The Use of Non-Invasive Halo System (NIHS) in Atlantoaxial Rotatory Subluxation/Fixation in Childhood (AARS/AARF): Case Series

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ABSTRACT

The use of conventional Halo braces was frequently accompanied by complications owing to the invasive nature of the stabilization pins. Hence interest in Non-Invasive Halo System (NIHS) gathered pace, but its therapeutic ability in providing clinically resonant stabilization with a better safety profile, remains to be established. We performed a retrospective review of 2 patients treated for Type 1 AARS/AARF in childhood with the help of immobilization provided by the NIHS and reflected on a previous case of AOD which was successfully managed with the NIHS. We reviewed the patients' clinical and operation case notes to collect data regarding the reason for admission, indications for orthotic management, follow-up regimen, challenges associated with the NIHS and weaning plan. The NIHS was a clinically effective and safe method for realignment and stabilization of paediatric atlanto-axial and atlanto-occipital subluxation. with sustainable radiological and physical alignment, that was well tolerated by the patients. Due to the lack of invasive pins, the pressure points were instead translated to the skin on bony prominences, as our patients experienced varying degrees of compromises to their skin, hence careful attention is required for the best type of padding and pressure distribution to protect the patient's skin.

Keywords: Atlanto-axial rotatory subluxation, Non-Invasive Halo Brace, Atlanto-occipital Dislocation.

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BACKGROUND

As the name suggests, the atlantoaxial joint consists of the atlas (C1) and axis (C2) aligned as a biaxial, pivot joint to bridge the occiput of the cranium and the cervical spine.[1,2] The atlas has a circular shape with zygapophyseal joints on its lateral masses to articulate with the occipital condyles of the cranium superiorly and to articulate with the axis inferiorly. The axis possesses an odontoid process, commonly referred to as the dens, that projects superiorly from its anterior surface to articulate with the inner surface of the atlas above. This articulation is an addition to the superior and inferior articular facets to form zygapophyseal (facet) joints with the atlas above and C3 vertebrae below. The axis itself develops from 5 ossification centres and the secondary ossification centre between the dens and the body of the axis remains unfused as a cartilaginous junction until 6 years of age.[3]

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Hence the atlantoaxial joint is in fact made of 3 distinct synovial joints i.e., one medial joint and two lateral, gliding joints.[2]

The complex architecture of the atlantoaxial joint caters to its multifaceted function which includes supporting the head in neutral position, stabilizing the occipito-atlantal joint, protecting the spinal cord from external compression as it traverses the craniovertebral junction, protecting the vertebral artery which is integral to the posterior circulation and facilitating the greatest range of head and neck mobility (flexion, extension and rotation) whilst maintaining stability.[1,2,4] Ligamentous stability of the atlantoaxial joint is provided by the dens and its supporting ligaments, namely the cruciate ligament (consisting of the transverse ligament, that runs horizontally between the lateral masses of the axis enclosing the dens posteriorly and a vertical longitudinal band running from the basion to the axis), apical ligament (running from the tip of the dens to the basion) and paired alar ligaments (running from the tip of the dens to the borders of the foramen magnum).[2,5] An Atlanto-Dens Interval (ADI) greater than 5 mm indicates that the transverse ligament incompetent and hence atlanto-axial instability. This ligamentous stability is reinforced by the anterior longitudinal ligament, tectorial membrane of the posterior longitudinal ligament, zygapophyseal joint capsules and posterior neck muscles.[1,6]

Atlantoaxial Instability (AAI) is usually congenital but maybe due to an acute, high-energy traumatic event or inflammatory disease.[1,2] AAI is a spectrum of disease that ranges from mild subluxation (Atlanto-Axial Rotary Subluxation; AARS) to fixed facet dislocation (Atlanto-Axial Dislocation; AOD), with the underlying predisposing factor thought to be related to ligamentous laxity and mechanism described to be extreme hyperextension of the neck followed by lateral flexion.[2,7] AAI can be divided into 3 types according to the alignment of the facets on lateral imaging with the head kept in neutral position (Table 1).[8] Multiple studies have quoted numerous parameters in diagnosing AAI in children with the help of MRI scans, CT scans and three-view imaging of cervical spine as supported by the National Emergency X-Radiography Utilization Study (NEXUS) study.[1,9,10] These parameters are detailed in Table 2. Children with AAI present with a spectrum of symptoms including being asymptomatic to experiencing neck pain in a cape-like distribution, restriction in neck movements and in serious cases of spinal canal stenosis symptoms may include lower cranial nerve palsies, myelopathy, respiratory insufficiency, or death.[10,11]

In the paediatric population, Atlanto-Axial Rotary Subluxation (AARS) is common, due to subluxation of the lateral masses of the atlas relative to the axis. AARS in children is commonly associated with trauma, referred to as traumatic torticollis, or infection of the pharyngeal space (referred to as nasopharyngeal torticollis or Grisel's syndrome).[7] Fielding and Hawkins have classified AARS into 4 types based on the direction of rotary dislocation (Table 3).[6] Children with AARS may present with head in the "cock-robin" position (i.e., head titled to one side and rotation of head to contralateral side), neck pain, headache, sternocleidomastoid spasticity on the side towards which the chin is rotated and a decreased range of cervical spine motion.[12,13] As an example, a left sided facet subluxation will result in chin rotated towards the right and spasm of the right sternocleidomastoid muscle. Similar to imaging for AAI, standard radiography for AARS includes anteroposterior, open-mouth, lateral and flexion-extension views, while a CT scan remains the gold standard for AARS. CT scans may also help classify chronic atlantoaxial rotary fixation depending on the lateral inclination angle of the atlas.[14] In addition, MRI imaging helps provide information regarding spinal cord compression, integrity of the ligaments and any other compromise to the soft tissue. According to the POSNA guidelines, management of AARS depends on the duration of symptoms and clinical presentation and conceptually aims for relieving the muscle spasm, achieving reduction and satisfactory alignment and ultimately facilitating stability by immobilization using the halo vest or surgical arthrodesis.[15]

The halo vest or brace is a device that provides rigid external immobilization of the occipitocervical and atlantoaxial junction by restraining the cranium to the upper torso. The conventional halo brace had previously been the gold standard for providing rigid and clinically effective immobilization, however as a study by Stacey *et al*. had discussed the high rate of complications including pin site infections, loose pins, neck pain, skin ulcer, restriction of movement and dysphagia has introduced challenges in the management.[16] However, owing to the high rate of complications resulting from invasive nature of the pins in the conventional halo brace (also known as conventional Halo vest), interest in the use of non-invasive pin-less halo brace has gained momentum in recent years.[17-19] Several studies have discussed the benefits of applying the Non-Invasive Halo System (NIHS) and have highlighted its good safety profile and patient-friendly nature. While there were complications due to the pressure applied on the skin, these have been minor, fully resolvable and amenable with slight modification of the NIHS brace. Nevertheless, it was noted that the non-invasive halo braces offer lesser immobilization hence raising questions regarding its efficacy.[17] Hence it is essential to expand our literature and we would like to discuss the efficacy, benefits and complications with the use of NIHS brace in our patients.

METHODOLOGY

We performed a retrospective review of 2 patients treated for Type 1 Atlanto-Axial Rotary Subluxation (AARS) in childhood with the help of immobilization provided by the Non-Invasive Halo Brace (NIHS). In addition, we also reflected on a previous case of Atlanto-Occipital Dislocation (AOD) which was successfully managed with the NIHS. We reviewed the patients' clinical and operation case notes to collect data regarding the reason for admission, indications for orthotic management, follow-up regimen, challenges associated with the NIHS and weaning plan. These data, coupled with imaging studies enabled us to study the functional (neurological status) and physical (cranio-cervical alignment and healing) outcomes as well as complications. The patients are fully aware of this study and have consented to data collection and presentation in an anonymous manner. Written informed consent was obtained from a legally authorized representatives for anonymized patient information to be published in this article.

CASES PRESENTATION

1st Patient-Type 1 Atlantoaxial Rotatory Subluxation (AARS)

Our first patient was 6-year-old girl who presented early 2021 with acute torticollis on waking and complained of sore and tight muscles on right side of her neck. A detailed medical history failed to yield any preceding trauma nor was the patient unwell recently. On examination, patient was noted to present with neck in lateral flexion towards the left and head rotated towards the right. Pain worsened on palpation of right cervical paraspinal muscles. Patient

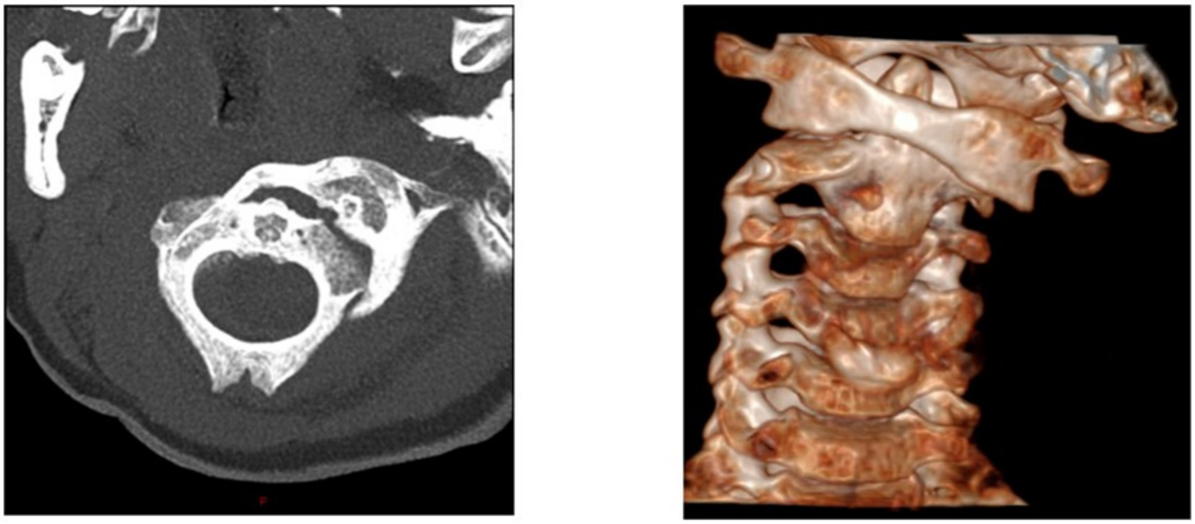

Figure 1: MRI findings of our first patient. MRI depicts the anterior displacement of anterior C1 facet relative to C2, indicating rotatory subluxation. Bone marrow and neck musculature signals were normal.

Table 1: Types of Atlanto-Axial Instability.

Type of AAI	Description
Type 1	Characterized by the anterior dislocation of the facet of the atlas relative to the axis.
Type 2	Characterized by the posterior dislocation the facet of the atlas relative to the axis with rotatory atlantoaxial dislocation.
Type 3	Characterized by instability is confirmed by clinical and specific radiological cues despite normal alignment of facets.

Table 2: Criteria for diagnosing Atlanto-Axial Instability (AAI).

Criteria for diagnosing Atlanto-Axial Instability (AAI) as highlighted by Lacy *et al.*	
1.	Atlanto-dens interval of more than 5 mm.
2.	Overriding of the anterior arch of the atlas over the dens.
3.	Space available for the spinal cord less than 13 mm or violation of Steel's rule of thirds (one-third occupied by spinal cord, one-third occupied by dens and one-third safe space).
4.	Translation of the tip of the odontoid of more than 4 mm of the basion.

did not want to engage on assessing Active Range of Movement (AROM) of cervical spine and passive range assessment was not performed due to the muscle guarding and pain. Full AROM were preserved in thoracic and lumbar spine. Similarly full range of motion was unperturbed in respective myotomes and no altered sensation in dermatomes. Patient was able to ambulate with limited range due to neck pain and stiffness. Initial management was conservative with pain relief in the form of Ibuprofen, gentle massage, warm packs and AROM exercises for back and neck. Patient was then admitted for CT of cervical spine which revealed Type 1 rotary atlantoaxial subluxation as highlighted in Figure 1. A joint neurosurgical and orthotics assessment of patient's clinical presentation and CT findings, led to the decision of manipulating the atlantoaxial joint under general anaesthesia and fitting in a hard collar. This did not fully correct the AARS. Two weeks later, a repeat joint assessment by the neurosurgical and orthotics team prompted a repeat manipulation with under general anaesthesia and application of the Lerman paediatric Non-Invasive Halo System (NIHS) by Becker. Botulinum toxin was used to relieve cervical paraspinal muscle spasm. Repeat CT imaging the day after manipulation confirmed the reduction of atlanto-axial subluxation as predicted by the teams as the NIHS brace fitted better. During their hospital stay, a small blister was noted on anterior chest wall and appropriate wound care was initiated. 6 days after manipulation, patient was discharged home with NIHS brace. Parents were briefed on caring for the NIHS brace and were followed up with telephone and in-person consultations and MRI or CT imaging every 2 weeks. As per the initial plan of the team, the NIHS brace was to be worn for 6 to 8 weeks and the patient managed to maintain the brace for 6 weeks and 6 days. The orthotics team weaned the patient down to a hard collar to be always worn except nights and gradually weaned over a month. MRI confirmed normal C1 and C2 alignment with no evidence of rotary subluxation (Figure 2). Patient was eventually discharged from the neurosurgical team after 7 months of initial presentation, having completed 8 weeks without the hard collar.

2nd patient-Type 1 Atlantoaxial Rotatory Subluxation (AARS)

Our second patient was a 9-year-old girl who also presented in early 2021 with a 2-week history of right sided torticollis. This patient experienced a protracted course due to recurrent AARS. Patient complained of soreness and restriction in neck range of movement

Table 3: Fielding and Hawkins classification of Atlantoaxial Rotary Subluxation (AARS).[2]

Type of AARS	Key Points
Type I	Characterized by unilateral facet subluxation with an intact transverse ligament. Dens acts as a pivot point with 1 facet subluxating anteriorly and 1 facet subluxating posteriorly. Type 1 AARS is the most common but benign.
Type II	Characterized by unilateral facet subluxation with 3 to 5 mm of anterior displacement (atlanto-dens interval of between 3 to 5 mm). Integrity of transverse ligament is compromised. 1 facet acts as a pivot point and lateral mass on contralateral side is displaced anteriorly.
Type III	Characterized by anterior displacement of both lateral masses of the atlas (C1). Imaging will reveal an anterior facet displacement of more than 5 mm. Type III AARS is rare with a higher risk of neurologic involvement or instantaneous death.
Type IV	Characterized by the posterior displacement of the atlas (C1) and frequently accompanied by odontoid fracture or hypoplastic dens. Type IV AARS is rare with a higher risk of neurologic involvement or instantaneous death.

punctuated by episodes of improvement. Patient presented with head in left-sided rotation, tilt and flexion. A cervical CT scan confirmed Type 1 atlanto-axial rotatory subluxation (Figure 3). Patient was managed according to the POSNA guidelines. Within a week from initial presentation, patient was submitted to the theatre, for manipulative correction of the rotary subluxation under general anaesthesia and stabilization with the Miami J hard collar. It was noted clinically and with imaging that subluxation was milder but had not completely resolved as they chose to wait for conservative management to determine the appropriate size of soft cervical collar**.** Patient's family noticed gradual improvement over the course of 2 weeks, with improved neck mobility and were content with maintaining the hard collar for 4 according to the POSNA guidelines. This was followed by application of a soft collar; however, within 4 days of application, it was evident that patient was intermittently holding her head to help stabilize her neck. Consequently, the soft collar had to be removed and Miami J hard collar was re-fitted. The hard collar did a commendable job over the next 8 weeks, as patient had begun their weaning down regimen.

However, the torticollis returned after patient played the trampoline. impaired patient's ability to ambulate, due to restriction in neck range of motion. This prompted the neurosurgical team to devise a plan for NIHS. MRI confirmed

Figure 2: Sagittal MRI depicting the normal alignment of the craniocervical junction, after being on the NIHS brace for 6 weeks and 6 days. In addition, the cervical spine, ligaments and intervertebral disc were all inspected and no abnormalities were detected.

C1/C2 rotary subluxation presenting as a Type 1 AARS. The application was postponed for a month due to intercurrent viral illnesses. Application of the NIHS brace was performed in theatre under general anaesthesia with 50 units (1 mL) of botulinum toxin A injection into right sternocleidomastoid muscle to relieve the muscle spasm. 6 weeks after application, a CT scan of cervical spine confirmed reduction and satisfactory alignment of the atlantoaxial joint. Patient completed 12 weeks of NIHS brace application and the brace was weaned down to hard collar (P2 Miami Jay) for 4 weeks. However, after 2 days of being free from the collar, the AARS recurred necessitating the re-installation of the NIHS brace. Despite the initial plan to maintain the NIHS brace for 12 weeks, approximately 4 weeks after application, patient developed a pressure sore measuring 1.5cm by 1.5 cm above right ear. Due to pressure wounds, the brace had to be removed and substituted with the hard collar again (P2 Miami Jay) and the patient was started on a 7-day course of Flucloxacillin. Patient was maintained on the hard collar for the next 8 weeks, as the wounds healed well. CT scan performed 12 weeks after application confirmed improved C1/C2 alignment (Figure 4). After being on the hard collar for 6 months, it was agreed to wean down the collar application. Patient was symptom free with no repeated episodes of torticollis nor neck spasms for 5 months. However, in early 2023, patient developed frequent neck tics which were characterised by forwards flexion of head with rotation to the right. CT imaging confirmed normal alignment of the atlanto-axial junction. Patient was given the Aspen collar to maintain a neutral neck position and had scheduled to meet the neurologist for botulinum injections to reduce the frequency of tics that may lead to recurrent atlanto-axial instability. Given the patient's ongoing challenge with recurrent AARS, the team have discussed about Occipito-cervical arthrodesis as an option for definitive management.

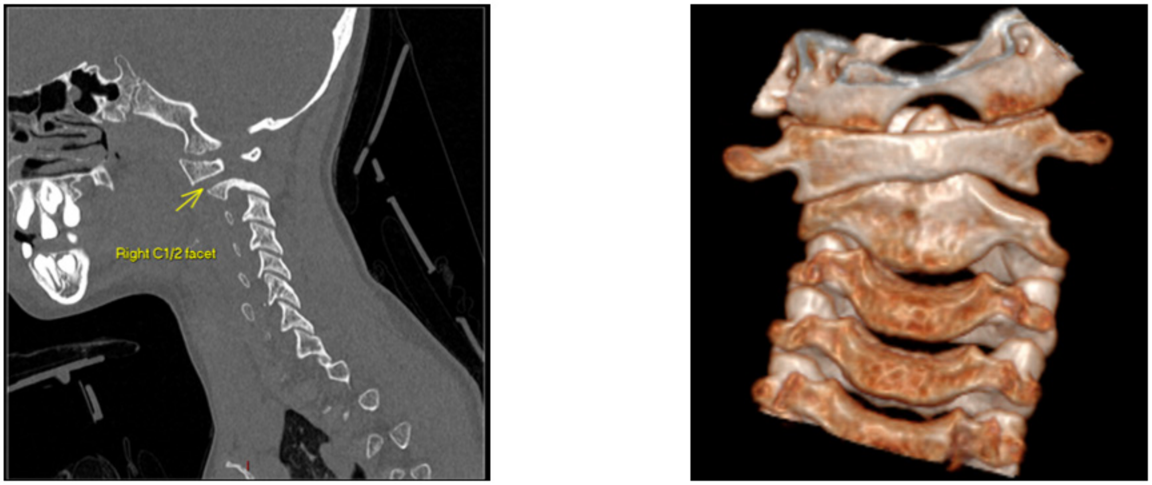

Figure 3: Index CT scan images of our second patient. A 3-dimensional reconstruction of the CT scan (left) confirmed that the right C1 facet is placed anterior to the C2 facet and the left C1 facet is placed posterior to the C2. The odontoid process was not central within the anterior arch of C1 and was mildly displaced to the left. A sagittal view of the cervical spine (right) confirmed this. The remainder of cervical spine maintained a normal alignment and no injury to bone nor soft tissue was noted.

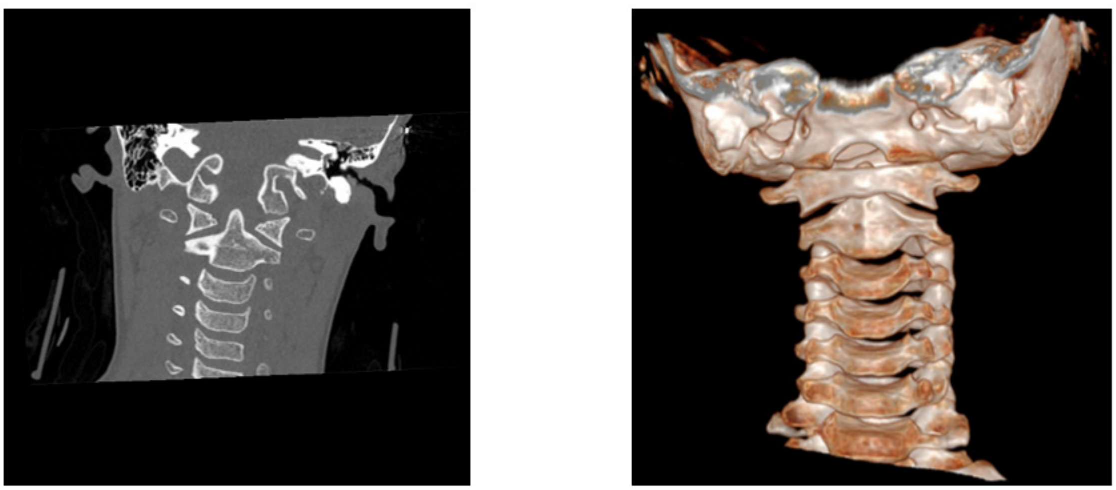

Figure 4: CT of cervical spine, confirming improved cervical alignment with no significant residual subluxation. As noted previously, otherwise normal vertebral alignment.

3rd Patient-Atlantoaxial Dislocation

Our third patient for discussion, had been previously described in detail in a case report. Considering the success of the NIHS brace for the patient, it merited further discussion and reflection. Patient was a 10-year-old boy who attended following collision with a metal barrier sustaining a hyperextension injury of his cervical spine. A trauma CT scan revealed that the collision had initially resulted in a raised Intracranial Pressure (ICP) due to subdural, subarachnoid and intraventricular haemorrhage. During the initial presentation no evidence of Atlanto-Occipital Dislocation (AOD) was noted on imaging, despite the presence of a minimally displaced fracture of the right occipital condyle with focal hematoma. However, after 7 days, CT and MR angiograms initially performed to analyse the degree of vascular injury, identified disruption of the apical ligament and an increase in the basion-dens interval from 6 mm to 11 mm as compared to initial imaging. These findings were accompanied by oedema of the surrounding soft tissues including the ligamentum nuchae and effusion in the prevertebral space. This led to the confirmation of AOD and prompted a multidisciplinary meeting that decided on the application of the NIHS brace. This was performed on day 10 of the injury after reduction of the AOD. The NIHS brace was always maintained for 3 months with weekly cervical spine X-rays, periodic CT of the craniocervical junction to monitor atlanto-occipital alignment and soft tissue healing, as well as regular review of the NIHS brace by the orthotics team. In addition, the patient sustained an occipital laceration which progressed to a pressure sore that required debridement and IV antibiotics. On top of these, patient received input from the pain team, physiotherapists, occupational therapists, speech therapists and psychology services as well to support him and his family. At 3 months, an MRI of the cervical spine confirmed healing of the soft tissue at the craniocervical junction and dynamic

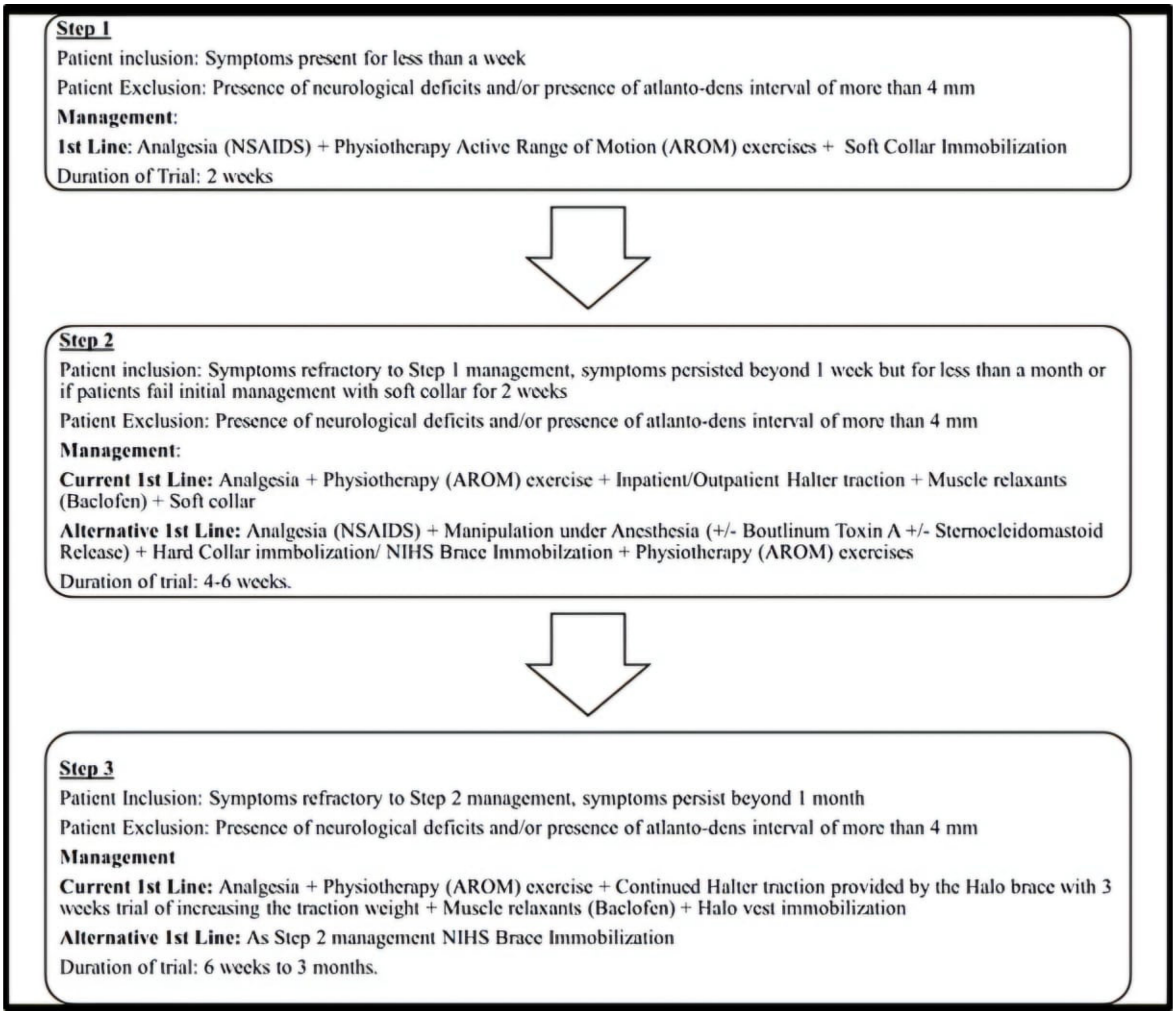

Figure 5: Proposed non-conservative management algorithm of managing Type 1 AARS.[1,15,20,21] Patients presenting with neurological deficits and/or presence of atlanto-dens interval of more than 4 mm are excluded from conservative management and should be expedited to surgical management.

cervical spine X-rays confirmed satisfactory alignment in flexion and extension. The NIHS brace was replaced with a hard collar with a weaning regimen over the next 2 weeks. At 2 years, patient was noted to have made an excellent recovery without any neurological symptoms nor signs of craniocervical instability.

DISCUSSION

This case series describes the use of the non-invasive halo brace in managing atlanto-axial subluxation and atlanto-occipital dislocation. As understood from these cases, the NIHS can be an effective treatment option for realignment and stabilization.

What are the current guidelines?

Both patients presenting with AARS were managed according to the POSNA guidelines. Conceptually the aim is to reduce and realign the subluxation followed by a period of immobilization to promote and attain stability. Management is split according to nonoperative or operative; this can be categorised into 3 pathways that maybe selected according to the timeline of patients' presentation, severity of subluxation and/or failure of initial early conservative management.[15]

Pathway 1: In accordance with POSNA guidelines, patients presenting with subluxation with symptoms present for less than a week are recommended non-operative conservative management in the form of analgesia (NSAIDS) and physiotherapy with Active Range of Motion (AROM) exercises. In addition, immobilization was provided by a soft collar during ambulation. This would be Step 1.

Pathway 2: If symptoms persisted beyond a week but for less than a month or if patients fail initial management with soft collar for 2 weeks, discussions will be made to provide analgesia, AROM exercise with halter traction (5 lbs weight) combined with muscle relaxants to reduce the subluxation. This will then be followed by application of soft collar for 4-6 weeks. More recently, interest has gathered in employing Manipulation Under Anaesthesia (MUA) as a substitute to halter traction in achieving immediate closed reduction. This entails induction of anaesthesia followed by gentle manual traction and rotation in direction opposite to subluxation.[20,21] Botulinum toxin A injection or sternocleidomastoid release maybe employed at this point to relieve sternocleidomastoid or paraspinal muscle spasm and facilitate reduction.

Pathway 3: For symptoms persisting beyond a month or failure of management with pathway 2, patients will be continued on halter traction provided by the Halo brace with 3 weeks trial of increasing the traction weight, in addition to ongoing pain and spasm relief coupled with AROM exercise. This is then followed by immobilization with the halo vest for 6 weeks to 3 months. In recent times, with the endorsement of MUA for immediate reduction and re-alignment, the hard collar or halo brace were applied after the procedure to maintain stability, reduction and satisfactory alignment.[20,21]

Failure of management at pathway 3 or persistence of symptoms beyond 3 months or the presence of neurological deficits or atlanto-dens interval of more than 4 mm and calls for operative management.[1] Different methods of posterior arthrodesis have been employed and although they have demonstrated commendable reduction and outcomes, they carry the risk of complications including failure of implants, fracture of atlas or axis during surgical instrumentation, vertebral artery injury, infection and gradual loss of cervical spine lordosis.[9]

How did we select patients for the NIHS brace?

Given the presentation of our patients, management was initially selected to be conservative and non-operative as recommended by the POSNA guidelines and the algorithm in a paper by Hill *et al.*[15,20] A thorough initial history and neurological examination confirmed the absence of neurological deficits and initial imaging confirmed an acceptable atlanto-dens interval. As mentioned previously, failure of conservative management and soft or hard collar application in pathway 1 prompted us to step-up management to MUA followed by application NIHS brace before considering the conventional invasive halo brace or surgery. Frequent examination and follow-up sessions enabled us to monitor the progress of clinical and radiological improvement, rule out any worsening of symptoms and ensure no neurological compromise was sustained from MUA and the NIHS brace. Ultimately, in our patients this approach was able to avoid surgical intervention. In addition to these, due to index intracranial injuries and scalp laceration in our third patient presenting with AOD, it was discussed that a conventional halo brace with invasive pins will not be suitable. This further highlighted the advantage of a non-invasive halo system in such scenarios.

How were the guidelines applied to our patients?

In the management of our patients, we employed a staged management strategy (Figure 5). It is firstly important to note that initial, conservative management did not resolve their symptoms. The team was quick in monitoring patients' progress as long-standing untreated subluxation is a risk factor for recurrent subluxation.[22] The team then proceeded to Manipulation Under Anaesthesia (MUA) instead of halter traction, avoiding the need for young patients to comply with confinement to bed and prolonged hospital stay.[20] This is also taking into consideration that the duration of halter traction varies widely with reports of reduction attained within days (1-28 days) or in some cases taking up to 6 weeks.[23,24] The procedure involved maintaining mild sustained extension for 2-3 minutes, followed by physiological extension in both cases of AARS. Following the procedure, meticulous attention was paid to ensure that patient did not develop and neurologic compromise because of the procedure. It is worth to note the clinical utility of Botulinum toxin A injection into the paraspinal cervical muscles or ipsilateral or contralateral sternocleidomastoid muscle to relieve muscle spasm and aid manual reduction. In both patients, no neurological deficit nor neurovascular injuries were sustained based on meticulous examination and follow-up. Nevertheless, it was noted that MUA was challenging for both patients, as the first patient required a repeat MUA at 2 weeks and the second patient only achieved a milder degree of subluxation instead of complete reduction. It is also worth to note that CT imaging provided a reliable confirmation regarding the success of the reduction.[25] Ultimately, MUA was successful on second attempt for both patients as confirmed by CT imaging and prompt immobilization with the NIHS brace, maintained the reduction and realignment.

What was our experience on the application of the NIHS brace?

The NIHS brace was ordered according to patients' age and size. The conventional halo brace provided immobilization without the use of invasive cranial pins to secure patient's head to the circumferential halo ring, which is in turn fastened to a vest. However, this was commonly associated with complications as discussed above, due to the invasive nature of the pins. The NIHS brace immobilizes the craniocervical junction by fastening a head brace with three non-invasive locking points, to a contoured vest with the help of a dual upright rod-construct. With the patient lying supine, a contoured vest is applied to their anterior chest wall. The vest can be moulded to be a perfect fit for the patient using heat. The vest is then secured to the patient using waist bands around patient's torso and criss-crossed posterior shoulder straps. The three locking points for the head are the forehead band, a free-floating chin support and a free-floating occipital support. These locking points form the core of the immobilization as they closely appose and adhere to patient's skin, thus enabling the NIHS brace to hold the head, serving the role of the invasive pins in a conventional Halo brace. Using a series of straps, clips and hooks, the position of the chin support, occiput support and forehead band can be adjusted and secured to the frame of the head brace. The head brace construct is then secured to the contoured vest with the help of two upright rods that slot into serrated connectors on the vest. The points of skin contact are cushioned with breathable and non-allergenic silicone adherent pads.[26] It is important to note that the orthotics team were involved at every stage in the process and reviewed the patient on a weekly basis to ensure that the construct of the NIHS brace was stable and fitted well for the patient. This follow-up regimen by the Orthotics team mirrored that of the application of the conventional halo brace with invasive pins.

What were the problems we encountered with the NIHS brace?

The main challenge that we identified with the NIHS was the compromise to skin/scalp in association with a stable well-fitted construct. Despite the absence of invasive pins which portend a greater risk of infection, the Non-Invasive Halo brace relies on apposition against skin and as noted in one of our patients, a blister was noted, but with some fine-tuning of the support points, prompt wound care and diligent monitoring this was managed. In our patient with recurrent AARS, unfortunately due to the pressure wounds, management with the NIHS brace had to be terminated prematurely and patient was successfully switched to a hard collar in the last stage of management (patient recovered without operative management). In our patient with AOD, the application of NIHS brace was challenged by a pre-existing index event causing an occipital laceration that then progressed to a pressure sore necessitating debridement and antibiotics. Apart from that it was not caused by the NIHS brace, it is worth to reflect on altering the support points of the head brace frame for patients with pre-existing wounds and ensuring that the NIHS brace does not interfere with wound management.

How did we follow-up and care for the patients with the NIHS brace?

From our experience, caring for the brace encompasses 4 domains i.e., assessing and maintaining the stability of the construct, ensuring that patient is tolerating the brace well, monitoring for improvement and maintaining hygiene. A significant responsibility was shared between the neurosurgery and orthotics team. Application of the NIHS brace was performed by both paediatric neurosurgeons and orthotics team and both teams engaged in fine-tuning the brace after application and following up closely with the patients.

The orthotists reviewed the patients weekly in person and assisted parents in the cleaning of the brace. Thanks to the absence of invasive pins, the orthotics team found it much easier to care for patients' hygiene as the construct can be dismantled temporarily with manual immobilization provided by the hands of another member of their team. After cleaning the brace was reconstructed. The fastening straps, clips and hooks were checked for looseness and tuned and they regularly checked sites of skin apposition to ensure no pressure wounds had developed. Cleaning the shell of the brace was done with soap and water and the straps could be removed for a wash with soap and water. The orthotists played a significant role in educating patients and their parents.

The neurosurgeons responsible for the patients with AARS, organized in-person consultations every fortnight with the flexibility of hosting telephone consultations in later stages of management. Review consisted of enquiring how well patients were tolerating the brace, examining for clinical improvement, ensuring no new neurological and skin compromise as well as CT or MRI imaging to assess for radiological resolution. The imaging modality and frequency was selected in line with our local paediatric protocols to minimize radiation dose, hence was performed every fortnight initially followed by clinical decision depending on clinical progress, severity of subluxation and degree of soft tissue injury.

It is important to also note that the decision to apply the NIHS brace was made by a multidisciplinary team in patients with AARS and our patient with AOD. The team consisted of paediatric neurosurgeons, paediatricians, orthotists providing management and physiotherapists, speech and language therapists and occupational therapists providing rehabilitation. Care for the patients was coordinated by a paediatric nurse practitioner (Child Life and Development Nurse (CLDN). In addition to improvement in symptoms, patients had to be supported physically to ensure developmental milestones were attained and given care from a mental health perspective as well. Depending on the severity of index presentation, patients may be managed inpatients, as our patient with AOD, or as outpatients, as our patients with AARS.

Confirmation of normal craniocervical and atlantoaxial alignment was made clinically, following resolution of torticollis and radiologically as depicted in the figures. Imaging was performed prior to initiation of weaning down regimen and once again after 3 months. Upon confirmation, the NIHS brace was removed and a weaning down regimen with the hard collar was started for our patients who were successfully managed with the NIHS brace. The weaning down regimen with the hard collar was planned by the orthotics team and lasted between 2 and 4 weeks, with the hard collar maintained throughout the day except for nights.

CONCLUSION

Incorporating the NIHS brace into the algorithm as an option to be considered prior to conventional invasive pin Halo brace and surgery

The conventional halo brace had previously been the gold standard however it is worth noting that the invasive nature of the pins has been responsible for most of the challenging complications. Hence interest in the non-invasive set-up gathered momentum and more studies have begun exploring its therapeutic efficacy. Going back to our initial question regarding the clinical efficacy and therapeutic, in our experience the NIHS brace has demonstrated good clinical stabilization and efficacy in our patients and we would like to conduct more studies to incorporate the NIHS brace into the algorithm of managing craniocervical instability before resorting to the conventional halo brace/vest with invasive pins or surgical arthrodesis (Figure 5).

Considering these, it is important to plan and assess a patient's suitability for application of the NIHS brace by accounting for the patient's age, size, severity of AAI (AARS or AOD), concomitant skull, scalp, or torso injury. Along with this careful planning of the timing of application, follow-up regimen, care plan, criteria to wean down application and the weaning down regimen. Management with the NIHS brace requires close clinical and radiological follow-up to assess improvement. Moreover, careful attention needs to be paid to points of skin apposition and better padding and material is needed to protect the skin at pressure points.

LIMITATIONS

Due to changes in patients' place of care, we were unable to follow-up patients more closely for the purpose of monitoring outcomes following the use of NIHS brace. We recognize this as a potential limitation of our report and would like to address this by following up this report with a comprehensive cohort observational study.

CONFLICT OF INTEREST

The authors declare no conflict of interest in preparing this article. We would like to confirm that this report has been discussed as a poster presentation in ISPN 2023, WFNS 2023 and Edinburgh Undergraduate Research Symposium 2023. A copy of the presentation of our manuscript is available at EXBO ePosters.

ABBREVIATIONS

AAI: Atlanto-Axial Instability; **AARF:** Atlantoaxial rotatory fixation; **AARS:** Atlantoaxial Rotatory Subluxation; **ADI:** Atlanto-Dens Interval; **AOD:** Atlantoaxial Dislocation; **MUA:** Manipulation under Anaesthesia; **NIHS:** Non-Invasive Halo System; **POSNA:** Paediatric Orthopaedic Society of North America.

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