Soft-helmet skull remodeling in canine models: intracranial volumeunchanged by compensatory skull growth

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Object. Habitual sleeping positions in infants can produce occipital plagiocephaly, which causes strabismus as well as skull and facial asymmetry. This condition can be managed using a hard helmet, but maintaining an infant in such a device is often intolerable. The authors studied whether the shape of a young canine skull could reform while inside a soft helmet and whether intracranial volume would be preserved by the compensatory growth of the skull.

Methods. The authors tracked the head sizes of 14 1-week-old beagles who wore long, soft helmets (study group) and seven beagles who did not (control group). From these measurements, the intracranial volume in each beagle was calculated. All crania were also studied radiologically by using plain skull radiography, computerized tomography (CT), and magnetic resonance (MR) imaging.

The crania of all 14 beagles who wore soft helmets quickly adapted, resulting in a narrow, long head only 2 weeks into the experiment. This configuration continued to develop throughout the 7-week experimental period. At 8 weeks of age, animals in the study group showed no significantly different alteration in calculated intracranial volumes (p > 0.05). It is interesting that the helmet-treated animals initially underwent a paradoxical increase in intracranial volume growth. No structural difference in their brains was evident from CT or MR imaging findings, nor was there any functional disability.

Conclusions. Intracranial volume can be preserved by the compensatory growth of the skull during successful remodeling of the developing skull achieved using a soft helmet.

Key Words • positional plagiocephaly • skull orthosis • helmet • skull remodeling • intracranial volume • pediatric neurosurgery • dog

Even in the absence of developmental delay or anomalous fusion of posterior skull bones, many infants who sleep supine develop occipital asymmetry, that is, positional plagiocephaly.10 In most affected infants, this condition resolves spontaneously, but in some cases it persists and, when modification of the sleep position is ineffective, positional plagiocephaly results in craniofacial asymmetry and developmental delay.23,30 Moreover, surgical intervention in infants entails the possibility of serious complications and therefore is rarely performed.7 Recently, the introduction of molding-helmet therapy has afforded a nonsurgical alternative that is safer and easier to perform.25,28,41

Clarren, et al.,4 developed the first molding helmet that passively led to compensatory growth because of the flat area of the skull no longer was compressed. Ripley, et al.,41 revised the molding helmet not only to prevent compression of the flat area but also to compress the protuberant area. This helmet is the so-called active or dynamic orthosis. The materials used in these molding helmets are hard, however, and active compression can lead to complications such as pressure sores,17 neurodevelopmental delay,33 and poor compliance of the infant, resulting in difficulty in clinical applicability. As a result of their attempts to overcome these problems, Bruner, et al.,7 reported a high compliance rate of 88% through the use of a new soft-molding helmet, but they did not adequately describe the character of their helmet, which compresses the skull area of compensated growth, and they did not supply a means of verifying the safety of such procedures. In our study, we attempted to ascertain whether cranial remodeling by a soft molding helmet is effective and safe by evaluating cranial growth and volume changes in an animal model.

Materials and Methods

The helmet used in this study consisted of a soft inner layer made of polyethylene foam and a hard outer layer made of ethylene vinyl acetate fused under high pressure. To minimize skin irritation and enhance ventilation, an additional layer of fine textile mesh was added to the inner foam layer. The helmet had an open top for ventilation (Fig. 1). The size of the helmet was determined by consecutive measurements of the width and length of the cranium in a beagle whose growth pattern was normal. These dimensions were then adjusted so that the biparietal width of the helmet was the same as the mean width of normal beagle heads and the anteroposterior length was 30% longer than the mean length. In young dogs the soft molding helmet gently compressed both parietal areas while leaving sufficient room in the frontal and occipital areas.

We applied a series of these soft, cap-like helmets to 14 1-week-old beagles (the study group) in increasingly greater anteroposterior...
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Fig. 1. Photograph showing soft helmets of various sizes for young beagles. The soft molding helmet consisted of a soft inner layer of polyethylene and a hard outer layer of ethylene vinyl acetate, both of which were fused under high pressure.

Fig. 2. Graph depicting measurements of maximal cranial length. The mean maximal cranial lengths measured from the glabella to the opisthocranium (the most prominent posterior point of the occiput), at the beginning and end of the 1st week the dogs wore the soft helmet, were 4.59 ± 0.3 and 5.45 ± 0.3 cm in the study group and 4.51 ± 0.21 and 5.29 ± 0.2 cm in the control group, respectively. There was no statistically significant difference in cranial lengths between the beginning and end of the 1st week in either group (p = 0.51 for the treated group and p = 0.24 for the control group). At the end of the 2nd week of helmet application, however, the mean difference in the mean maximal cranial lengths between the two groups was significant (study group 6.03 ± 0.29 cm; control group 5.52 ± 0.13 cm; p < 0.001), and at the end of the 7th week we observed that the maximal cranial length was 7.47 ± 0.23 cm in the study group and 6.71 ± 0.14 cm in the control group, demonstrating a significant increase in cranial length for the former (p = 0.017; Fig. 2).

The maximal cranial width measured from euryon to euryon (the most lateral points on the head) after only 1 week of helmet application demonstrated that cranial growth was restricted horizontally. In the 1st weeks in the control group, the mean horizontal growth was 0.7 cm, whereas in the study group it was only 0.08 cm (p = 0.002). This restriction of cranial growth in the helmet-wearing group was observed continuously up to the 7th week of the study (p = 0.002).

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The mean head circumference as measured from the ophryon to the opisthocranium was 15.33 ± 1.07 cm in the study group and 15.36 ± 1.16 cm in the control group, demonstrating no significant difference at the outset. This similarity continued throughout the 7 weeks. At the 7th week, the head circumference was 21.17 ± 1.04 cm in the study group and 20.86 ± 0.99 cm in the control group (p = 0.69; Fig. 4).

The mean auricular head height from the porion (the most superior point on the upper margin of the external auditory meatus) to the vertex was measured to determine the intracranial volume, which was 2.40 ± 0.31 cm in the study group and 2.21 ± 0.25 cm in the control group at the outset (p = 0.25). The measurements differed in a statistically significant manner during the 2nd week (3.18 ± 0.40 cm in the study group and 2.61 ± 0.16 cm in the control group, p =...
0.005). This difference persisted for all 7 weeks. Finally, the mean auricular head height was greater by 0.77 cm in the study group compared with the control group at the 7th week, a significant difference (p = 0.026; Fig. 5).

**Calculated Ratio and Intracranial Volume.** The ratio of maximal cranial length to width was similar in the two groups during the 1st week (p = 0.068), but by the 2nd week this ratio had a value of 1.28 ± 0.06 in the study group, which was significantly greater than the 1.04 ± 0.02 value for the control group (p < 0.001). This increased ratio in the study group compared with that in the control group was maintained continuously for 7 weeks. At the final week, this ratio was 1.45 in the study group, which was significantly greater than the 1.07 figure for the control group (p = 0.004)—indicating that the cranial length significantly increased anteroposteriorly at the end of the study period. We observed an increased ratio of maximal cranial length to width during the study period, demonstrating that cranial remodeling, even in terms of height, begins within 1 week of soft-helmet application (Fig. 6).

The intracranial volume was calculated using the maximal cranial lengths and widths in combination with auricular head heights. We found no difference between the study and control groups initially and during the 1st week (p = 0.446 and 0.448, respectively). Interestingly, the intracranial volume in the study group increased more than that in the control group from the 2nd through the 4th weeks (p = 0.026, 0.005, and 0.029 for each week, respectively); however, the intracranial volume increases in the two groups were similar during the later study period (p = 0.711, 0.146, and 0.222, respectively). The volume increase in the study group was paradoxically more rapid than in the control group during the 2nd to 4th weeks, but from the 5th week this rate of growth decreased to the normal growth rate observed in the control group (Fig. 7).

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**Fig. 4.** Graph depicting measurements of head circumference. All through the 7 weeks, the mean head circumference was nearly identical between the helmet and control groups, even though significant differences developed in the cranial length, width, and height.

**Fig. 5.** Graph depicting measurements of auricular head height. The mean auricular head height from the porion to the vertex was measured to determine the intracranial volume, and our data revealed that it was similar between the study and control groups initially (p = 0.25), but it became statistically different during the 2nd week (p = 0.005). This difference was maintained for all 7 weeks.

**Fig. 6.** Graph depicting the ratio of maximal cranial length to width. The mean ratio of maximal cranial length to width was similar between the two groups during the 1st week (p = 0.068), but by the 2nd week, this ratio was significantly greater for the study group than it was for the control group (p < 0.001). This increased ratio of the study group was maintained continuously for 7 weeks.

**Fig. 7.** Graph depicting measurements of intracranial volume. The intracranial volume was calculated from the maximal cranial length and width and the auricular head height, and it was similar in both groups initially and during the 1st week. From the 2nd to the 4th weeks, however, the intracranial volume in the study group paradoxically increased more than that in the control group.
Morphological Comparison

Using visual observation (Fig. 8) as well as three-dimensional CT scanning (Fig. 9), we noted that after 7 weeks of helmet application, the anteroposterior lengths of the crania were increased and the widths of the crania decreased in the study group, compared with crania in the control group, giving the heads of the helmeted dogs a dolichocephalic appearance. No morphological difference in the brain parenchyma in either group was discerned on MR imaging (Fig. 10).

Motor Function and Compliance. In the study group of dogs wearing the soft molding helmet, there was no difference with respect to measures of height, weight, systemic growth, 5-m walking, and 10-m running compared with animals in the control group at both the start and completion of the study (data not shown). No complications (such as pressure sores) were found that were attributed directly to the helmet.

Discussion

Incidence and Adverse Effect of Positional Plagiocephaly

The incidence of brachycephaly due to true lambdoidal synostosis is less than 2 to 3%,21 and most cases are caused by positional head deformities. Because there is no clear numerical definition, the reported incidence varies widely, ranging from 0.3 to 25%;3,11,13 and it has been reported to be 1.46% when accompanied by severe facial anomalies.29 The incidence of positional head deformity (positional plagiocephaly) according to age has also been shown to be variable. It is reported to be 13 to 16% at birth, but at 4 months of age the incidence peaks at 19%; thereafter, it decreases gradually to 6.8% at 12 months and 3.3% at 24 months.22,37 The condition seems to improve naturally with age in many patients, although some patients have definite severe residual deformity at 24 months of age that does not improve thereafter.25,32,44

Positional plagiocephaly involves not only asymmetry of a portion of the structure as well as the facial bones.45 This condition has been classified clinically into the following five categories by Argenta:2 Type 1, posterior asymmetry; Type 2, ear malposition; Type 3, frontal asymmetry; Type 4, facial asymmetry; and Type 5, temporal bossing or posterior vertical cranial growth. In another classification system, Littlefield, et al.,30 suggested that positional plagiocephaly is mild when the cranium is flat and is not deformed at the ear location, moderate when there is a discrepancy of more than 0.5 in, and severe when the ear misalignment is greater.
than 1 in. Problems that arise in patients having positional plagiocephaly include craniofacial deformities as well as asymmetry of brain structures leading to eye and optic nerve asymmetry, strabismus, and visual acuity abnormalities. Other reported complications are learning disability and delay in language development, as well as possible inhibition of psychosocial development as a result of the abnormal appearance.

Treatment of Positional Plagiocephaly

The proposed treatment for positional plagiocephaly has been correction of the factors that cause it (such as torticollis, strabismus, and hypotonia) in the early stages of symptom onset, modification of the sleep position together with physiotherapy, and the application of a molding helmet. Nevertheless, in children 2 to 4 years of age who have severely deformed cranial development, reconstructive surgery is often necessary. Given such an invasive procedure, the possible complications of surgery and anesthesia can preclude surgical intervention for positional plagiocephaly in many young patients; therefore, early diagnosis and treatment have been emphasized.

The infant skull has considerable anatomical flexibility, and the hinge-like connection between the sutures allows relative movement of the skull plate and remodeling of the cranium. Because 85% of skull growth occurs within the 1st year after birth, greater potential exists for remodeling from external forces or from tension during this early period of life. By taking advantage of these characteristics of the infant skull, it has been demonstrated that therapy with a molding helmet will subsequently lead to two different types of remodeling: compensatory growth and pressure on the protuberant portion. The former is the classic molding helmet of Clarren et al., which passively prevents compression of the flat area of the skull, and the latter is the active or dynamic orthosis, or dynamic orthotic cranioplasty, which not only prevents compression of the flat area but also constrains the frontal and occipital prominences. Both types of helmet have been effective in correcting asymmetry of the skull but the active (also called dynamic) helmet seemed to be more so in terms of the range of ages and treatment periods for which it is useful. This is because remodeling by passive molding helmets is usually most effective between 3 and 12 months after birth, whereas active molding helmets are effective for young children 20 months of age. The passive molding helmet also compresses the protuberant area to some degree, depending on its fit and weight, and thus factors that can make the diff-

Fig. 9. Three-dimensional CT scans of the heads of both groups showing that beagles in the helmet-wearing group (lower) have a more dolichocephalic skull shape than beagles in the control group (upper).
ference between passive and active helmets become less signi-
cificant.31,33

All molding helmets—especially those with active com-
pression—exert some degree of pressure on the skull, a fea-
ture that results in poor compliance when they are worn by
infants and young children. In our experience, the applica-
tion of these commercial helmets is very difficult clinically.
Because of this poor compliance, a concern has arisen that
they might limit cranial growth and subject the wearers to
the risk, although slight, of increased intracranial pressure
or direct brain injury.33 This supposition was partially refut-
ed in a small clinical study by Kelly, et al.,24 in which it was
reported that craniofacial asymmetry was decreased by
the molding helmet, whereas head circumference, maximal
cranial length, and maximal cranial width measurements
showed continuous growth of the skull. Kelly and cowork-
ers estimated cranial growth by using two-dimensional
measurements and a crude statistical method, however;
thus, it is difficult to infer from their data the safety of three-
dimensional skull growth after helmet therapy.

Experimental Skull Remodeling From Soft-Helmet Therapy

We attempted in this study to ascertain the efficacy of a
soft helmet that exerts mild compression and induces com-
 pensatory growth that can successfully remodel the skull.
In addition, we endeavored to confirm the safety of such re-
modeled skull growth by using skull volume measurements
as well as neuroimaging, behavioral, and histological find-
ings. Our application of relatively narrower and longer hel-
mets to young dogs led to rapid volumetric compensation
of skull growth within 1 to 2 weeks, resulting in a long, nar-
row high head. In addition to the anteroposterior elongation
of the head, we observed that skull height increased rapid-
ly from growth restriction of the skull width when the long,
narrow helmet was in place. It is important to note that the
head circumference, the most important and widely used
parameter in clinical practice, did not change during the en-
tire remodeling period. We therefore recommend that pa-
rameters such as head length, width, height, and volume
should be used in addition to head circumference to com-
pare head growth of patients clinically.

Between the study and control groups at 7 weeks, we
found no difference in intracranial volumes that were cal-
culated roughly from length, width, and height of the skull
measurements. We believe that skull growth was not de-
layed with regard to intracranial volume during active skull
remodeling. Although the results we obtained during ob-
servation of motor function, MR imaging studies, and his-
tological examination of the autopsied brain tissue of the
beagles demonstrated no structural or functional abnormal-
ities, the possibility of injury to the infant brain during the
compensatory overgrowth cannot be completely excluded.
Authors of a previous report on molding helmets that com-
press the cranium stated that such orthotics may lead to
possible retardation of brain development.33 Further confir-
mation of the safety of this type of treatment for long-term
intelligence function must be obtained from a careful re-
view of clinical studies in humans.

We also observed that the growth of intracranial volume
in our study group paradoxically increased compared with
that in the control group during the early study period (the
2nd to 4th weeks) but decreased in the control group at the
5th week after application of the molding helmet. Many
patients with syndromic craniosynostosis who later exhib-
ted neurodevelopmental problems19,27,36 have had variable
intracranial pressure as well as normal intracranial vol-
umes, or even volumes greater than those of healthy volun-
tees serving as controls.1,6,15,39,43 Their abnormally large
skull shape may result from insufficient intracranial vol-
ume together with variable intracranial pressures, or from
inappropriately increased cerebrospinal pulsation (Wind-
kessel effect).14,16 Connolly, et al.,20 have also suggested that
abnormal skull shape can result in increased intracranial
pressure and subsequent developmental deficits. From this
point of view, the paradoxically increased overgrowth of
the head in the study group during the 2nd to 4th weeks
might be a compensatory reaction to intracranial volume
changes, and the intracranial volumes during the 5th to 7th

Fig. 10. Two sequences of T1- and T2-weighted, fluid-attenuated inversion-recovery and diffusion-weighted MR im-
ages of the brain, respectively, obtained in beagles wearing soft helmets (lower) and control animals (upper) at 8 weeks
after birth. No structural abnormalities in the ventricular system are evident, and there are no intraparenchymal lesions
such as cortical atrophy or brain swelling.
weeks might reflect decompensated growth. However, the small paradoxically increased overgrowth and the subsequent decreased growth rate in the study group does not reflect significant compensation, nor does it imply that any helmet therapy is detrimental to brain development. To confirm the safety of helmet therapy, we need to follow up all patients who undergo it with respect to skull, brain, and psychosocial development.

Our study has four limitations. The first is that our soft helmet may have compressed the young dogs’ heads, even though it was larger than the heads. The second is that the sample size was small; the third is that the equation for volume estimation may be crude; and the last is that a difference in skull growth might exist between dogs and humans. It seems clear, however, that abnormal skull shape restricts brain growth, resulting in variable compensatory skull growth.

Conclusions

We conclude that in normal young dogs that were subjected to a soft molding helmet, skull remodeling was effective and caused no discernible functional abnormalities.

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References

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