity for several years) or already carried the virus when they joined the collection. As several European mink conservation programmes involving species restoration and reintroduction use animals bred in captivity (Mañas et al., 2001), future studies should investigate whether these HVs are present in wild European mink populations. Due to the fact that several HV infections predispose the host to secondary bacterial infections (Cabello et al., 2013), and considering the small size of the European mink population, the authors believe that monitoring for these viruses should be considered when implementing conservation strategies including translocations, as has been advised for other species, for example, the Darwin's fox (*Lycalopex fulvipes*) (Cabello et al., 2013).

5 | CONCLUSIONS

This is the first report of HV in European minks. Four European minks were positive to one of the two identified novel herpesviruses: *Mustelid gammaherpesvirus 2* (MuGHV-2) and *Mustelid gammaherpesvirus 3* (MuGHV-3). Several neoplasms, including B-cell lymphoma, adenocarcinoma and biliary and preputial cystadenomas, as well as neurological signs, were observed in some of the γ-HV-infected European minks. Aside from the B-cell lymphoma case potentially associated with MuGHV-2, the relationship between γ-HV infection and the remaining lesions is unclear.

This study contributes to the conservation of European minks by expanding the current knowledge on the viral diseases affecting this species. Additional research is needed to establish the prevalence of these novel γ-HVs in free-ranging European mink populations, and to investigate their pathogenicity and the role of herpesvirus and other potential cofactors in the neoplasms detected in this particular European mink captive breeding population. This information will be critical to take more scientifically based decisions and adopt management techniques for the conservation of this endangered species, as well as to determine if infected captive bred European minks could be released into the wild without negatively impacting the species' conservation.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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ETHICAL APPROVAL

Ethical approval for this study was granted by the R(D)SVS Veterinary Ethical Review Committee (VERC, process number 57.17) and the Government of Catalonia (Wildlife and Plant Service within the Department of Sustainability and Territory).

DATA AVAILABILITY STATEMENT

The data that support our findings are available in the manuscript and in the supplementary material.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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