Chiari-like malformation (CM) in dogs is a complex developmental abnormality of the craniocervical junction, characterized by rostrocaudal shortening and sphenoo-occipital angulation of the skull base, reduced occipital crest, occipital bone hypoplasia, decreased caudal fossa volume, and rostral shift of the atlas and axis. This leads to overcrowding of the caudal fossa, resulting in displacement of the neural parenchyma, compression of the hindbrain or cerebellum, displacement of the caudoventral portion of the cerebellar vermis through the foramen magnum, and pressure alteration of CSF flow, which results in a fluid-filled cavity within the spinal cord, typically in the cervical portion, known as syringomyelia (SM).

CM commonly affects brachycephalic small-breed dogs, especially Cavalier King Charles Spaniels and Brussels Griffon, as well as Chihuahuas and Yorkshire Terriers. Neuropathic pain and phantom scratching (i.e., a tendency to scratch toward one shoulder or neck region without skin contact) are common clinical signs secondary to CM-SM; in the most severe cases, scoliosis and paraplegia have also been reported. Medical treatment, with the primary aim of reducing CSF production and pain, has been reported with variable success rates. Overall, almost 75% of patients exhibit a progression of the clinical signs.

Surgical management of CM via foramen magnum decompression (FMD), which is subsequently associated with partial dorsal C1 laminectomy, is among the most effective treatments reported in veterinary literature.
scribed the use of titanium mesh covered with polymethylmethacrylate (PMMA) for treatment, with a rate of repeated surgery < 1%. However, some patients require adjunctive medical treatment for their entire life. The use of a customized titanium prosthesis has been previously described in veterinary literature concerning restoration of skull anatomy after removal of bony tumors. To the authors' knowledge, no previous reports exist of CM-SM in dogs treated with FMD and occipital cranioplasty using customized titanium prostheses. Therefore, the purposes of the present study were to describe the use of a customized cranioplasty implant for the treatment of CM in dogs, assuming it may help in medium- to long-term outcomes by minimizing the risk of relapses, to analyze the feasibility of this type of implant, and to report outcomes of implant use in a specific group of dogs.

Materials and Methods

Dogs

Dogs were included in the study if they were admitted to the Diagnostica Piccoli Animali between January 2017 and December 2019, had CM-SM treated by FMD and occipital cranioplasty using a customized prosthesis, and had at least 1 year of follow-up.

Data collection

Signalment, history, neurological signs, duration, and MRI findings for each dog were retrospectively evaluated and recorded. Previous treatment, in particular the drugs used and the duration and efficacy of those drugs, was also recorded. Dogs were scored based on a previously used system as no pain and phantom scratching (grade 0), occasional (< once per week) signs of pain or yelping (grade 1), mild neuropathic pain (grade 2), moderate neuropathic pain (grade 3), severe neuropathic pain (grade 4; Supplementary Appendix S1). The frequency of phantom scratching was also scored, according to the data provided by the owner, as ≤ 1 episode/wk (grade 1), ≥ 2 episodes/wk (grade 2), once or twice daily (grade 3), or more than twice daily (grade 4). Other causes of scratching were excluded based on dermatological examination.

All MRI scans were performed using either a 0.27-T (ESAOE Vet-MRGrande) or 1.5-T (Achieva; Philips Healthcare) scanner and included both T1- and T2-weighted images of the whole brain and cervical vertebral column acquired in the sagittal and transverse planes. Additional images, such as post-contrast T1 images or scans of the thoracolumbar vertebral column were also evaluated when available. The degree of CM-SM was graded according to the British Veterinary Association scheme and ranged from grade 0 to 2 (Supplementary Appendix S2). Cerebrospinal fluid was collected from the lumbar cistern if an inflammatory disease was suspected based on clinical signs or MRI images. Dogs were excluded from the study if any craniocervical changes other than CM-SM were observed, except for the occurrence of mild hydrocephalus or a dural band, which may be encountered in small brachiocephalic dogs.

Prosthesis design

Computed tomography was performed on a 16-slice scanner (Optima 520 series; GE Healthcare) in helical acquisition mode, with a slice thickness of 1.25 mm (reconstruction interval, 0.6 mm). The dogs were positioned in sternal recumbency, with the head aligned with the cervical vertebral column. The CT images were reconstructed with a high-resolution filter for bone and were processed using a DICOM viewer (Osirix version 5.8; Pixmeo SARL).

The 3-D reconstruction was used to simulate the occipital craniectomy and to design the prosthesis, with the goal of covering the bone defect and enlarging the caudal fossa. In the simulation (Mimics 20.0 and Magics 23.01; Materialise NV, and Geomagic Freeform 2019.01.67; 3DSystme Inc), 3 holes were created to anchor the implant on the thickest aspect of the occipital bone (Figure 1). Based on the simulated model, a 0.6-mm-thick titanium prosthesis was created using direct metal laser sintering technology (Eosint M 280; EOS GmbH, and CORITEC 350 I; IMES-ICORE GmbH).

The prosthesis had a triangular shape, with the apex at the level of the external occipital protuberance and the base approximately 1 mm above the C1 arch. The lateral margins of the prosthesis covered the inner borders of the occipital bone and followed them ventrally to the occipital condyles. Each prosthesis was rounded and smoothed to avoid any potential damage to the neural structure and surrounding soft tissue. The implant curvature followed the rostrocaudal shape of the skull. The implant surface was perforated with holes ranging from 0.8 to 1.2 mm in diameter, to facilitate surrounding soft-tissue integration (Figure 2). A 3-D polyamide anatomic model of the skull of each patient was also created using selective laser sintering technology (Jet Fusion 3D 4200; Hewlett-Packard). These 3-D models were sterilized for intraoperative use as a reference for craniectomy and optimum prosthesis-screw positioning (Figure 3).

Surgical procedure

A single surgeon (CF) performed all surgeries. All dogs were positioned in sternal recumbency, with the head flexed and restrained with tape to avoid undesired movement. The surgical approaches to the craniocervical junction and FMD were performed as previously described. However, the craniectomy was enlarged bilaterally to expose the caudal and most medial aspects of both cerebellar hemispheres. The atlanto-occipital membrane, the meninges covering the caudal aspect of the cerebellum, and any adhesions were gently removed from the cerebellar vermis to allow caudal dislocation of the cerebellum (Figure 4). The sterilized 3-D model of the skull was used to guide the craniectomy and to place the prosthesis. The prosthesis was placed on the skull and was used as a guide to...
create the three screw holes. Three 1.5 mm flat head titanium screws were used to fix the prosthesis to the bone. The screw lengths were calculated on the preoperative CT images, and ranged from 4 to 6 mm for all patients.

**Follow-up**

Immediately after surgery, orthogonal radiographs, CT images of the craniocervical junction, or both were obtained to evaluate the positioning of the prosthesis. Follow-up neurological examinations were scheduled at 1, 6, and 12 months after surgery. Data for additional follow-up examinations were recorded when available. Based on the clinical score given upon the preoperative examination, each patient was classified as improved (if the clinical score was reduced by at least 1 degree), worsened (if the clinical score was increased by at least 1 degree), unchanged (if no improvement or deterioration was noticed), or normal (if the clinical signs completely resolved). Data regarding scratching frequency, pain intensity, and postoperative drug administration were recorded. Repeated MRI scans were also requested a minimum of 6 months after surgery to compare changes in cerebellar shape and maximum transverse syrinx width with the preoperative dimensions. Based on this comparison, the syrinx was categorized as decreased, worsened, unchanged, or resolved.

**Complications**

Complications related to the implant or surgical procedure had been recorded in the medical records. Complications were classified as minor when surgical revision was not necessary, or major if revision surgery was required. Complications were classified as short-term if they developed within the first month following surgery, and long-term if they developed after the first month.

**Results**

**Dogs**

A total of 8 dogs were included in the study. There were 6 Cavalier King Charles Spaniels and 2 Chihuahuas, with an equal distribution of males and females. Median and mean age at the time of surgery were 35 months and 34 months, respectively (range, 14 to 77 months). All dogs presented with cervical hyperesthesia and excessive scratching; the duration of clinical signs prior to surgery ranged from 2 months to 5 years. On neurological examination, 3 dogs were scored as grade 2 (cases 2, 4, and 5), 4 as grade 3 (cases 1, 3, 6, and 7), and 1 as grade 4 (case 8; **Supplementary Table S1**). Cases 2 and 6 exhibited a reduced menace response and a proprioceptive deficit in the left hind limb, respectively.

Medications administered before surgery were summarized (**Supplementary Table S2**). These included a combination of prednisone (0.5 mg/kg, q 12 h, PO for cases 1, 2, 4, 5, 6, and 8), carprofen (2 mg/kg, q 12 h, PO for case 3), meloxicam (0.1 mg/kg, q 24 h, PO for case 7), tramadol (3 to 4 mg/kg, q 12 h, PO for cases 1, 4, 6, and 8), gabapentin (10 mg/kg, q 8 to 12 hours, PO for cases 1, 2, 3, 5, 6, 7, and 8), acetazolamide (4 mg/kg, q 24 h, PO for case 6), and PEA-q (Alevica; Innovet Italy; half tablet each, PO).

Each dog had exhibited progression of clinical signs, and the owners...
considered the initial medical treatment response to be unsatisfactory. Seven dogs underwent examination with low-field MRI and 1 dog (case 8) with high-field MRI. Based on MRI images, CM was rated as grade 1 in 2 dogs (cases 3 and 4) and grade 2 in the remaining 6 dogs. The SM was rated grade 1 in 2 dogs (cases 3 and 7), and grade 2 in the remaining 6 dogs. Maximum syrinx length ranged from a single vertebral body to a span of C2-L5, with a median maximum transverse width of 3.4 mm (range, 1 to 7.3 mm; Supplementary Table S3). Mild bilateral middle ear effusion was reported and considered incidental in cases 6 and 7. In 2 dogs, CSF examination was performed and showed no important abnormalities.

Each dog received methadone (0.3 mg/kg, IM) before anesthesia was induced with propofol (2 to 4 mg/kg, IV). Anesthesia was maintained using inhaled isoflurane and oxygen. Isoflurane vaporizer settings ranged from 1.5 to 2.5%, and the dogs were mechanically ventilated. Cefazolin (25 mg/kg, IV) was administered just before surgery and every 90 minutes throughout. The mean ± SD surgical time was 110 ± 43 minutes.

Postoperative period

All 8 dogs showed optimal prosthesis positioning on the radiographs (cases 1, 6, and 8) or CT images (cases 2 through 8) obtained immediately after surgery (Figure 5). Postoperatively, all patients received methadone (0.2 mg/kg, q 4 h, IM for the first 24 hours), followed by tramadol (2 mg/kg, q 8 h, IM for another 24 hours and then q 12 h for 3 to 5 days, PO); cefalexin (25 mg/kg, q 12 h, PO for 5 days); gabapentin (10 mg/kg, q 8 to 12 hours, PO for 2 weeks); and prednisone (0.5 mg/kg, q 12 h, PO for 5 days), after which the dose of prednisone was progressively decreased and discontinued within a month. All dogs were discharged from the hospital within 24 hours to 5 days after surgery. Cases 7 and 8 exhibited mild cerebellar ataxia immediately after surgery, which resolved within 1 and 2 weeks, respectively.

Follow-up

At the 1-month follow-up examination, 7 dogs showed complete resolution of the clinical signs (grade 0), whereas in 1 dog (case 8), both pain and scratching had improved, although they were still present (grade 1). All drugs were discontinued 1 month after surgery in 6 dogs (cases 2, 3, 4, 5, 6, and 7), although 2 dogs continued medication (prednisone, 0.5 mg/kg, q 48 h, PO for case 1; and prednisone, 0.5 mg/kg, q 48 h, PO plus gabapentin, 10 mg/kg, q 12 h, PO for case 8), with a daily dosage that was substantially reduced compared to the preoperative levels (Supplementary Table S2).

At the 6-month follow-up examination, clinical signs remained resolved without any medical treatment (grade 0) in 3 dogs (cases 2, 3, and 7), and 2 dogs (cases 1 and 8) were considered unchanged from the 1-month follow-up point (grades 0 and 1, respectively). Three dogs were scored as grade 1 (cases 4, 5, and 6) because they experienced mild worsening with phantom scratching and pain relapse; therefore, medical treatment was reintroduced (Supplementary Table S2). However, the severity of the clinical signs and the overall number and dosages of drugs were significantly reduced compared to those preoperatively, and all dogs had improvement with respect to the preoperative assessment.

At the 12-month follow-up examination, 3 dogs (cases 2, 3, and 7) were free of medications with complete resolution of clinical signs. The remaining 5 dogs were considered unchanged or only mildly improved compared with the 6-month follow-up point and were still receiving: continuous (case 8) or pulsatile medication (cases 4, 5, and 6) due to relapsing episodes of pain or scratching. However, compared with the preoperative neurological status, the frequency and intensity of the episodes of scratching and pain decreased by more than 50%, the drug dosages were overall reduced, and the dogs were eventually considered improved compared with the preoperative assessment, and scored as grade 1.

Seven dogs (cases 1 to 7) had an additional follow-up examination between 16 and 52 months after surgery, with an overall mean follow-up time of 28.5 months (range 12 to 52 months). Clinical signs and medications were considered unchanged compared with findings of the 12-month
This retrospective study provided a description of the use of customized titanium prostheses in association with FMD as an alternative treatment for CM-SM in dogs.

In the last decade, the surgical management of the CM-SM complex in dogs has been discussed, and is often considered partially satisfactory because the published data have not documented long-term persistent improvement or sustained reductive effect of the syrinx postoperatively. The relapse rate with other surgical techniques of clinical signs was approximately 25% to 50%, and the syrinx size, when evaluated, was considered unchanged at both short- and long-term follow-up points, except for a slight reduction in 1 patient. Possible explanations for the relapse include insufficient removal of the supraoccipital bone or inability of the chronic syrinx to collapse. Scar tissue formation at the site of bone removal, compression of the cerebellum, or prevention of the restoration of a normal CSF flow. This last listed explanation would most likely be secondary to the incomplete removal of the hypertrophic meninges and atlanto-occipital membrane, or to the use of graft or sponge to cover the meningeal defect, potentially leading to adhesion or compression at the craniovertebral junction.

Cranioplasty using titanium mesh and PMMA to cover bony defects has already been proposed, with the aim of preventing the formation of constrictive tissue, and substantial recurrence necessitating revision surgery was reported. It was supposed that scar tissue formation with new cerebellar compression could be the cause of relapse after surgical treatment of CM; it was also suggested that a prosthesis could prevent this major issue.

Our data, although collected from only 8 dogs, is of interest for CM-SM in dogs. FMD as an alternative treatment for CM-SM was considered partially satisfactory in dogs has been discussed, and is often considered partially satisfactory because the published data have not documented long-term persistent improvement or sustained reductive effect of the syrinx postoperatively. The relapse rate with other surgical techniques of clinical signs was approximately 25% to 50%, and the syrinx size, when evaluated, was considered unchanged at both short- and long-term follow-up points, except for a slight reduction in 1 patient. Possible explanations for the relapse include insufficient removal of the supraoccipital bone or inability of the chronic syrinx to collapse. Scar tissue formation at the site of bone removal, compression of the cerebellum, or prevention of the restoration of a normal CSF flow. This last listed explanation would most likely be secondary to the incomplete removal of the hypertrophic meninges and atlanto-occipital membrane, or to the use of graft or sponge to cover the meningeal defect, potentially leading to adhesion or compression at the craniovertebral junction.

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the design of the prosthesis allowed the surgeon to insert the screws in the thickest bone, ensuring that the implant would maintain its position and remain stable during the postoperative period as well as avoiding potential harm to the underlying neural structures. The curvature of the implant was established during the design stage and allowed for the enlargement of the caudal-cranial fossa to better accommodate the cerebellum. Other differences of titanium versus PMMA include the reduced thickness of the implant and the relationship between its external surface and the surrounding soft tissue. The perforated surface encouraged soft tissue integration, reducing localized inflammation caused by friction and the potential for seroma or excessive scar formation. The holes also allowed for the drainage of liquids, such as CSF or blood, from the surgical site, avoiding cerebellar compression. Finally, the implant material is characterized by higher biocompatibility and osseointegration as well as bone-like elasticity and strength, and it is also associated with lower susceptibility to infection. Although artifacts due to the metal nature of the implant made it difficult to evaluate the postoperative MRI images, the use of different sequences on different planes and the comparison of pre- and postoperative images allowed us to rule out a residual or new compression of the cerebellum in all cases.

Because of the detailed planning of the surgery and creation of the 3-D model, and therefore the design of the customized prosthesis for each individual patient, the surgical technique as reported herein was safe, with no major complications and an excellent correspondence between the model and the surgical scenario. A fundamental point in the planning and creation of the prosthesis was to establish its dorsoventral length to avoid possible compression of the medulla oblongata or cranial-cervical spinal cord. For this reason, it was important to standardize the positioning of patients during the CT examination, which in our experience can be achieved by placing the head and cervical spine aligned in the same horizontal plane.

No short- or long-term complications due to the prostheses were found in the present study; intraoperative bleeding was the only complication that occurred during surgery, and it was easily controlled. In the immediate postoperative period, only 2 patients showed mild and transient cerebellar ataxia, likely due to cerebellar manipulation during adhesion removal. All dogs included in the study remained alive at final follow-up; thus, no information about histologic changes between the bone, surrounding soft tissue, and integration of the implant was available. However, no inflammation or excessive soft tissue reaction was found on clinical examination or detected on repeated MRI scans.

The craniectomy procedure was mildly modified from the previously described technique because it needed to be enlarged bilaterally to expose the medial aspect of the cerebellar hemispheres, and the vermis was then totally freed from the hypertrophic membrane, meninges, and adhesions. Although this procedure may result in cerebellar damage and consequent ataxia-related deterioration, the latter tends to resolve spontaneously within a few weeks, and we felt it necessary to possibly restore normal cerebellar size and CSF flow. These modifications, in addition to the use of the prosthetic implant, could explain the different results between our study and previously published data. Moreover, we believe that the opportunity to plan the surgery using a 3-D volume-rendering software, along with the intraoperative use of a 3-D model of the craniocervical junction in association with the prosthesis to accurately create the holes, may have improved the final results by minimizing the risk of damaging the neural tissue or any other complications.

All dogs in the present study showed improvement in clinical signs, with 3 of them returning to full neurological function at the long-term follow-up point. Some dogs still required continuous or regular medical treatment, although a smaller number and dosage of drugs were required, compared with the preoperative period. All dogs except for one experienced substantial long-term improvement in the quality of life. Comparing the results of our study with the data previously reported, we concluded that the main purpose of the surgical treatment is to improve the quality of life of patients with a poor response to the medical treatment. Although severe adverse effects may develop after long-term steroid administration, none of the dogs in our study developed major problems. Moreover, the amounts of medications administered and their dosages were able to be substantially reduced, decreasing the risk of side effects in the long time period. The long-term outcomes were also influenced by the preoperative duration of the clinical signs and the syrinx width. Patients with clinical signs lasting longer than 2 years and a maximum syrinx width > 5.7 mm had a worse outcome, with poor scratching and pain control, despite concomitant medical treatment, as observed in the present study in cases 6 and 8. Of the 8 dogs included in the present study, the syrinx resolved in 1 dog, and 3 dogs displayed a reduction in the syrinx width, which may have been related to the preoperative size of the syrinx, with better results in small syringes. Although definitive conclusions could not be drawn based on our small number of cases, early surgical treatment with smaller syrinx may ensure better long-term outcome, as previously suggested. However, the possibility of a false reduction of the syrinx size due to sectioning on low field MRI or human error could not be excluded. The use of steroid medications may further have modified the MRI appearance of the syringes, especially those of the presyringes, decreasing the edema. For this reason, any changes or improvements observed on MRI should be considered a consequence of the surgical procedure and medical treatment.

A limitation of the present study was the lack of repeated MRI in 3 patients; the owners of these dogs refused further investigation because they
felt it unnecessary due to the satisfactory improvement.

Furthermore, the use of 2 different MRI fields could potentially represent a bias in the syrinx evaluation, although the quality of the images was good enough with low field MRI to accurately measure the syrinx size. Moreover, due to the retrospective nature of this study, we were unable to properly correlate the clinical signs and especially the phantom scratching with the MRI findings in 3 dogs (cases 1, 3, and 7), since they lacked a severe dorsal horn involvement which is usually behind the scratching itself.

Although the present study included only 8 dogs and our results should therefore be interpreted cautiously, our findings suggested that modified FMD procedure that includes occipital cranioplasty using a customized titanium prosthesis is a safe technique and could be considered in the future as an adjunctive option for the treatment of CM and SM in refractory cases. Further studies with larger sample sizes are necessary to confirm the long-term efficacy of this technique.

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**Supplementary Materials**

Supplementary materials are posted online at the journal website: avmajournals.avma.org