Ventrolateral temporal lobectomy in normal dogs as a counterpart to human anterior temporal lobectomy: a preliminary study on the surgical procedure and complications

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ABSTRACT. Anterior temporal lobectomy (ATL) is a surgical procedure for drug-resistant mesial temporal lobe epilepsy that is commonly performed in human medicine. The purpose of this study was to determine whether ATL-like surgery, i.e., removal of the amygdala and hippocampal head, is possible in dogs, and to investigate its safety and postoperative complications. Eight healthy beagles underwent ATL-like surgery and were observed for 3 months postoperatively. Samples from the surgically resected tissues and postmortem brain were evaluated pathologically. The surgical survival rate was 62.5%. The major postoperative complications were visual impairment, temporal muscle atrophy on the operative side, and a postoperative acute symptomatic seizure. Due to the anatomical differences between dogs and humans, the surgically resected area to approach the medial temporal structures in dogs was the ventrolateral part of the temporal lobe. Therefore, the ATL-like surgery described in this study was named "ventrolateral temporal lobectomy" (VTL). This study is the first report of temporal lobectomy including amygdalohippocampectomy in veterinary medicine and demonstrates its feasibility. Although it requires some degree of skill, VTL could be a treatment option for canine drug-resistant epilepsy and lesions in the mesial temporal lobe.

KEY WORDS: dog, epilepsy surgery, temporal lobectomy, surgical complication

Epilepsy is a common neurological disorder in human and veterinary medicine, and antiseizure drug (ASD) therapy is the primary approach for human and animal patients with epilepsy. Despite adequate ASD treatment, proper seizure control is not achieved in approximately 30% of human and canine patients [18, 22, 27].

In humans, epilepsy surgery is a generally accepted treatment option for patients with drug-resistant epilepsy. The surgical techniques are classified into three types: resection, disconnection, and neuromodulation. These are selected for each patient depending on the situation, e.g., seizure type, location of the epileptogenic zone, presence of structural abnormalities, position of the eloquent area, and wishes of the patient or their family. However, there are very few reports about epilepsy surgery in the veterinary literature, which describe corpus callosotomy (disconnection surgery) [1], vagus nerve stimulation or deep brain stimulation (neuromodulation) [16, 19], and resection of the lesion in structural epilepsy [23], and partial cortico-hippocampectomy (feline cadaveric study; resection surgery) [45].

Anterior temporal lobectomy (ATL) is a type of resection surgery that is characterized by the removal of unilateral mesial temporal lobe structures, including the amygdala and hippocampus, that cause epileptic seizures as the epileptogenic zone. It is commonly accepted that ATL is a recommended treatment option for achieving seizure control in eligible patients with drug-resistant temporal lobe epilepsy [38]. This surgical procedure is performed with a temporal craniotomy to expose the sylvian fissure and remove temporal structures, i.e., the anterolateral neocortex, part of the fusiform gyrus, amygdala, uncus, hippocampus,

and parahippocampal gyrus [28, 42]. Regarding the prognosis of ATL, consistent results have been reported by many groups over the last 40 years [24, 33, 38, 43]. Most of the human medical centers performing ATL report low operative morbidity and mortality, and freedom from or reduction of seizures is achieved in 60–80% of patients with temporal lobe epilepsy after ATL [14, 20, 25, 30, 37, 38]. In particular, approximately 90% of patients with drug-resistant temporal lobe epilepsy associated with hippocampal sclerosis experience seizure freedom or a reduction in their rate [33, 38]. In veterinary medicine, there is only one case report in which a hemangioma in the mesial temporal lobe was removed from a dog using a surgical technique similar to ATL [32]. This paucity of reports may be attributed to the difficulty of accessing the canine temporal region; if a surgeon attempted to perform temporal lobe surgery on a dog, it could be expected that access to the surgical site would be restricted by the large amount of temporal muscle, zygomatic arch, and vertical arm of the mandible [32].

The aims of the present study were 1) to establish an ATL-like procedure for dogs, 2) to identify its surgical complications, and 3) discuss its feasibility. In order to achieve these aims, we performed ATL-like surgery on normal dogs and evaluated the success rate and postoperative complications by follow-up observations using magnetic resonance imaging (MRI) and histopathology.

MATERIALS AND METHODS

Ethics and experimental animals

This study was approved by the Animal Care and Use Committee of Nippon Veterinary and Life Science University (accession nos.: 26S-20, 27K-11, 28K-5, S28K-5, 29K-3, S29K-3, 30K-3, and S30K-3) and performed according to the guidelines of the committee.

Prior to the study using live dogs, we simulated and confirmed the surgical procedure using three beagle cadavers that had been euthanized due to reasons unrelated to this study. The cadavers had been stored frozen and were used after thawing.

Eight healthy laboratory beagles (Dogs #1–8; 5 males and 3 females) were used in this study. All dogs had normal physical, neurological, and blood (complete blood count and serum biochemistry tests) findings. The median age of the dogs was 120 months (range: 101–140 months) and the median body weight was 9.3 kg (range: 8.4–12.4 kg).

Imaging protocol

Under the general anesthesia described below, all dogs underwent MRI and computed tomography (CT) of the head before surgery. MRI was obtained with a 3.0-Tesla unit (Signa HDtx 3.0 T; GE Healthcare, Tokyo, Japan). The obtained sequences included transverse plane T2-weighted imaging (T2WI), fluid-attenuated inversion recovery (FLAIR), T1-weighted imaging (T1WI), contrast-enhanced (CE) T1WI, 3D T2WI, 3D T1WI, and CE-3D T1WI. CE sequences were obtained after the intravenous administration of gadodiamide (0.05 mmol/kg). The acquisition parameters of each sequence are summarized in Supplementary Table 1. CT was performed with an 80-row multi-detector CT scanner (Aquillion PRIME TSX-303A; TOSHIBA, Tokyo, Japan).

Anesthesia

In all dogs, anesthesia was induced by intravenous administration of propofol (10 mg/kg) and maintained with 2.0% isoflurane and 100% oxygen with mechanical ventilation. Lactated Ringer's solution (5–10 ml/kg/hr) was administered throughout surgery. Intraoperative analgesia was provided by constant rate infusion of fentanyl (1–3 µg/kg/hr). To prevent intraoperative infection, cefazolin sodium (25 mg/kg) was administered intravenously every 2 hr during surgery. Electrocardiography, rectal temperature, non-invasive blood pressure, end-tidal CO_2, oxyhemoglobin saturation, and end-tidal isoflurane concentration were monitored while under anesthesia.

Surgical procedure

All surgeries were performed by one board-certificated neurologist (DH). We defined the procedural goal as the removal of the gray and white matter of part of the left ventrolateral temporal lobe, amygdala within the piriform lobe, and ventral part of the hippocampus (hippocampal head).

The dog was positioned in a sternal recumbent position with the head held slightly higher than the trunk. To access the surgical site, the head was tilted as much to the right side as possible. The head was shaved from the level of the superior orbital margin to the occipital bone area and sterilized as usual.

A horseshoe-shaped (inverse U) incision was made on the left scalp rostral from the temporal fossa to the caudal end of the zygomatic arch. Following the scalp incision, the left temporal muscle was cut along the external sagittal crest and detached from the parietal bone to the level of the zygomatic arch. To maintain the surgical field, the scalp and temporal muscle were turned over and fixed laterally using a Gelpi retractor and wide spatula.

A rectangular craniectomy (approximately 2.5 cm dorso-ventral × 2.0 cm rostro-caudal) was performed on the left pterion area (junction site of the frontal, parietal, temporal, and sphenoidal bones) (Fig. 1A). At first, four burr holes were made and connected in the parieto-temporal region, and the bone within the area was removed using a high-speed drill with a saline flush. Following fenestration, the ventral edge of the surgical window was extended cranioventrally with a rongeur to expose the anteroventral part of the temporal lobe. Bleeding from the diploic layer was controlled using bone wax.

Intracranial surgery was performed under a surgical microscope (OPMI 6-CH; Carl Zeiss Meditec, Tokyo, Japan). A U-shaped durotomy was performed with a #11 scalpel and microscissors, and the ventrolateral aspect of the lateral temporal lobe was exposed (Fig. 1B). The resection area in the lateral temporal cortex was composed of the ventral part of the caudal sylvian gyrus, which was caudal to the pseudosylvian fissure, and the ventral part of the caudal ectosylvian gyrus and caudal composite gyrus,
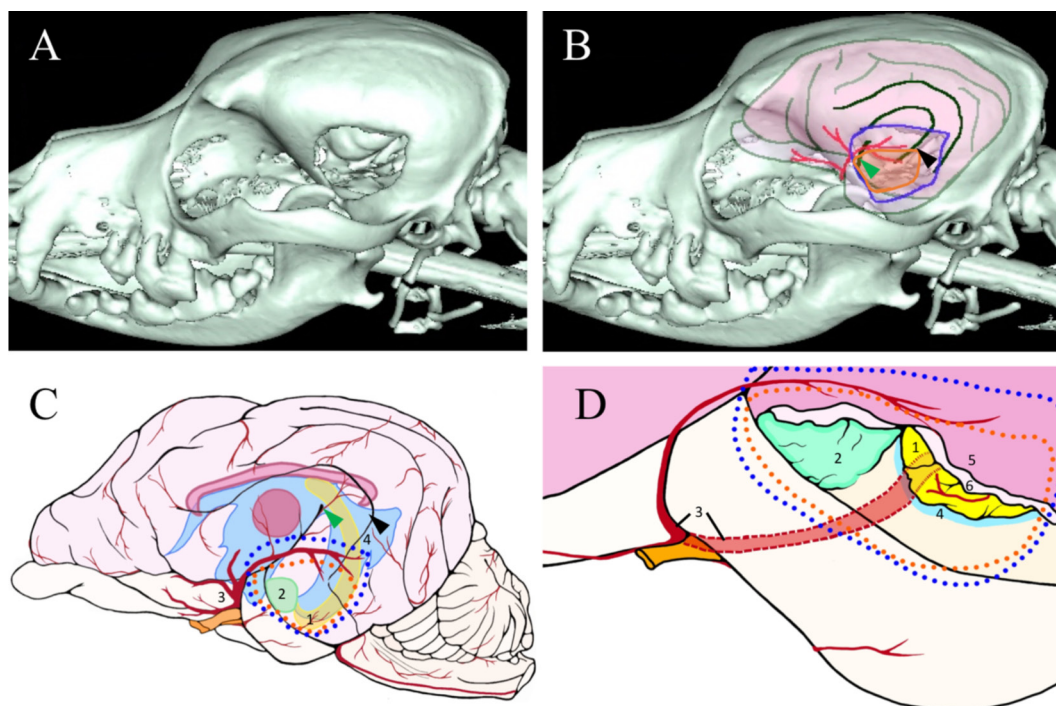
Fig. 1. Postoperative volume rendering computed tomography (CT) of Dog #7 and surgical illustration of ventrolateral temporal lobectomy (VTL). **(A)** The extent of craniectomy (~2.3 cm square). **(B)** An illustration of the representative surface landmarks of the surgical field. Blue enclosure, extent of craniectomy; orange enclosure, resection area of the temporal cortex; red line, course of the middle cerebral artery (MCA); green arrowhead, pseudosylvian fissure; black arrowhead, caudal ectosylvian fissure. **(C)** Illustration of VTL-related brain structures and **(D)** illustration of the VTL microsurgical field. Blue enclosure, extent of craniectomy; orange enclosure, resection area of the temporal cortex; green arrowhead, pseudosylvian fissure; black arrowhead, caudal ectosylvian fissure; 1 (yellow), hippocampal head; 2 (light green), amygdala; 3 (red), MCA; 4 (light blue), lateral ventricle; 5 (D, pink), gray matter of the lateral cortex; 6 (D, pale pink), white matter. See also the intraoperative video (Supplementary Movie).

which were rostral to the caudal suprasylvian sulcus, under the main course of the middle cerebral artery (MCA) (Figs. 1B–D, 4A). During cortical resection, the MCA was preserved using neurosurgical sheets (SERECEET; Fuji Systems, Tokyo, Japan). The arachnoid mater covering the temporal lobe cortex was removed. The temporal cortex, including the gray and white matter within the abovementioned area, was removed with bipolar cautery and suction until the ventral horn of the lateral ventricle was reached. This cortical resection allowed visualization of the mesial temporal structures, i.e., the tip of the ventral part of the hippocampus (hippocampal head) interiorly and the amygdala rostrally, via the lumen of the lateral ventricle. Removal of the amygdala and piriform lobe was also performed with bipolar cautery and suction. Partial removal of the ventral part of the hippocampus was performed; at first, the hippocampal body was cut transversely with thin-tip bipolar cautery, and then the rostral part of the hippocampus (hippocampal head) was removed gently from the internal structures, such as the rostral choroidal artery, choroid plexus, and fimbria, using bipolar cautery, microforceps, and microscissors. The removed part of the hippocampus was stored in 10% formalin for pathology. Bleeding from the brain parenchyma or surrounding tissues was controlled with bipolar cautery, fibrin tissue adhesive (Beriplast P Combi-Set Tissue Adhesion; CSL Behring, Tokyo, Japan), microfibrillar collagen hemostat (Avitene; ZERIA Pharmaceutical, Tokyo, Japan), and oxidized regenerated cellulose (SURGICEL Absorbable Hemostat; Johnson & Johnson, Tokyo, Japan). Only a 3D-T2WI sequence was used intraoperatively to determine whether the procedural goal had been achieved. If not, additional resection was performed until the remaining target was removed. A summary of the micro-surgical procedures is shown as a movie in Supplementary Movie.

To close the surgical site, the area of craniectomy was covered with artificial dura mater (Gore-Tex EPTFE patch II; W. L. Gore & Associates, Tokyo, Japan) and sealed with fibrin tissue adhesive. The temporal muscle, subcutaneous tissues, and scalp were closed as usual. After finishing all surgical procedures, postoperative CT and MRI were performed.

Postoperative management and follow-up observations

The dogs were administered cefazolin sodium (20 mg/kg, BID, PO) and levetiracetam (20 mg/kg, TID, PO) for 1 week. A fentanyl patch (4.2 mg/head) was applied as postoperative analgesia for 3 days after surgery.

Follow-up observations included visual assessments of mental and neurological signs such as abnormal behavior and seizure activity for 3 months with direct observations (video-monitoring at night), daily general physical examinations, weekly neurological examinations, and monthly follow-up MRI scans.

After the 3-month observation period, the dogs were euthanized with an intravenous injection of pentobarbital sodium (50 mg/kg) or propofol (30 mg/kg) followed by potassium chloride (2 mEq/kg). Immediately after euthanasia, the surgical site was

observed macroscopically and the brain was removed from the skull and immersed in 10% formalin for pathological evaluation.

Histopathology

After fixation, the partially resected ventral hippocampus and postmortem brain tissues were embedded in paraffin, and 4-μm-thick sections were made in the transverse plane. These sections were stained with hematoxylin-eosin and evaluated by two board-certificated neuropathologists (JKC and KU).

RESULTS

Surgical findings, achievement of procedural goal, survival rate, and mortality

Postoperative MRI revealed that the procedural goal, i.e., resection of part of the lateral temporal cortex, amygdala, and hippocampal head, was achieved in six (75%) dogs (Dogs #1, 3, 4, 5, 7, and 8), (Fig. 2). In these cases, intraoperative views and anatomical structures were confirmed during the stable surgical phase (Supplementary Movie). Intraoperative MRI was performed at least once in those dogs, and was required twice in two dogs (Dogs #1 and 5) and three times in two dogs (Dogs #3 and 7) until surgery was completed. However, one of the six dogs (Dog #4) had a sudden cardiac arrest during skin suturing and resuscitation was attempted, but the dog did not recover and was euthanized. After euthanasia, postmortem MRI and autopsy were performed, but no surgical-related intracranial lesion such as hemorrhage or infarction was identified, and no link between surgery and cardiac arrest was revealed. The remaining five dogs recovered completely from surgery, but two had a convulsive seizure during the recovery phase (mentioned below). The median total anesthesia time and operation time (from incision to closure) were 640 min (range: 603–1,147) and 500 min (range: 400–745), respectively.

The other two dogs (Dogs #2 and 6) developed a massive arterial hemorrhage from the origin of the MCA, where it branches from the arterial circle (Fig. 2A, 2B), during the basal approach procedure for hippocampal resection. The surgeon tried to stop the bleeding by various approaches, but it could not be controlled. As a result, the operation was discontinued and both dogs were euthanized.

Finally, the overall survival rate and mortality of ATL-like surgery in this study were 62.5% (5/8 dogs) and 37.5% (3/8 dogs), respectively.

Postoperative observations and complications

As mentioned above, Dogs #1 and 3 showed a single generalized convulsive seizure immediately after surgery, which terminated spontaneously within 5 min. After that, both dogs recovered from anesthesia normally.

During the observation period, none of the surviving dogs exhibited any negative mental signs or recurrent seizures. On neurological examination (Supplementary Table 2), Dogs #1, 3, and 5 had a loss or reduction of the menace response in the right eye, which lasted for 1 month in Dog #3, but it was sustained to the end of the observation period in Dogs #1 and 5. Dogs #1 and 3 had a reduction of postural reactions in the right limbs for 1 week and 1 month, respectively. Other abnormalities noted included mydriasis of the left eye with loss of pupillary light reflexes in Dog #5 and left circling in Dog #3 throughout the observation period. Conversely, Dogs #7 and 8, which were operated on in the latter part of the study, had no clinical signs and no abnormal findings on neurological examination.

Follow-up MRIs of all surviving dogs showed no evidence of bleeding, hematoma, or cerebrospinal fluid leak. In Dogs #1 and 7, a fluid accumulation area with hyperintensity on T2WI/FLAIR and hypointensity on T1WI without contrast enhancement was located outside of the resection area (Fig. 3). This lesion seemed to be a small seroma surrounded by autologous dura, artificial
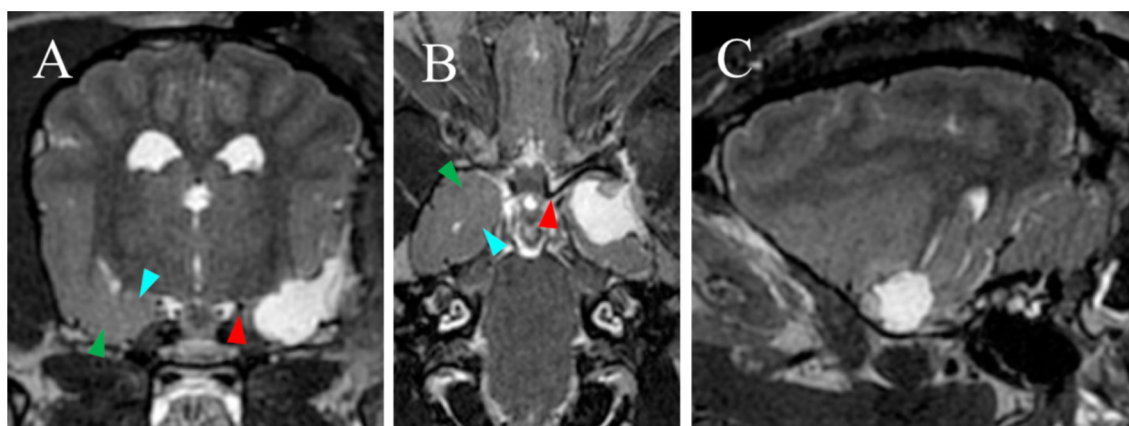
Fig. 2. T2-weighted magnetic resonance imaging (MRI) immediately after surgery of Dog #7. **(A)** Transverse, **(B)** dorsal, and **(C)** sagittal images showing the resected area. The left amygdala and hippocampal head were removed; compare with the right amygdala (green arrowhead) and hippocampal head (cyan arrowhead). Red arrowhead, site where the middle cerebral artery (MCA) branches from the arterial circle, which was damaged in Dogs #2 and 6.

dura, and adhesive fibrous tissues without communication to intracranial or other extracranial structures during macroscopic observation at necropsy, although the accumulated fluid could not be analyzed. Dogs #1 and 5 had focal lesions with hyperintensity on T2WI/FLAIR and iso- to hypointense lesions on T1WI without contrast enhancement, which were considered to represent ischemic changes, in the ventral margin of the internal capsule including the optic tract and endopeduncular nucleus and in the external medullary lamina including the reticular nucleus, respectively (Fig. 3). These lesions persisted during the 3-month observation period. In addition, persistent temporal muscle atrophy of the operated side compared with the contralateral side was observed in Dogs #1, 3, and 5.

Histopathology

On microscopic examination, the surgically resected tissue samples revealed hippocampal structures such as Ammon's horn, demonstrating that partial hippocampectomy was definitely performed (Fig. 4B).

On macroscopic observation at necropsy (Fig. 4A), severe adhesions were noted at the surgical site of the left temporal area. The craniectomized area adhered to the artificial dura and original dura, and the cerebral parenchyma of the operative site had also adhered to the skull base.

On histopathological examination of the surgical site, ischemic changes and extensive gliosis were observed in the temporal
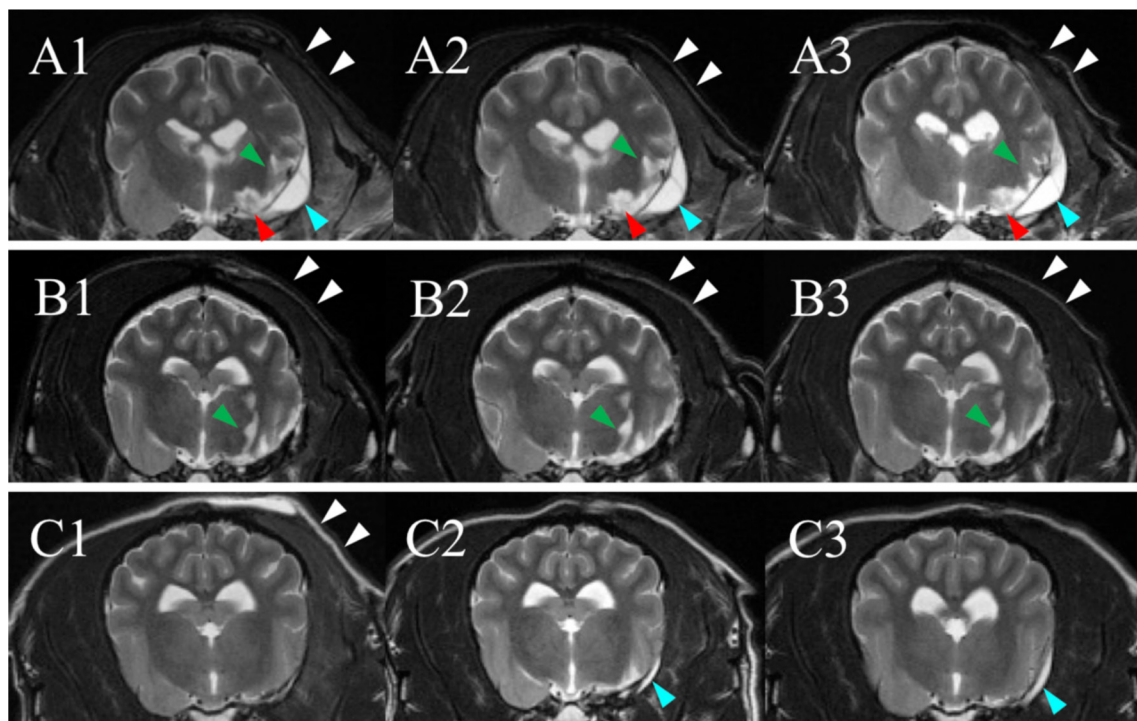
Fig. 3. Follow-up magnetic resonance imaging (MRI) (T2-weighted transverse images) of Dogs #1, 5, and 7. MRI was performed at 1 month (A1, B1, and C1), 2 months (A2, B2, and C2), and 3 months (A3, B3, and C3) postoperatively. (A1–A3: Dog #1) MRI series showing persistent temporal muscle atrophy (white arrowheads), optic tract damage (green arrowheads), and internal capsule damage (red arrowheads). (B1–B3: Dog #5) MRI series showing persistent temporal muscle atrophy (white arrowheads) and optic tract damage (green arrowheads). (C1–C3: Dog #7) MRI series showing transient inflammation of the temporal muscle (white arrowheads). In Dogs #1 and 7, a fluid accumulation that was suspected as seroma was found at the outside of surgical site (cyan arrowheads).
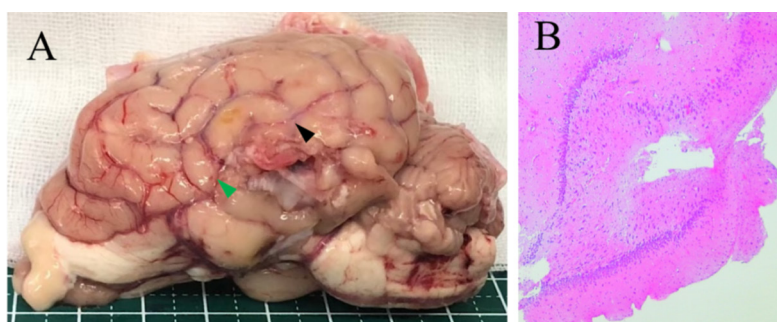
Fig. 4. Pathological findings of the brain. **(A)** Macroscopic appearance of the surgical site in Dog #7. Green arrowhead, pseudosylvian fissure; black arrowhead, caudal ectosylvian fissure. **(B)** Hematoxylin-eosin staining (×100) of tissue removed during surgery. A portion of the dentate gyrus and Ammon's horn were identified, i.e., the hippocampus.

lobe cortex adjacent to the resected area in all dogs. In the specimens of Dogs #1 and 5 with parenchymal damage on follow-up MRI, tissue defects were observed in the corresponding area to the MRI lesions, which were surrounded by ischemic changes with gliosis.

Taking all of the results of this study into consideration, because the surgically removed area of the temporal lobe for resecting mesial temporal structures was different from ATL in humans due to the anatomical differences between humans and dogs, we named this ATL-like surgery in dogs "ventrolateral temporal lobectomy" (VTL).

DISCUSSION

This is the first report describing the procedure, availability, and complications of ATL-like surgery, i.e., VTL, in dogs. The results of this study provide fundamental information for veterinarians to perform temporal lobe surgery. Although the procedural goal was achieved in 6 dogs (75%), the final survival rate and mortality of VTL in this study were 62.5% and 37.5%, respectively. In contrast, the operative mortality rate of ATL for humans is less than 1% [25, 28, 30, 38]. This major disparity in surgical outcome may be associated with surgical proficiency and the visibility of the surgical field. In humans, ATL is one of the classic forms of epilepsy surgery. Reports of stable surgical outcomes clearly indicate that ATL is a mature technique [24, 33, 38, 43]. In contrast, reports of surgery in the temporal lobe area in veterinary medicine are extremely limited [32, 45], and even experienced veterinary neurosurgeons are not familiar with this approach. As reasons for this disparity, there are obvious differences in the size and shape of the head and anatomical location of the temporal region between humans and dogs. Humans have a large dome-shaped cranium with a minimum amount of temporal muscle covering the temporal region, and the temporal lobe is located superior (dorsally) to the level of the zygomatic arch, which is easy to approach and secure a wide and good surgical field. In humans, the accumulation of ATL cases has defined the appropriate extent of resection, allowing cortical resection of up to 6 cm (non-dominant hemisphere), and the visibility of medial tissues such as the temporal horn and tentorial dura are well-known landmarks to avoid over-invasiveness [28, 42]. During ATL surgery in humans, it is important to avoid injury to the inferior cerebral vein (vein of Labbe) and the major temporal basal vein, but there are significant individual differences in their development and distribution [9, 40]. Conversely, the canine cranium, especially in mesaticephalic (e.g., beagles in this study) and dolichocephalic breeds, has a massive temporal muscle, and the temporal region is located at the same level or inferior (ventrally) to the zygomatic arch. As a result, the craniectomy range for VTL in the present study was very limited, the operative field was deep, and the surgeon (using a surgical microscope) had to peer into the operative site from a limited angle. The extent of cortical resection in this study was approximately 1 cm (see Figs. 1 and 3). This narrow field of view made it difficult to confirm the internal structures, especially the medial side of the hippocampal head, where the origin of the MCA branches from the cerebral arterial circle (Fig. 2A, 2B); we had to abandon surgery and euthanize two dogs due to an uncontrollable hemorrhage caused by damage to this site. Experimental occlusion studies of the MCA and anterior choroidal artery in dogs revealed great diversity in infarct lesions and neurological deficits [2, 7]. The results of those studies indicated that there is considerable variation in the blood vessels and their collateral circulation from the MCA and anterior choroidal artery in dogs. Thus, the importance of preserving arterial structures in a mesial temporal lobe approach such as VTL is supported by these studies. In contrast, however, defensive surgery to protect these vessels may result in incomplete resection of the hippocampal head and amygdala. As an improvement of the approach to the temporal region in dogs, amputation (and re-fusion) of the zygomatic arch could be considered. In addition, detailed anatomy of the vessels in the mesial temporal lobe of dogs is needed; although we found descriptions in a textbook [8] and a paper [7] and a few reports investigating this region using MR angiography [13, 26, 36], there is no three-dimensional or direction atlas of the mesial temporal lobe in dogs. Although we had investigated these areas in preliminary surgery using three cadavers, our preoperative knowledge of small vessels in the mesial temporal area was extremely limited. Unfortunately, we were not able to determine any useful landmarks in this area during surgery. Preoperative MR and/or CT angiography to evaluate arterial structure such as the MCA was not performed in the present study, but such assessments may improve the success rate of VTL.

This study did not use an ultrasonic aspirator or navigation system commonly used in human medicine. The use of these devices has the potential to improve the surgical success rate. However, regarding the use of an ultrasonic aspirator, there is a canine case series in which the use of this device to remove diencephalic mass lesions led to postoperative hyperthermia, hypernatremia, and death [17]. Therefore, we had decided not to use an ultrasonic aspirator for VTL when planning this study because the amygdala and hippocampus are located adjacent to the diencephalon (thalamus). In the present study, despite not using an ultrasonic aspirator, iatrogenic lesions in the internal capsule and thalamus were observed in two dogs, although the previously reported clinical signs were not observed. The use of an ultrasonic aspirator during resection of the lateral temporal and pyriform cortexes including the amygdala should be considered. Additionally, we could not use a navigation system in this study, but we believe that a neuronavigator may be helpful for this narrow and deep surgical site and could contribute to an increase in the success rate of VTL in canine patients.

The most common complications in this study were loss of the menace response and atrophy of the temporal muscles. Visual abnormalities and temporal muscle damage are also common adverse effects in humans [31, 35, 41]. However, their occurrence is thought to be an inevitable secondary iatrogenic effect when the benefits of surgery, i.e., liberation from severe seizures, are considered.

In this study, the reduction and loss of the menace response occurred in the right eye of three dogs. The visual pathway structures associated with the surgical area of VTL in the present study include the optic tract adjacent to the resection area and the occipital (visual) to frontal (motor) cortex liaison fibers running through the internal capsule. MRI and pathology confirmed that the sites of visual pathway damage in this study were mainly the optic tract and internal capsule. In human ATL, visual

field defects are frequently reported as a postoperative complication, of which contralateral superior quadrantanopia is the most common symptom [4, 41]. This deficit is caused by damage to the anterior portion of the optic radiation and anterior bending of the temporal radiation in the temporal lobe (Meyer's loop). The rate of optic crossover in dogs is higher than in humans; therefore, it is reasonable to assume that contralateral visual impairment was caused by damage to these areas during left-side VTL. Although the visual pathways that are damaged during VTL/ATL are different in dogs and humans, the visual impairments observed in the present study were thought to be complications corresponding to the visual field defects observed in humans.

In human brain surgery, fronto-temporal craniotomy is highly invasive to the temporal muscle [3, 6, 12, 21, 35]. Damage to the temporal muscle may include muscle break, muscle fiber damage due to avulsion or traction, blood flow disturbances, nerve transection during surgery, and fibrosis and contracture of the temporal muscle by displacement when the surgical field is closed. Surgical complications include skin depression due to temporal muscle atrophy and jaw movement disorders such as a limitation of mouth opening and decreased occlusal function. To reduce these side effects, incisional and closed head reconstruction methods have been studied in humans [6, 35], in addition to the importance of protecting muscle tissue during surgery. In the present study, persistent temporal muscle atrophy was observed in three dogs, which may be due to injury from surgical manipulation, as in humans. Even in dogs, the possibility of a limitation of mouth opening cannot be ignored and further study of muscle incision and reconstruction methods should be considered. However, none of the three dogs presented with limited mouth opening and jaw movement postoperatively, and the other two dogs showed no temporal muscle atrophy. Therefore, we believe that even with the present surgical procedure, it is possible to reduce or prevent muscle atrophy by handling the muscle carefully during surgery by moisturizing or releasing the retracted tissue adequately.

In the present study, a convulsive seizure was observed postoperatively in two dogs, but it occurred only once immediately after surgery and was non-repetitive, so it was considered to be a postoperative acute symptomatic seizure (ASS). In human medicine, the incidence of ASS following supratentorial craniotomy is reportedly 15–20%, regardless of the surgical technique or cause of the disease [10]. Therefore, in the present study, we had used levetiracetam, which is safe and easy to use in the short term in dogs [5], to prevent postoperative ASS, however, it could not be prevented as a result. At the present, the utility of preventive administration of ASD for postoperative ASS is controversial and still under investigation [11].

The loss or reduction of postural reactions occurred in Dogs #1 and 3 after surgery. This complication may have been caused by damage to the internal structures (thalamus and internal capsule) in the surgical target area. Dog #1 showed surgery-related damage to the internal capsule, and the reduction of postural reactions persisted throughout the observation period. In Dog #3, there was no damage other than to the resection site on MRI, and the reduction of postural reactions was transient, suggesting that the symptoms were caused by transient pressure or ischemia due to surgical manipulation.

The VTL performed in this study used a mesial temporal lobe approach. Brain tumors such as gliomas in dogs are more likely to develop in mesial temporal structures including the hippocampus, piriform lobe, and amygdala [15, 29, 34, 39, 44]. VTL could be applied not only for the treatment of epilepsy but also for approaches to the temporal lobe region for neoplastic diseases.

The main limitation of this study is that we operated on a small number of normal beagle dogs. As the same breed of dog was used, the difficulty and success rate of VTL in other breeds may differ from those of the present study. However, the purpose of this study was to evaluate the availability and complications of the ATL-like technique in dogs. Finally, to determine the appropriate extent of resection and efficacy of VTL in dog patients with drug-resistant epilepsy, a clinical study based on adequate presurgical evaluations and sufficient informed consent is needed.

CONFLICT OF INTEREST. The authors declare no conflict of interest for this research.

REFERENCES

1. Bagley, R. S., Baszler, T. V., Harrington, M. L., Pluhar, G. E., Moore, M. P., Keegan, R. D. and Greene, S. A. 1995. Clinical effects of longitudinal division of the corpus callosum in normal dogs. *Vet. Surg.* **24**: 122–127. [Medline] [CrossRef]
2. Bertan, V. and Wilson, C. B. 1966. Anatomy of the anterior choroidal artery in the dog. *Arch. Neurol.* **14**: 526–529. [Medline] [CrossRef]
3. Bowles, A. P. Jr. 1999. Reconstruction of the temporalis muscle for pterional and cranio-orbital craniotomies. *Surg. Neurol.* **52**: 524–529. [Medline] [CrossRef]
4. Brotis, A. G., Giannis, T., Kapsalaki, E., Dardiotis, E. and Fountas, K. N. 2019. Complications after anterior temporal lobectomy for medically intractable epilepsy: a systematic review and meta-analysis. *Stereotact. Funct. Neurosurg.* **97**: 69–82. [Medline] [CrossRef]
5. Charalambous, M., Shivapour, S. K., Brodbelt, D. C. and Volk, H. A. 2016. Antiepileptic drugs' tolerability and safety--a systematic review and meta-analysis of adverse effects in dogs. *BMC Vet. Res.* **12**: 79. [Medline] [CrossRef]
6. de Andrade Júnior, F. C., de Andrade, F. C., de Araujo Filho, C. M. and Carcagnolo Filho, J. 1998. Dysfunction of the temporalis muscle after pterional craniotomy for intracranial aneurysms. Comparative, prospective and randomized study of one flap versus two flaps dieresis. *Arq. Neuropsiquiatr.* **56**: 200–205. [Medline] [CrossRef]
7. Epstein, J. A., Lennox, M. A. and Noto, O. 1949. Electroencephalographic study of experimental cerebro-vascular occlusion. *Electroencephalogr. Clin. Neurophysiol.* **1**: 491–502. [Medline] [CrossRef]
8. Evans, E. H. and De Lahunta, A. 2012. Miller's Anatomy of the Dog, 4th ed., Elsevier Science & Technology, Oxford.

9. Fujii, S., Kanasaki, Y., Matsusue, E., Kakite, S., Kminou, T. and Ogawa, T. 2010. Demonstration of cerebral venous variations in the region of the third ventricle on phase-sensitive imaging. *AJNR Am. J. Neuroradiol.* **31**: 55–59. [Medline] [CrossRef]

10. Greenhalgh, J., Weston, J., Dundar, Y., Nevitt, S. J. and Marson, A. G. 2018. Antiepileptic drugs as prophylaxis for postcraniotomy seizures. *Cochrane Database Syst. Rev.* **5**: CD007286. [Medline]

11. Gunawardane, N. and Fields, M. 2018. Acute symptomatic seizures and provoked seizures: to treat or not to treat? *Curr. Treat. Options Neurol.* **20**: 41. [Medline] [CrossRef]

12. Hwang, S. W., Abozed, M. M., Antoniou, A. J., Malek, A. M. and Heilman, C. B. 2010. Postoperative temporalis muscle atrophy and the use of electrocautery: a volumetric MRI comparison. *Skull Base* **20**: 321–326. [Medline] [CrossRef]

13. Jacqmot, O. D., Snaps, F. R., Maquet, N. M., Heinen, M. P. A. and Gabriel, A. E. 2011. Arterial head vascularization cartographies of normal metencephalic dogs using magnetic resonance angiography. *Anat. Rec. (Hoboken)* **294**: 1834–1841. [Medline] [CrossRef]

14. Kerezoudis, P., McCutcheon, B., Murphy, M. E., Rajjoub, K. R., Ubl, D., Habermann, E. B., Worrell, G., Bydon, M. and Van Gompel, J. J. 2018. Thirty-day postoperative morbidity and mortality after temporal lobectomy for medically refractory epilepsy. *J. Neurosurg.* **128**: 1158–1164. [Medline] [CrossRef]

15. Liu, C. H., Liu, C. I., Liang, S. L., Cheng, C. H., Huang, S. C., Lee, C. C., Hsu, W. C. and Lin, Y. C. 2004. Intracranial granular cell tumor in a dog. *J. Vet. Med. Sci.* **66**: 77–79. [Medline] [CrossRef]

16. Long, S., Frey, S., Freestone, D. R., LeChevoir, M., Stypulkowski, P., Giftakis, J. and Cook, M. 2014. Placement of deep brain electrodes in the dog using the Brainsight frameless stereotactic system: a pilot feasibility study. *J. Vet. Intern. Med.* **28**: 189–197. [Medline] [CrossRef]

17. Marino, D. J., Dewey, C. W., Loughin, C. A. and Marino, L. J. 2014. Severe hyperthermia, hypernatremia, and early postoperative death after transethmoidal cavitron ultrasonic surgical aspirator (CUSA)-assisted diencephalic mass removal in 4 dogs and 2 cats. *Vet. Surg.* **43**: 888–894. [Medline] [CrossRef]

18. Martlé, V., Van Ham, L., Raedt, R., Vonck, K., Boon, P. and Bhatti, S. 2014. Non-pharmacological treatment options for refractory epilepsy: an overview of human treatment modalities and their potential utility in dogs. *Vet. J.* **199**: 332–339. [Medline] [CrossRef]

19. Martlé, V., Van Ham, L. M. L., Boon, P., Caemaert, J., Tshamala, M., Vonck, K., Raedt, R., Polis, I. and Bhatti, S. 2016. Vagus nerve stimulator placement in dogs: surgical implantation technique, complications, long-term follow-up, and practical considerations. *Vet. Surg.* **45**: 71–78. [Medline] [CrossRef]

20. McIntosh, A. M., Kalnins, R. M., Mitchell, L. A., Fabinyi, G. C. A., Briellmann, R. S. and Berkovic, S. F. 2004. Temporal lobectomy: long-term seizure outcome, late recurrence and risks for seizure recurrence. *Brain* **127**: 2018–2030. [Medline] [CrossRef]

21. Missori, P., Paolini, S., Ciappetta, P., Seferi, A. and Domenicucci, M. 2013. Preservation of the temporal muscle during the frontotemporoparietal approach for decompressive craniectomy: technical note. *Acta Neurochir. (Wien)* **155**: 1335–1339. [Medline] [CrossRef]

22. Muñana, K. R. 2013. Management of refractory epilepsy. *Top. Companion Anim. Med.* **28**: 67–71. [Medline] [CrossRef]

23. Oliver, J. E. Jr. 1965. Surgical relief of epileptiform seizures in the dog. *Vet. Med. Small Anim. Clin.* **60**: 367–368. [Medline]

24. Radhakrishnan, A., Menon, R., Abraham, M., Vilanilam, G., Sharma, S., Thomas, B., Kesavadas, C., Cherian, A., Varma, R. and Thomas, S. V. 2018. Predictors of outcome after surgery in 134 children with drug-resistant TLE. *Epilepsy Res.* **139**: 150–156. [Medline] [CrossRef]

25. Ryvlin, P., Montavont, A. and Kahane, P. 2005. The impact of epilepsy surgery on mortality. *Epileptic Disord.* **7** Suppl 1: S39–S46. [Medline]

26. Sager, M., Assheuer, J., Trümmler, H. and Moormann, K. 2009. Contrast-enhanced magnetic resonance angiography (CE-MRA) of intra- and extra-cranial vessels in dogs. *Vet. J.* **179**: 92–100. [Medline] [CrossRef]

27. Sander, J. W. 1993. Some aspects of prognosis in the epilepsies: a review. *Epilepsia* **34**: 1007–1016. [Medline] [CrossRef]

28. Schaller, K. and Cabrilo, I. 2016. Anterior temporal lobectomy. *Acta Neurochir. (Wien)* **158**: 161–166. [Medline] [CrossRef]

29. Scott, S. J., Elliot, K., Philibert, H., Summers, B. A., Godson, D., Singh, B. and Simko, E. 2015. An unusual lipomatous brain mass in a Golden Retriever dog. *J. Vet. Diagn. Invest.* **27**: 772–776. [Medline] [CrossRef]

30. Seymour, N., Granbichler, C. A., Polkey, C. E. and Nashef, L. 2012. Mortality after temporal lobe epilepsy surgery. *Epilepsia* **53**: 267–271. [Medline] [CrossRef]

31. Shan, Y. Z., Wang, Z. M., Fan, X. T., Zhang, H. Q., Ren, L. K., Wei, P. H. and Zhao, G. G. 2019. Automatic labeling of the fanning and curving shape of Meyer's loop for epilepsy surgery: an atlas extracted from high-definition fiber tractography. *BMC Neurol.* **19**: 302. [Medline] [CrossRef]

32. Shihab, N., Summers, B. A., Benigni, L., McEvoy, A. W. and Volk, H. A. 2014. Novel approach to temporal lobectomy for removal of a cavernous hemangioma in a dog. *Vet. Surg.* **43**: 877–881. [Medline] [CrossRef]

33. Sindou, M., Guenot, M., Isnard, J., Ryvlin, P., Fischer, C. and Mauguière, F. 2006. Temporo-mesial epilepsy surgery: outcome and complications in 100 consecutive adult patients. *Acta Neurochir. (Wien)* **148**: 39–45. [Medline] [CrossRef]

34. Smith, S. H. and Van Winkle, T. 2001. Cerebral vascular hamartomas in five dogs. *Vet. Pathol.* **38**: 108–112. [Medline] [CrossRef]

35. Takigami, M., Higashiyama, N., Iihoshi, S., Sohma, T. and Nakamura, E. 2006. How to prevent a limitation of mouth opening following fronto-temporal craniotomy. *Surg. Cereb. Stroke* **34**: 355–359. [CrossRef]

36. Tanaka, T., Akiyoshi, H. and Mie, K. 2018. Anatomical variations in the circle of Willis in canines. *Anat. Histol. Embryol.* **47**: 609–612. [Medline] [CrossRef]

37. Téllez-Zenteno, J. F., Hernández Ronquillo, L., Moien-Afshari, F. and Wiebe, S. 2010. Surgical outcomes in lesional and non-lesional epilepsy: a systematic review and meta-analysis. *Epilepsy Res.* **89**: 310–318. [Medline] [CrossRef]

38. The International League Against Epilepsy. 1997. A global survey on epilepsy surgery, 1980–1990: A report by the commission on neurosurgery of epilepsy, the international league against epilepsy. *Epilepsia* **38**: 249–255. [Medline] [CrossRef]

39. Thomovsky, S. A., Packer, R. A., Burcham, G. N. and Heng, H. G. 2011. Imaging diagnosis-magnetic resonance imaging features of metastatic cerebral lymphoma in a dog. *Vet. Radiol. Ultrasound* **52**: 192–195. [Medline] [CrossRef]

40. Uddin, M. A., Haq, T. U. and Rafique, M. Z. 2006. Cerebral venous system anatomy. *J. Pak. Med. Assoc.* **56**: 516–519. [Medline]

41. van Lanen, R. H. G. J., Hoeberigs, M. C., Bauer, N. J. C., Haeren, R. H. L., Hoogland, G., Colon, A., Piersma, C., Dings, J. T. A. and Schijns, O. E. M. G. 2018. Visual field deficits after epilepsy surgery: a new quantitative scoring method. *Acta Neurochir. (Wien)* **160**: 1325–1336. [Medline] [CrossRef]

42. Walker, A. E. 1967. Temporal lobectomy. *J. Neurosurg.* **26**: 642–649. [Medline] [CrossRef]

43. West, S., Nevitt, S. J., Cotton, J., Gandhi, S., Weston, J., Sudan, A., Ramirez, R. and Newton, R. 2019. Surgery for epilepsy. *Cochrane Database Syst. Rev.* **6**: CD010541. [Medline]

44. Young, B. D., Levine, J. M., Porter, B. F., Chen-Allen, A. V., Rossmeisl, J. H., Platt, S. R., Kent, M., Fosgate, G. T. and Schatzberg, S. J. 2011. Magnetic resonance imaging features of intracranial astrocytomas and oligodendrogliomas in dogs. *Vet. Radiol. Ultrasound* **52**: 132–141. [Medline] [CrossRef]

45. Zilli, J., Kressin, M., Schänzer, A., Kampschulte, M. and Schmidt, M. J. 2021. Partial cortico-hippocampectomy in cats, as therapy for refractory temporal epilepsy: A descriptive cadaveric study. *PLoS One* **16**: e0244892. [Medline] [CrossRef]