Aus der Universitätsklinik

für Neurochirurgie Tübingen

Ärztlicher Direktor: Professor. Dr. M. Tatagiba

Chiari Malformation, retrospective analysis of 74 patients treated at the university hospital of Tübingen: indications, outcomes and complications

Inaugural-Dissertation zur
Erlangung des Doktorgrades der
Medizin

der Medizinischen Fakultät
der Eberhard Karls Universität
zu Tübingen

vorgelegt von
Inas Hajjar
aus Casablanca, Marokko
2012

Dekan:	Professor Dr. I.B. Autenrieth
1. Berichterstatter:	Privatdozent Dr. B.E. Will
2. Berichterstatter:	Professor Dr. H. Ackermann

TABLE OF CONTENTS

1 History and Classification

Hans Chiari (1851-1916) born in Austria, son of J.B.V.L Chiari an Austrian gynaecologist and brother of Ottokar Chiari a rhino laryngologist, served as professor of pathology in Prague in 1882 and in Strasbourg in 1906. Between 1891 and 1896 he described a series of anomalies of the caudal cerebellum and brainstem on the basis of autopsy observations.

His first publication in 1891 was a preliminary report introducing 3 types of cerebellar changes occurring in some hydrocephalic children. With repeated recognitions of abnormal anatomical patterns, Chiari began to give more attention to the relation between medulla pons and cerebellum. In the type 1 anomaly, Chiari described: “peg like elongation of the tonsils and medial portion of the inferior lobe of the cerebellum which go along the medulla into the cervical canal”. A second type consisted of the displacement of a portion of the cerebellum into the enlarged vertebral canal, the cerebellum lying within the fourth ventricle which is elongated and also extends down into the vertebral canal. In his second report, Chiari changed this description to: “displacement of the medulla oblongata into the cervical canal and elongation of the fourth ventricle into the cervical canal”. This change demonstrates that Chiari has come to understand the major importance of the hindbrain displacement in the malformation, that the cerebellar anomaly was quite different from the usual form of tonsilar herniation and that the inferior vermis was displaced as well. About the third type he wrote: “the third type of consecutive changes in the cerebellum caused by chronic congenital hydrocephalus […] demonstrates the greatest degree of displacement of the cerebellum out of the cranial cavity through the foramen magnum into the vertebral canal […] involving the deposition of nearly the entire cerebellum which was itself hydrocephalic into a cervical bifida”.

Eight years before (1883) Chiari’s publication, John Cleland F.R.S (1835-1925) – poet, teacher, Darwinist, a surgeon, and anatomist who during his 53 years of academic career published papers on morphology, teratology, and embryology – presented a paper entitled ”Contribution to the Study of the Spina bifida, Encephalocele and Anencephalus” (12), where he described the pathophysiological findings in 9 infants at autopsy and two chick embryos: the brain stem was elongated and the fourth ventricle extended well into the cervical canal (12). Cleland paid attention and made meticulous observations to “the distortion of the inferior vermiform process, which extends up so far that what appears to be the pyramid touches the corpora quadrigemina, while the uvula looks backward and the laminated tubercle

hangs down from an exaggerated velum posticum, as an appendix ¾ of an inch in length, lying in the fourth ventricle" (12). Cleland concluded that primary dysgenesis of the brainstem was responsible for the human malformation and doubted that hydrocephalus could be the main factor. He stated that: "the hydrocephalus was obviously of much later origin, when the different parts of the brain where already formed" (12). His work went unnoticed and Cleland lost eponymic recognition.

In 1894, Julius Arnold (1835-1915) a former student of Rudolf Virchow M.D and who graduated in Heidelberg, published an article in 1894 describing an infant with spina bifida. Arnold described an elongated inferior portion of the cerebellum that covered the fourth ventricle and extended halfway into the spinal canal, and an unchanged medulla with absence of hydrocephalus and intact ventricles. Arnold defined the parts of the myelomeningocele and characterized the spina bifida in detail. Chiari referred to this case in his 1896 publication (in which he acknowledged Arnold and Cleland) and believed that the abnormal formation of the rhombocephalon in the presence of spina bifida was similar to his type 2 classification. However, he referred to the hydrocephalus as the cause of the described alteration of the rhombocephalon. He also added, based on 2 cases, a fourth entity to his classification and characterized it by cerebellar hypoplasia.

In 1907, two students from Arnold's laboratory (Schwalbe and Grodig) first applied the controversial eponym of Arnold Chiari to patients previously called Chiari type 2 malformations (Wilkins 66, Kohlers 30, Carmel 9). They attributed the cerebellar elongation to Arnold's and the medullary step like deformity (kink) to Chiari's definition, thus ignoring the original Chiari type 2 description which included cerebellar and medullary deformities.

The initial classification system has not significantly changed since his initial report more than a hundred years ago:

- The type 1 malformation consists of a downward displacement of the cerebellar tonsils and sometimes part of the medulla below the foramen magnum. Badie et al. demonstrated that patients with type 1 have a significantly smaller posterior fossa ratio compared to a control group (3). They tend to develop symptoms earlier and respond better to suboccipital decompression than those with normal posterior fossa ratio.

- The type 2 malformation as described by Chiari included herniation of the cerebellar vermis, the fourth ventricle, a greater part of the medulla and sometimes

part of the pons through the foramen magnum. This type is commonly associated with lumbar myelomeningocele and hydrocephalus.

- The type 3 malformation includes herniation of the posterior fossa contents into the high cervical canal and to various degrees into a cervical-occipital meningocele (47).

- Type 4 refers to cases of hypoplasia or aplasia of the cerebellum.

The conventional classification described above does not permit to introduce intermediary forms (especially type 1 and 2) and does not consider the presence or the absence of syringomyelia, which is important from the standpoint of clinical presentation, management and outcome. In 1991 Pillay et al. presented a novel classification of symptomatic Chiari malformation taking into account the syringomyelia but being independent from the degree of herniation (53). The Chiari malformation is defined as a hindbrain herniation without associated mass lesion or hydrocephalus:

- Category 1 would include any Chiari malformation, irrespective of the degree or amount of herniation but exclusive of associated lumbar myelomeningocele or occipital-cervical encephalocele. This is further subdivided into congenital and acquired categories with specific clinical associations.

- Category 2 would include any Chiari malformation in association with lumbar myelodysplasia. Also, this type may or may not be associated with hydrocephalus or syringomyelia.

- Category 3 would include any Chiari malformation, irrespective of the amount of herniation, but with associated occipital-cervical encephalocele. It may or may not be associated with syringomyelia.

A comprehensive classification is proposed synthesizing the above categories into a simple, but relevant working scheme:

I. Hindbrain herniation (tonsils, brain stem) without lumbar myelomeningocele or occipital-cervical encephalocele.
    a. Congenital
    b. Acquired
        i. Basal arachnoiditis
        ii. Lumboperitoneal shunts
        iii. Multiple lumbar punctures
        iv. De novo

II. With a lumbar myelomeningocele

III. With an occipital-cervical encephalocele

Each of the above categories is further divided according to the presence or absence of associated syringomyelia.

1.1 Chiari 1 malformation

Type 1 Chiari malformation (CM1) consists of a herniation of the cerebellar tonsils through the foramen magnum. According to this definition, the diagnosis of Chiari malformation is based mainly on the demonstration of an abnormal position of the cerebellar tonsils outside the cranial cavity.

The extent of tonsillar ectopia varies, ranging from a few millimetres to several centimeters. The 5 mm cut-off point in the diagnosis of Chiari malformation is the result of several studies of the relative position of the cerebellar tonsils in healthy volunteers and symptomatic CM1 population. Barkovich et al., after analysing a large series of normal patients, found a 99.5% specificity assuming the lowest normal position of the cerebellar tonsils to be 3 mm below the foramen magnum (5). In 1985, Aboulezz et al. used MRI imaging and studied the position of the cerebellar tonsils in the normal population of 82 individuals and in 13 patients with Chiari malformation (11 with type 1 and two with type 2) (2). In the normal population, the position varied from 2.8 mm below the foramen magnum to 20 mm above, whereas for patients with CM they extended 5 mm or more below the foramen magnum.

Due to the benefits of surgery, the impact of surgical treatment on the natural history has never been explored with randomized prospective studies. The major areas of controversy are around the definition of significant hindbrain herniation, the timing of surgery and the specifics of the operation.

1.1.1 The hindbrain herniation controversy

Milhorat et al. studied 364 symptomatic patients with Chiari I malformation and found that in 32% of the 364 symptomatic patients tonsillar ectopia of less than 5 mm was demonstrated, but a compression of the CSF space posterior and lateral to the cerebellum was present (42). They concluded that herniation of less than 5 mm does not exclude the diagnosis

The position of tonsils changes with age as demonstrated by Milkulis et al. (41). A physiological ascent with increasing age with two peaks was observed; one in the late childhood/adolescence period and one in the last decade of life. It was therefore concluded that a single reference standard that indicates the normal distance of the cerebellar tonsils from the foramen magnum is inappropriate unless age is considered. Milkulis et al. assumed that a distance greater than two standard deviations beyond the normal values is pathological for the patients. For the ages of 1^{st} decade of life, 2^{nd} and 3^{rd} decades of life, 4^{th} to 8^{th} decades of life and 9^{th} decade of life these distances correspond to respectively 6 mm, 5 mm, 4 mm and 3 mm.

With MRI imaging an increasing number of patients are found with significant degrees of asymptomatic tonsillar herniation. Elster and Chen (15) found that approximately 30% of the patients with tonsillar herniation between 5 and 10 mm below the foramen magnum were clinically asymptomatic. Meadows et al. retrospectively reviewed the records of all brain MRI obtained in a tertiary care hospital of 22 591 patients (39). 0.77% of patients were found to have CM1 with tonsillar herniation that extended more than 5 mm below the foramen magnum. Of these, 24% were found to be clinically asymptomatic. Meadows suggested that the isolated findings of tonsillar herniation are of limited prognostic value and should be considered in the clinical and pathological context.

In an aim to improve the definition of the severity of CM1, Caldarelli and Rocco (8) proposed other neuroradiological aspects which should be investigated, such as the crowding of the neural structures within the posterior cranial fossa and their impactation at the foramen magnum, the configuration of the tonsillars tips and the coexistence of spinal cord cavitation. To estimate posterior cranial fossa crowding, Nishikawa et al. (47) suggested calculating “the

volume ratio" defined as brain volume divided by the cranial volume of the posterior fossa (evaluated by means of MRI and CT, respectively). Although it is not always the case, posterior fossa volume tends to be smaller in CM1 when compared with normal individuals. Badie et al. and Iskandar found that patients with reduced posterior cranial fossa tend to present more relevant clinical manifestations and conversely respond more favourably to posterior fossa decompression (4, 29). The few patients who did not respond to decompressive operation had normal posterior fossa volumes.

1.1.2 The surgery timing controversy

The availability of MRI and the frequent use of it in the assessment of children with behavioral disorders have led in the recent years to an increasing number of patients diagnosed with Chiari malformation, some symptomatic and some asymptomatic.

Nishizawa et al. (48) presented a small series of patients with asymptomatic incidentally diagnosed Chiari I malformation and syringomyelia. Those patients were monitored with neurological examination and MRI for 10 years. Only one patient required surgery 7 years after the first visit and none of the remaining patients exhibited any neurological changes during the follow up period. Furthermore, no statistically significant differences were found in MRI between the symptomatic and asymptomatic patients. The authors concluded that MRI parameters did not provide an enough predictable value to recommend interventional surgery and that long term clinical course of patients with asymptomatic incidentally identified syringomyelia associated with Chiari I malformation were observed to be benign. The authors recommended avoiding early surgery unless changes in neurological or MRI findings are detected. The management dilemma can however be solved by imaging cerebrospinal flow (CSF) across the cranio vertebral junction. Ventureyra et al. have in fact reported a good correlation between clinical symptoms and CSF abnormalities; there was no flow abnormality in asymptomatic patients (66).

In an attempt to clarify how neurosurgeons manage these clinical problems, Schijman and Steinbok undertook an international survey on Chiari malformation and related syringomyelia (59). A questionnaire on the expected natural course of the disease and on aspects of the surgical technique for a number of hypothetical cases related to Chiari malformation with and without syrimgomyelia was used to survey paediatric neurosurgeons worldwide. There was a consensus that no operation should be carried out in an asymptomatic

patient with a Chiari I malformation unless there is associated syringomyelia. Nevertheless, 40% of the respondents indicated that they still would operate on the Chiari I malformation in a patient with occipital headaches as the only symptom in the absence of syringomyelia. There was also a consensus that decompression of the Chiari I malformation should be performed in patients with scoliosis when syringomyelia is present. However, the majority again responded that they would decompress the Chiari malformation even in the absence of syringomyelia

1.1.3 The operation specifics controversy

While it is becoming well established that symptomatic Chiari I malformation should be treated to prevent further clinical deterioration, the best treatment paradigm is subject to debate. This is mainly because the results of treatment are difficult to assess in the absence of uniform outcome measures and a randomized controlled trial in which the different treatments are compared.

There have been several reports of results of different surgical approaches. These include: suboccipital craniectomy with or without exposure of the fourth ventricle, plugging of the obex with muscle, upper cervical laminectomy for foramen decompression, shunting from the syrinx to the subarachnoid spaces pleura or peritoneum, intermittent percutaneous aspiration of the syrinx, terminal ventriculostomy, ventriculoperitoneal and lumboperitoneal shunting, and finally resection or cauterization of the cerebellar tonsils.

In the Schijman and Steinbok international survey on aspects of the surgical technique used in Chiari malformation and related syringomyelia, suboccipital decompression was the standard surgical procedure for Chiari I malformation. The majority of the paediatric neurosurgeons preferred routine dural openings at surgery with closure with a pericranial or synthetic patch graft. The majority of the respondents avoided intradural manoeuvres such as tonsillar coagulation or resection, plugging the obex or shunting. In the case of persistent or progressive syrinx, after suboccipital decompression, the majority recommended shunting the syrinx to the subachnoid space or to the pleural cavity.

Another survey was organised by the paediatric section of the American Association of Neurological surgeons (24). There, a wide variety of surgical adjuvants to the standard bone decompression have been advocated in the treatment of the Chiari I malformation, especially when the tonsillar herniation is associated with syringomyelia. These included various

shunting procedures, duraplasty, obex plugging and resection of the cerebellar tonsils. The American neurosurgeons were surveyed on their surgical approach they used in paediatric patients with Chiari I malformation. Only 9% recommended performing decompression surgery in asymptomatic patients. For the treatment of symptomatic patients, many approaches were used; approximately 20% recommended only osseous decompression, 30% recommended osseous decompression with dural grafting and intradural dissection of adhesions and 30% recommended osseous decompression with dural grafting intradural dissections, tonsillar manipulation and resection.

Despite the controversy of operation specifics, some principles are agreed on. In a case of Chiari I malformation accompanying hydrocephalus, there is a consensus that priority should be given to hydrocephalus before considering a decompression. After shunting, if the symptoms do not resolve or if a large syrinx is coexisting, then the decompression is considered.

Historically, the surgical management of Chiari malformation has centered on bone decompression of the foramen magnum. Penfield and Coburn published the first case of a posterior fossa exploration in a woman with myelomeningocele (54); the following years were marked with numerous publications of small series in which the procedure was used.

The Chiari malformation decompression surgery has three main goals:

- decompression of the inferior aspect of the cerebellum,
- enlargement of the total volume of the posterior fossa,
- establishment of CSF flow.

Initial workup includes examination of supratentorial structures to ensure the absence of a mass lesion or hydrocephalus. In a patient in whom a shunt of any kind is in place it is important to determine that the device is functioning adequately. To assess causation and to allow presurgical planning it is important to evaluate spinal stability, especially in the setting of neck brace or spinal dysfunction. Besides, Grabb et al. have advocated the assessment of the degree of ventral brainstem compression (22). In patients with significant ventral brainstem compression, an anterior decompression procedure may be warranted prior to treating the malformation.

Although not all the steps are necessary, the aspects of the decompressive surgery are:

- positioning of the patient,
- incision,
- craniotomy or craniectomy,
- dural opening,
- decompression,
- resection of arachnoid adhesion,
- removal of inferior tonsils,
- opening of the obex,
- syrinx decompression (if desired),
- dural closure,
- closure of the craniotomy,
- fascial and skin closure.

More recently many authors advocated less invasive procedures such as a cranio-cervical junction (CCJ) decompression by using a simple duraplasty and little or no manipulation of the intradural contents. Or even less invasive, the recent reports for extradural CCJ decompression in patients with Chiari I malformation were also recommended. In the series of Limonadi et al., the authors hypothesized that extradural CCJ decompression may be better tolerated by patients than intradural procedures and may also require fewer medical resources (33). The authors performed a dura splitting technique in paediatric Chiari patients with syringomyelia where the middle dura was split from above the foramen magnum to below the C1 arch and dissected into two discrete anatomical leaves. The midline portion of the outer leaf was tented to the periosteum to encourage the dorsal expansion of the more supple inner leaf. The authors compared the findings with duraplasty in patients with syringomylia and found that the technique was safe, well tolerated and results in excellent early clinical outcome. This technique was also without exposure to the risk of CSF related operative complications and with less operative and total operating room time than the CCJ decompression. Other reports have described the simple FMD (removing the tight dural epidural band and the outer layer of the dura) and found same good results as with

conventional FMD and duraplasty (18). The authors concluded that leaving the dura closed prevents arachnoid membrane laceration which may result in scarring. Other surgeons advocated the method in a way to prevent delayed post-operative tethering (61).

The extent of bony resection to be performed is controversial. Extensive craniectomy has been incriminated as a factor of postoperative deterioration likely due to a slump of the lower part of the cerebellum in the wound. Large bony removal may result in cerebellar ptosis, wherein the cerebellum settles into the bony defect and can cause a new obstruction to CSF flow in the region of the cisterna magna. Klekamp et al. found statistically significant improvement in their results when they switched to smaller craniectomy (30). A current trend is to recommend that craniectomy should be tailored to match the size of a normal cisterma magna (i.e. 3 mm^2) (46).

Resection of the cerebellar tonsils has been promulgated by Williams (69) to maximally augment the free flow of CSF at the level of the foramen magnum and was initially advised as an intraoperative option in patients showing insufficient decompression by FMD alone. Gardner and Goodhall were against this option because of the complications (17), and after showing that it could be done safely, Fischer concluded that it offered no therapeutic advantage (15). Studies with modern imagery (2) such as ultra-sound and cine-mode MRI have confirmed that CSF flow is re-established to a satisfactory degree by the foramen magnum decompression alone without the need for tonsillar resection.

Plugging the obex of the fourth ventricle was first described by Gardner. In 1950 Gardner and Goodhall published their results of treatment of 17 patients with Chiari and proposed plugging the communication at the obex in combination with posterior fossa decompression (17). Subsequently, a large number of series describing posterior fossa decompression and occlusion at the obex have been published, with operation results varying widely. The idea was to prevent the development of hydromyelia resulting from excess flow of CSF from the fourth ventricle directly into the central canal of the spinal canal due to a blockage of other outflow pathway from the fourth ventricle. This theory was abandoned for the simple reason that on pathologic examinations, syringes are rarely seen to communicate with the fourth ventricle. Klekamp et al. evaluated 31 patients with cardiac gated dynamic MRI (30). In no case was a communication seen between the cyst and the fourth ventricle. In their study, Parks et al. found that not more than 3% of 127 patients demonstrated syringes that communicated with the fourth ventricle (51).

The issue of dural closure is disputed, some have advocated no dural closure at all. In a review of patients who underwent Chiari malformation with and without duraplasty,

Munschi et al. reported an increased rate of syrinx resolution when suboccipital decompression is combined with duraplasty (44). They found that all of their nine patients with Chiari I malformation and a syrinx, who underwent duraplasty, had a postoperative decrease in syrinx size in contrast to three of six in whom the syrinx decreased in size after suboccipital craniotomy alone. The authors noticed also that there seems to be a subset of patients whose symptoms will resolve and whose syringomyelia cavity will decrease with the removal of bone alone. The authors suggested further studies to better characterize these patients to determine which patients with Chiari I malformation are better served with bony decompression alone and which will require duraplasty to resolve their syringomyelia. Matsumoto and Symon noted no difference in the reduction of syringomyelia (35). However, regarding the improvement in symptoms, patients without duraplasty had a significantly worse outcome compared to those who underwent duraplasty.

Krieger et al. recommended durotomy without duraplasty in their series of 31 Chiari malformation patients treated over 6 years and mainly with concomitant syringomyelia (32). The dura mater was left open and overlaid with oxidized cellulose. The authors reported surgery-related outcomes and complications comparable with those achieved by authors who advocate duraplasty. These included plugging of the obex and tonsillar resection. In the Krieger series of 31 patients, there were three cases of transient CSF leaks that responded to bedside suturing without further sequelae. In the Klekamp et al. series where the dura was closed, 14 of the 131 patients had leaks and 10 needed operative revisions (30). For some authors this procedure does not negatively affect the outcome and it eliminates the need to implant foreign material that can cause intern inflammatory reactions and hemorrhagic reactions. Other authors strongly advocated water tight dural closure to avoid posterior fossa syndrome (meningism, headache, nausea and vomiting), prevent CSF leaks and potential meningitis, and emphasized that duraplasty is essential for the prevention of scar formation and recurrent symptoms. In most cases, closure is obtained using an artificial dural substitute. In some series, the pericranium has been used for the dural graft, others use an autograft obtained from the fascia lata which gives the patient additional incision. The use of heterologous graft has occasionally been associated with Creutzfeld-Jacob disease, effusion, pseudomeningocele, aseptic meningitis, bacterial infections and haemorrhage.

Once the dura is opened, the debate still exists as to whether arachnoid dissection should be performed. One benefit of arachnoid dissection in the setting of Chiari malformation is that it allows the surgeon to release adhesions that could potentially contribute to obstruction of CSF flow from the fourth ventricle to the spinal canal (52). Some

authors advise leaving the arachnoid intact if a duraplasty has to be performed because most of the complications, such as post operative arachnoiditis, meningitis, pseudomeningocele, hydromyelia development, hygroma and hydrocephalus, arise after the opening of the arachnoid (46).

One of the most disputed issues in the surgical management of Chiari malformation is the decompression of the syringomyelia. The methods employed can be grossly classified into two groups, those aiming at reduction of syringomyelia by direct drainage of the cavity and those aiming at restoration of normal CSF dynamics at the foramen magnum by decompression of the hindbrain and cerebellar tonsils. Thus, in patients with Chiari I malformation and syringomyelia, neurosurgeons may opt to decompress the syrinx at the first surgery or to perform only the suboccipital decompression and follow the syrinx conservatively by using MRI imaging. Several authors have reported that suboccipital craniectomy with duraplasty in most patients will be sufficient treatment and that the syrinx will resolve after the initial decompression. Togneti and Calbucci made a comparison between the craniovertebral decompression and shunting, and found a better outcome with craniovertebral decompression (62). Others conducted similar comparison in large series and have advocated syrinx shunting procedures as the initial approach, since they are easy to perform, are generally well tolerated and are associated with the same results as those achieved by foramen magnum decompression and also in some studies even have a better outcome. While in a large report Goel and Desai concluded that posterior craniovertebral decompression and placement of syringosubachnoid shunt are superior to placing a shunt alone (20), other authors find that undertaking two such different techniques within one session makes it difficult to ascribe the surgical results to any particular procedure, especially if a deterioration should occur postoperatively. Nevertheless, it is generally considered that hindbrain malformations have a relative contraindication to shunting procedures of the syrinx as the initial mode of treatment, due to concerns that further herniation of the spinal cord and compromise of the brain stem will be precipitated.

There are two basic forms of syrinx drainage that may be employed. One is to open the syrinx to the subachnoid pathway called myelotomy. The other is to drain the syrinx to a site outside the neuraxis such as the pleural or peritoneal cavities. Several types of shunts have been proposed as an initial treatment for syringomyelia, including syringoperitoneal, syringopleural, syringocisternal, syringosubachnoid and lumboperitonal shunting. In general, these procedures have been recommended in patients showing symptoms related to

syringomyelia and not to the Chiari malformation itself and in whom MRI showed that the syrinx was large.

Serious complications of the shunting technique have been outlined, such as damage to the spinal cord and septic complications, insufficient drainage due to the septation of the syrinx, arachnoiditis, hyperdrainage with slit-syrinx syndrome and persisting neural compression of the foramen magnum. Syrinx shuntings have been associated with high malfunction rate and low efficacy as a primary therapy. They are not recommended by some authors for treatment of syringomyelia associated with Chiari malformation with the argumentation that it is not possible to perform myelotomy without causing some damage to the cord. In addition, the CSF will still accumulate if the factors leading to the cord's filling are undisturbed.

Nauta et al. have reported a precise description of microsurgical anatomy of the spinal subarachnoid space (45). Anatomically many trabeculae exist between the pia mater and arachnoid membrane on the dorsal side of the spinal cord, and their studies of the ventral subarachnoid space have shown that there are no trabeculae between pia mater and arachnoid membrane. Therefore, in their series of 59 patients with syringomyelia associated with Chiari I malformation, Kazutoshi et al. placed the subarachnoid end of the shunt ventrally in patients with large-sized syringes: the authors had no further cases of shunt malfunction. Iwasaki et al. also reported their experience with syringosubarachnoid shunt placement (28). They found that in patients who underwent dorsal root entry zone (DREZ) myelotomy and placement of shunt into the anterolateral subarachnoid space, reoperation was unnecessary. This finding is in contrast to that in patients who underwent midline or DREZ myelotomies and placement of the shunt into the posterolateral or posterior subarachnoid spaces.

1.1.4 Complications and operation revision

The most common non-neurological postoperative complication in Chiari decompression patients is the development of aseptic meningitis. Menezes categorized a set of complications associated with surgery (posterior fossa decompression, duraplasty, and fourth ventricle to subarachnoid shunt), these were divided into immediate, intermediate, and late complications (40).

- Immediate complications included excessive bleeding from venous lakes, failure to get into the fourth ventricle secondary to adhesions, persistent lability of blood pressure and heart rate, failure to awaken, respiratory compromise, and weakness.
- Intermediate complications included infections, wound dehiscence, pseudomeningocele, CSF leakage, internucluar ophtalmoplegia, and aseptic meningitis.
- Delayed complications included diplopia, cerebellar sag due to large bony decompression, severe kyphoscoliosis secondary to multiple laminectomies, and progressive neurological deficits due to C1-C2 instability, change in mental status secondary to hydrocephalus or infection, ventral craniovertebral junction anomalies, recurrent syringohydromyelia and missed diagnosis (e.g. tumour).

Progressive neurological deficits after the initial operation should lead one to suspect instability at the craniocervical junction, possible presence of craniocervical junction abnormalities, recurrent syringomyelia, shunt malfunction or regeneration of the foramen magnum, tethering of the lumbal or cervical spinal cord.

Sacco and Scott reported on their experience with re-operation for Chiari malformation (58). They concluded that factors that were associated with a higher incidence of repeated operation included: young age at initial surgery, complex bone anatomy at the foramen magnum, an association with syndrome and nonsyndrom craniosynostosis, failure at the initial operation to assess and ensure patency at the foramen magnum and improper placement of stent in the fourth ventricle.

Complications related to conservative surgery may occur for different reasons (persistent compression) (36):

- inadequate craniectomy,
- persistent occipitoatlantal membrane,
- inadequate dural opening/duraplasty,
- residual arachnoid adhesion,
- residual tonsillar compression.

Other complications after adequate decompression:

- persistent syringomyelia,
- occipitocervical instability,
- anterior basilar invagination,
- arachnoid cyst development/arachnoid scarring/spinal cord tethering,
- reformation of the posterior atlantooccipital membrane,
- persistence of symptoms despite negative imaging studies.

Big craniectomy may lead to further caudal displacement of the cerebellum causing re-stenosis of the subarachnoid space. The postoperative complication is a cerebellar sagging due to the over zealous decompression. Patients may present weeks or months after surgery with persistent or new complaints related to brainstem and/or cerebellar displacement that have caused cervico-medullary compression. An excessive increase in the posterior fossa volume may allow the cerebellum and brainstem to herniate or sag into the area of decompression. Revision surgery is indicated, or for patients with elevated intra-cranial pressure (ICP), VP shunts can be placed.

Klekamp, Samii and Batzdorf recommended a size of cranioctomy which should be limited to the width of the spinal canal and not extend further upward than 2 cm from the rim of the foramen magnum in order to prevent cerebellar herniation (30). Further, the authors recommended the use of devitalized or artificial graft material and advised against autologeous grafts such as fascia lata or galea which may receive pial vascularization leading to dense adhesion of such grafts to the cerebellar cortex and create tendency for arachnoid scarring.

Post-operative hydrocephalus and inadequate dural closure or gaps within the fascial closure are the most common cause of CSF leakage and wound breakdown. Pare and Batzdorf recommended that duraplasty should be sutured in with running sutures to prevent any large CSF collection or pseudomeningocele which may create epidural pressures high enough to press the graft against the underlying cord and cerebellar cortex leading to scar formation (53). The posterior atlantooccipital membrane has been reported as a cause of recurrent symptoms after an initial period of improvement following a suboccipital craniectomy and decompression.

Complications after adequate decompression

Repeated imaging studies should be obtained to assess the adequacy of foramen magnum decompression. If the decompression and duraplasty are found to be generous, attention should be directed to the syrinx. The expansion or development of hydromyelia after initial decompression has already been reported. In those patients who worsen after surgery, consideration should be given to re-operation. The expansion or appearance of hydromyelia warrants reassessment of the posterior fossa decompression rather than shunting the hydromyelia. Pare and Batzdorf have reported an association between persistent syringomyelia and pseudomeningocele formation after Chiari malformation decompression (53). They described three patients in whom syringomyelia resolved only after their postoperative pseudomeningocele were repaired. These authors theorized that the persistence of syringomyelia in the presence of pseudomeningocele may be the result of dissipation of the CSF systolic pressure wave into the distensible pseudomeningocele cavity. They further posited that this phenomenon suggested that CSF pressure exerted on the cord surface favours resolution of the syrinx. Some authors have suggested that the presence of a pseudomeningocele may contribute to this phenomenon due to the fact that resolution could be helped by dissipation of the CSF pressure into this cavity instead of exerting pressure on the spinal cord.

Instability may be due to congenital osseous deformities or ligamentous weakness if an over zealous suboccipital craniectomy is performed, or if the C-1 and C-2 lamina are removed. Also a widely postoperative instability may develop. Another cause of persistent or recurrent symptoms may be anterior basilar invagination and compression of the anterior CMJ. Patients with Chiari malformation should undergo careful preoperative assessment to determine if there is any component of anterior decompression.

Ventral approaches do not address the fourth ventricular outlet obstruction or impacted cerebellar tonsils observed with Chiari I malformation. Some authors advocate a combination with a dorsal procedure and recommend in this case craniocervical fusion. Other authors aim to avoid an additional anterior approach and to reduce the overall rate of major morbidity. Related to this, they have recommended that paediatric patients with basilar invagination and a Chiari malformation should undergo posterior decompression, occipito-cervical reduction and posterior fusion. Transoral odontoidectomy should be conducted only in a case of insufficient reduction.

1.2 Chiari type 2 malformation (CM 2)

1.2.1 Definition

The type 2 Chiari malformation is a complex malformation involving the hindbrain, spinal cord and mesodermal structures, and is uniquely associated with myelomeningocele. This condition includes downward displacement of the medulla, fourth ventricle and cerebellum into the cervical canal, and elongation of the pons and the fourth ventricle. Chiari type 2 is frequently associated with syringomyelie, Klippel Feil syndrome and tethered cord.

1.2.2 Epidemiology

The frequency is about 1 case per 1000 population in the United States.

1.2.3 Mortality/Morbidity

The symptomatic type 2 Chiari malformation accounts for more deaths before the age of two in patients with spinal dysraphism than for any other cause (18). Cranial nerve and brainstem dysfunctions are the most life threatening problems. Approximately one third of patients with CM 2 develop signs and symptoms of brainstem compression through the age of five, and more than one third of these patients do not survive (14). Central ventilatory dysfunction is the most common cause of death in the Chiari type 2 population (24). The incidence of central ventilatory dysfunctions in children with myelodysplasie has been reported to be as high as 30% (38), with mortality ranging from 20% (26) to 75 % (6) of cases. In 1992, Vandertop et al. reported a mortality rate of 11.7% in infant undergoing surgery before the age of one month (64).

1.2.4 Pathophysiology

To date, four main theories have been presented in an attempt to explain the main features seen in CM 2, but none has proven completely satisfactory. Two main streams have emerged:

1) *The mechanical theory*

a. Hydrodynamic theory:

Chiari attributed the hindbrain herniation to hydrocephalus (6). Gardner and Goodall believed that hydrocephalus and hydromyelia were normal physiologic events in early embryologic development, and if the pathway to the normal progress of the cerebrospinal fluid (from the embryological fourth ventricle to the normally opening at the foramina of Luschka and Magendie) did not develop, it may result in increased pressure; the neural tube distends and ruptures result in myelochisis (17). The hydrocephalus is associated with myelomeningocele and cerebellar vermian herniation is induced by a cerebrospinal fluid pressure differential in the cranial and spinal compartment, which impels the cerebellar tonsils down from the higher pressure intracranial compartment into the foramen magnum and the lower pressure spinal compartment (69).

This theory however fails to explain other components of the Chiari malformation; the small size of the posterior fossa, the upward herniation of the vermis and the multiple supratentorial anomalies. From prenatal imaging, it is observed that CM2 is often present prior to hydrocephalus (37,38). In addition, 10 to 20% of children with myelomeningocele and CM2 never develop hydrocephalus and do not require shunt placement (31).

b. The traction theory:

The traction theory or the pull theory was proposed by Penfield, Cobum and Lichtenstein (54). They suggested that a tethered cord may pull the cerebellum and the medulla in the cervical canal which results in the vermian and brainstem herniation. However, the spinal chord is not always tethered and beside that the traction force is nonexistent beyond the fourth spinal segment from the tethered cord (21). Furthermore, this theory fails to explain other CNS abnormalities.

2) *Abnormal embryological development:*

a. The developmental arrest theory

Cleland proposed a developmental arrest theory with dysgenesis of the brain. This theory fails to account the numerous cranial and supratentorial anomalies frequently associated with CM2 and myelomeningocele (9).

b. The mesodermal deficiency theory

Marin-Padilla and Marin-Padilla proposed that a small posterior fossa, related to mesodermal deficiency, results in overcrowding in the posterior fossa and is the cause of the vermian and brainstem herniation (34). In fact, hamsters with depleted vitamin A may present underdeveloped posterior fossa but fail to present the other features of CM2 and myelomeningocele .

3) The unified theory:

This theory was proposed by McLone and Knepper (38). According to this theory, the neural folds fail to neurulate completely leaving a dorsal myeloschisis. This abnormal neurulation is a prerequisite for later developing the Chiari 2 malformation. Consequently, the spinal cord wall does not become properly apposed and occluded. An excessive drainage of ventricular CSF can also be observed. This drainage leads to a failure to maintain distension of the primitive ventricular system and allows the primitive ventricular system of the brain to collapse. This alters the inductive effects of pressure and volume on the surrounding mesenchym, and on the endochondral bone formation, which results in an abnormal small posterior fossa.

The development of the cerebellum and the brainstem within a small posterior fossa leads to:

a) Upward herniation, resulting in an enlarged incisural opening and a dysplastic tentorium.
b) Downward herniation, resulting in a large foramen magnum and caudal displacement of the cerebellar vermis and brainstem into the cervical canal.

A failure of ventricular distension could result in:

a) A disorganisation of the cranial nerve nuclei.
b) A close approximation of the thalami with a small third ventricle and a large massa intermedia.
c) An inadequate support for the radial glial cells that direct the normal outward migration of neuroblasts with consequent migration defects.

d) Failure to maintain the normal radial pattern of collagen formation and ossification in the developing calvarium leading to *lückenschädel*.

Hydrocephalus is seen as secondary to misdevelopment of the CSF pathway in the posterior fossa.

1.2.5 Observed abnormalities

The spectrum of abnormalities in Chiari 2 malformation is broad, with many findings reported:

Anatomic findings are:

1) *Osseous changes:*
   - Lacunar scull or lückenschädel: cluster of areas of thinning, pits, and fenestrae due to dysplasia of the membranous bones of the calvarium. A lacunar skull may be observed in utero in a fetus as of 8 months of gestation. The lacunar skull persists until the age of one to three months and then disappears after approximately six months of age independently of hydrocephalus.
   - Concave clivus and petrous ridge.
   - Small posterior fossa and large foramen magnum.
   - Low-lying transverse sinuses.

2) *Changes to the dura:*

   - Fenestrated falx.
   - Hypoplastic tentorium.
   - Heart-shaped incisura.

3) *Changes to the cerebellum, medulla, and spinal cord:*

- Cerebellar peg: a protrusion of the vermis and the hemispheres through the foramen magnum results in a craniocaudal elongation of the cerebellum behind the spinal cord.
- Medullary kink: the medulla is kinked inferiorly and lies dorsal to the cord.
- Towering cerebellum.
- Elongated fourth ventricle.
- Obliteration of the cerebellopontine cistern and the cisterna magna.
- The combined displacement of the spinal cord, medulla, pons and cerebellum form a cascade of herniation, each of which compresses all of the tissue in front of it, displacing them anteriorly.

4) *Changes to the midbrain, the third and the lateral ventricles:*

- Beaked tectum.
- Hydrocephalus.
- Colpocephaly.
- Prominent massa intermedia.

5) *Most frequent associated anomalies:*

- Myelomeningocele (88-100%).
- Dysgenesis of the corpus callosum (80-90%).
- Obstructive hydrocephalus following closure of myelomeningocele (50-98%).
- Syringohydromyelia (50-90%).
- Aqueductal stenosis (70%).
- Absence of septum pellucidum (40%).
- Contracted narrow gyria (stenogyria) (50%).
- Low-lying often-tethered conus medullaris below the lumbar nerve L2.

Signs and symptoms:

The first sign of CM2 is an open neural tube defect.

a) In infancy:

- Respiratory distress and impaired swallowing (71%).
- Inspiratory stridor (59%).
- Episodic apnea (29%).
- Weak or absent cry (18%).
- Aspiration (12%).
- Nystagmus.
- Pain in the upper and lower extremities.
- Weakness or spasticity of the upper and lower extremities (53%).
- Depressed or absent pharyngeal reflex.
- Fixed retrocollis.
- Palsy of the seventh cranial nerve.
- Scoliosis.
- Worsening of bladder and/or bowel function.

b) In childhood:

- Syncopal episodes.
- Nystagmus.
- Spastic quadriparesis.
- Upper extremity weakness with increased tone.
- Exaggerated deep tendon reflexes.
- Mirror movement.
- Appenducular and/or truncal ataxia.
- Recurrent pneumonia secondary to aspiration.
- Gastroesophageal reflex.
- Depressed or absent cough reflex.

1.2.6 Age dependency

The natural history of the CM 2 seems to be age dependent and two distinct age dependent syndromes are identified; those for patients younger than the age of two and those for patients older than the age of two. Infants younger than two years of age present more frequently cranial nerve and brain stem dysfunctions. Older children are rarely a neurosurgical

emergency; the hallmark of this age group is the cervical myelopathie with upper-extremity weakness and spasticity.

65% of the clinical manifest CM2 patients are younger than three months (53). In the retrospective series of Pollak et al. (56), out of 25 symptomatic Chiari II patients, 13 neonates presented with symptoms of brainstem compression before three months of age and 12 patients presented after this age period. Within patients older than three months, none had died or had a poor outcome. In the series of patients younger than three months, 23% died and 16% had a poor outcome. Intrinsic brainstem abnormalities are thought to be the cause for the poor outcome.

1.2.7 Brainstem dysfunctions

Theories of brainstem abnormalities have included:

- Compression with traction on the cranial nerve, particularly when the cervical rootlets of the vagal nerve which innervate the cricoarytenoid muscle for vocal cord abduction, traverse and abnormally long course through the foramen magnum to their exit foramina in the skull (26). This produces ineffective vocal cord abduction (16).
- Vascular compromise with areas of brainstem ischemia, infarction, hemorrhage and necrosis in patients who exhibit stridor and apnea (10, 43). Papasozomenos and Roessmann found a combination of medullary hemorrhage, hemorrhagic necrosis, and bland infarction in 12 of 14 children with melomeningocele and Chiari malformation who died with symptoms of severe brain stem dysfunction (25).
- Primary dysgenesis including hypoplasia of the cranial nerve nuclei. Gilbert et al. noted defective myelenisation and an absence of various brainstem nuclei in 19 of 25 children with myelmeningocele and Chiari malformation (19). Sieben et al. (60) and Hollinger et al. (26) reported abnormalities of crucial lower cranial nerve nuclei in affected patients.

Cranial nerve nine and ten are frequently affected leading to chronic aspiration, pneumonia, choking, nasal regurgitation and prolonged feeding time. The neurogenic dysphagia which frequently appears prior to the onset of respiratory symptoms or other brainstem dysfunctions is nearly always progressive (56). Inspiratory stridor is often the most

noticeable sign of brainstem dysfunction in the infant and severe disorders of arousal to respiratory stimuli and neurological control of respiration are found to be present in infants with myelomeningocele with Chiari 2 malformation. Moreover, while approximately 30% of CM2 children have normal sleep-breathing, 20% of CM2 children show severe sleep-disordered breathing (68), apnea, hypoventilation and arousal deficits. These may predispose to prolonged apnea, which could increase the risk of sudden death during the first two years of life (67).

It is believed that apnea may result from central neural dysfunction (centrally mediated expiratory apnea with cyanosis) and should be distinguished clinically if not etiologically from the bilateral abductor vocal cord paralysis (BAVCP) (obstructive apnea) (26). BAVCP may be precipitated suddenly with hydrocephalus and increasing intracranial pressure, the patients can develop severe inspiratory stridor and asphyxia (26). The transient nature of the stridor and the reversibility of the BAVCP (and respiratory distress) after the relief of the increased intracranial pressure are seen as an argument against the involvement of a selective structural lesion of the brainstem. Persistent hydrocephalus is correlated with a less favourable prognosis of vocal cord function return; an immediate relief is a priority (6, 29). Cochrane et al., in a small number of patients, have also delineated between obstructive and central apnea and have found that obstructive apnea is usually reversed with an optimally functioning VP shunt, whereas central apnea does not respond to cervical decompression (13).

Another lethal respiratory sign is prolonged expiratory apnea with cyanosis (PEAC). It manifests itself as a total cessation of expiratory effort with cyanosis, which can also occur in mechanically ventilated patients. More than one half of patients with CM2 and apnea in the infancy can be expected to die of PEAC.

1.2.8 Surgery timing and patient selection controversy

In the recent past years, the major area of controversy was in determining which patients should be considered for operative intervention. To date, all evidence regarding the management and treatment of the symptomatic CM 2 are class III data. Treatment of the symptomatic infant with clinical evidence of brain stem dysfunction is quite controversial and problematic, inasmuch as clarification of the pathogenesis for the clinical symptoms is incomplete.

In his review of an experience with 22 symptomatic cases, Charney et al. concluded that decompression may be effective in certain infants but not all, independently if early or delayed surgery was taken (10). Since a better patient selection is a priority, Charney proposed in his article a new classification described here below.

Charney classification:

- Grade1: stridor alone as a result of vagal nerve traction often improves with ventricular shunt alone.
- Grade 2: stridor and apnea.
- Grade 3: cyanotic spells or dysphagia.
- Grade 2 and 3 are caused by more extensive and potentially irreversible brainstem damage from hemorrhage, infarction and necrosis. Infants show minimal or no improvement after neurosurgical procedures,

Because the pathogenesis of the brainstem abnormalities is still not clarified and the outcome after hindbrain decompression variable (25), the indication for hindbrain decompression is still controversial. In their article, Pollack et al. demonstrated that the symptoms and signs of brainstem dysfunctions are generally progressive rather than fixed in severity (56). In children who had developed particularly severe impairment with bilateral vocal cord paralysis and apnea, the prognosis was poor. The brainstem dysfunctions in many children resolved after hindbrain decompression. With early hindbrain decompression, a better outcome can be achieved. The conclusion was that brainstem dysfunctions are reversible up to a certain point after which the deficits are becoming fixed, presumably as a result of bulbar ischemia and infarction. Chiari II patients are now frequently operated at the first detectable symptom or evidence of syrinx. There is a consensus among paediatric neurosurgeons that if the patient is symptomatic, the chances for improvement are better after surgical intervention. Hoffman et al., in their review of symptomatic CM 2 patients, found 100% resolutions of symptoms in children treated immediately with posterior fossa decompression (53). In the Parks et al. study, although 38% of the 85 patients series had died in the most recent follow up, the authors still considered prompt decompression as essential for a successful outcome (52). Elsewhere, Pollack et al. found a good outcome approaching

60% when the symptomatic infant is identified and decompression is expeditiously performed (56). They recommended an aggressive approach to symptomatic CM 2. In cases of asymptomatic patients with extensive syrinx comprising 50% or more of the cross-sectional diameter of the spinal cord, these have great risk to progress and should also be considered as surgical candidates. The outcome of older children presenting with myelopathie who undergo hindbrain decompression is much better in the literature. It ranges from 79% to 100% improvement in symptoms whereas the mortality approaches 0% (56).

Often the symptoms of CM 2 are precipitated by increased pressure due to a malfunctioning shunt. The first step in preparing a child for surgery is ensuring that hydrocephalus is not the cause of symptoms and often a properly functioning ventricular shunt can obviate the need for decompression of hindbrain herniation. Tubbs and Oakes opened another subject of debate on how to define a properly functioning shunt (63)? Is it a radiological stable ventricle, normal shunt tabs or an operative visualization of flow from a ventricular catheter? Iskandar et al. found that in 20% of a study group of myelodysplastic children with shunted hydrocephalus, and in whom CT studies were interpreted as prospectively unchanged, shunt malfunctioning was operatively revealed (27). Milhorat et al. found in a retrospective study in a small series of 5 patients, that all patients had improvement in the syrinx size following a ventriculoperitoneal (VP) shunting or revision (42). Charney et al. found that lower cranial nerve dysfunction was shown to resolve in 50% of cases after a VP shunt revision (10). In contrast, Venes et al. have found that lower cranial nerve findings are not improved following the confirmation of a functioning shunt, but only after posterior fossa decompression (65). They recommended posterior fossa decompression with internal shunting for symptomatic patients. Finally, Caldarelli et al. found that of the 11 symptomatic CM 2 patients, 2 had resolution of their symptoms following shunt revision alone, 4 after decompression; 3 died after shunt revision and 2 died prior to any surgical treatment (8).

2 Summary

There is still much controversy regarding the best treatment paradigm of patients with Chiari malformation and until this time, clinical practice is based on individual surgeon's experience and training.

We reviewed the surgical experience, in the last four decades in our institution, of patients afflicted with Chiari malformation and we present this series of 74 patients in whom the diagnosis of Chiari malformation was confirmed and in which 61 patients underwent a surgical procedure. The patients were classified into three distinct groups; Chiari malformation type I (CMI), Chiari malformation type I with concomitant syringomyelia (CMI/SM) and finally patients afflicted with Chiari malformation and spina bifida which included three patients documented as Chiari I, nine patients as Chiari II and one patient as Chiari III. The presenting symptoms and signs, preoperative investigations and preoperative findings, surgical findings and progress following surgical decompression were analysed.

There is significant debate and variable results in the current neurosurgical literature regarding the evaluation of shunt function vs. Chiari decompression in patients with symptomatic Chiari II. In this aim to better perceive the outcome of symptomatic and not symptomatic patients with Chiari II, we analyzed separately their evolution over the years.

2.1 Summary of cases

A retrospective review of patients with Chiari malformation seen at the department of neurosurgery at the University Hospital of Tübingen from 1977 through 2006 was conducted. This review yielded 74 patients:

- 17 Chiari malformation Type I patients,
- 43 Chiari malformation Type I and Syringomyelia patients,
- 13 Chiari malformation and myelomeningocele patients (3 CM I, 9 CM II, 1 CM III),
- 1 Chiari malformation Type II patient.

Sex and age distribution, age of onset, prior surgical treatments, preoperative symptoms, neurological findings, radiological characteristics, operative procedures outcome and complications were analyzed from the admission history, physical examination and operative reports. All patients underwent a physical examination, a complete neurological examination, CT, MRI of the head and the spine (in some cases additional information was provided by

CINE-MRI), ophthalmologic examinations, vestibular function tests, 24-hour sleep monitoring and other diagnostic tests. A database was established for each patient and the statistical analysis was obtained with MATLAB.

	Age (years)								
	1-9	***10-19***	***20-29***	***30-39***	***40-49***	***50-59***	***60-69***	***70-79***	**Total cases**
Male	5	3	6	5	6	3	1	0	**29**
Female	4	5	3	5	10	11	6	1	**45**

Table 1. Age and sex distribution in patients with Arnold Chiari.

The age and sex distributions of the 74 patients are given in Table 1. There were 29 males and 45 females. The mean age was 37.24 years for the CMI, 43 years for CMI/SM and 11.69 years for the CM/MMC patients. Table 2 summarizes the characteristics of patients with the various forms of Chiari malformation, as well as their clinical presentation. The age of onset was defined as the patient's age at which initial symptoms appeared. Patients with CMI presented an age of onset with a mean of 32.54 years and received diagnosis with a mean of 1.93 years later. Patients with concomitant syringomyelia presented an older age of onset (37.35 years) and received their diagnosis with a mean of 2.84 years later. Patients with CM and MMC were the youngest at 11.69 years of mean age (range from 2 days to 31 years). They received their diagnosis at birth, since all these patients underwent the closure of their myelomeningocele (10 patients) or encephalocele (3 patients) mostly within the first 2 days of their life.

	CM1 (17 patients)	**CMI/SM (43 patients)**	**CM/MMC (13 patients)**	**CMII (1 patient)**	**All patients**
Gender (M/F)	10/7	14/29	5/8	0/1	**29/45**
Mean age (years)	37.24	43	11.69	27	**29.73**
Prior surgical treatment (number of patients)	3 (18%)	11 (26%)	13 (100%)	-	**27 (36%)**
Mean age of onset (years)	32.54	37.35	At birth	At birth	-
Mean age of definitive diagnosis (years)	34.47	40.19	At birth	At birth	-
Precipitating factors (number of patients)					
None	15	33	11	1	**59**
Trauma	-	4	-	-	**4**
Infection	-	2	-	-	**2**
Coughing or sneezing	2	4	2	-	**8**

Table 2. Characteristics of patients and their clinical presentation.

2.2 Clinical presentation of CM I and CMI/SM patients

Three patients (18%) from the CMI population had prior surgical treatment which included cystoperitoneal shunt followed by a shunt revision in one patient, ventriculoperitoneal shunts in a second patient and a third patient with an operated discal hernia. Eleven patients (26%) from the CMI/SM population underwent prior surgical treatment. These included three cases of ventriculoperitoneal shunting, three syringosubarachnoidal shunting, one ventriculostomie, one posterior fossa decompression, one syrinx decompression and two discal herniation. The majority described a spontaneous onset of symptoms; two CMI patients (12 %) from the CMI population cited coughing or sneezing as the precipitating factor. 23% (10 patients) with CMI/SM cited a precipitating factor, four patients cited trauma, four patients cited coughing and sneezing whereas two patients cited infection (Table 2).

Symptoms	CMI (17 patients)	CMI/SM (43 patients)	CM/MMC (13 patients)
Pain	**11 (65%)**	**38 (88%)**	**6 (46%)**
Headache	10 (59%)	21 (49%)	6 (46%)
Neck	7 (41%)	20 (47%)	2 (15%)
Back	1 (6%)	8 (19%)	-
Chest	1 (6%)	6 (14%)	-
Arm	4 (24%)	15 (35%)	-
Leg	1 (6%)	5 (12%)	-
Weakness	**2 (12%)**	**20 (46%)**	**8 (62%)**
arm	2 (12%)	14 (33%)	1 (8%)
Legs	1 (6%)	6 (14%)	1 (8%)
paraparesis	-	1 (2%)	5 (38%)
quadriparesis	-	1 (2%)	3 (23%)
Sensory Loss	**5 (29%)**	**26 (60%)**	**4 (31%)**
arm	3 (18%)	15 (35%)	-
Trunk	-	3 (7%)	-
legs	2 (12%)	8 (19%)	1 (8%)
Hemihypalgesia	1 (6%)	3 (7%)	2 (16%)
cervical level	1 (6%)	7 (16%)	2 (16%)
Ataxia	**8 (47%)**	**17 (39%)**	**2 (16%)**
Vertigo	6 (35%)	10 (23%)	-
Diplopia	2 (12%)	2 (5%)	3 (23%)
Dysphagia	3 (18%)	1 (2%)	2 (16%)
Dysarthria	2 (12%)	2 (5%)	1 (8%)
Apnea	-	-	2 (16%)
Incontinence	-	4 (10%)	7 (54%)
Parasthesia	3 (18%)	13 (30%)	-
Tinitus	-	2 (5%)	-
Drop attacks	-	1 (2%)	-
Vomiting	2 (12%)	1 (2%)	1 (8%)
Sleep apnea	1 (6%)	1 (2%)	-

Table 3. Preoperative symptoms in cases of Chiari malformation.

Table 3 summarizes the symptoms upon admission of the 74 patients. The most common symptom of CMI and CMI/SM was pain; 65% and 88% of cases respectively, and headache was the most frequent pain manifestation with 59% for CMI and 49% for CMI/SM. Headache in 41% of CMI cases and 47% of CMI/SM cases was associated with cervical pain, followed by arm pain in 24% of CMI and 35% of CM/SM cases.

Sensory loss comes in second place of claimed symptoms, and was experienced by 29% in the CMI population and by 60% of patients with CMI/SM. Elsewhere, 18% of CMI and 30 % of CMI/SM patients experienced a sensory disturbance in form of parasthesia. Sensory loss was mostly noticed in upper extremities followed by lower extremities; these included numbness or tingling and loss of temperature sensation. The CMI population showed more often lower cranial nerve, brainstem and cerebello-vestibular disturbance than did the

CMI/SM population. The most common symptoms were ataxia (47%), vertigo (35%), dysphagia (18%), dysarthria (12%) and diplopia (12%).

Neurological findings	CMI (17 patients)	CMI/SM (43 patients)	CM/MMC (13 patients)	Total (73 patients)
MotorWeakness	-	**9 (21%)**	**6 (46%)**	**15 (21%)**
Arm	-	6	1	7
Legs	-	1	-	1
Paraparesis	-	-	4	4
Quadriparesis	-	2	3	5
Muscle atrophy	-	**6 (14%)**	**3 (23%)**	**9 (12%)**
Hyperreflexia	**1 (6%)**	**4 (9%)**	**5 (38%)**	**10 (14%)**
Upper extremity	-	1	1	2
Lower extremity	-	2	1	3
Upper/lower Extremity	1	1	3	4
Sensory loss	**9 (53%)**	**18 (42%)**	**2 (15%)**	**29 (40%)**
Thermoanesthesia	3	10		13
Posterior columm sensation	8	15	2	25
Nystagmus	**5 (29%)**	**7 (16%)**	**4 (31%)**	**16 (22%)**

Table 4. Neurological findings in cases of Chiari malformation.

Motor weakness was claimed by 12% of CMI and 46% of CMI/SM patients, but objective findings showed motor weakness only in 21% in the case of CMI/SM as indicated by neurological findings summarized in Table 4. Motor weakness was concomitant with muscle atrophy in 14% of cases.

Objective sensory losses were found in 53% within the CMI and in 42% within the CM/SM population; 47% of CMI and 35% of CMI/SM patients suffered from a loss of posterior column sensations.

Signs	**CMI (11/15 patients)**	**CMI/SM (28/33 patients)**	**CM/MMC (13/13 patients)**	**Total (52/61 patients)**
Cranial nerve palsy	5 (33%)	6 (18%)	8 (61%)	19 (31%)
Scoliosis	2 (13%)	6 (18%)	7 (54%)	15 (25%)
Nystagmus	5 (33%)	6 (18%)	3 (23%)	14 (23%)
Ataxia	7 (47%)	17 (51%)	3 (23%)	27 (44%)
Spina bifida	-	-	13 (100%)	13
Encephalocele	-	-	3 (23%)	3
Myelomeningocele	-	-	10 (77%)	10

Table 5. Preoperative signs in cases of patients with Chiari malformation.

15 of the 17 CMI patients (88%) and 33 of the 43 patients with CMI/SM (77%) underwent a surgical intervention in our institution; their preoperative signs are summarized in Table 5. Among the patients selected for surgical treatment, 11 CMI (73%) and 28 CM/SM (84%) showed preoperative signs. The most common signs in CMI were ataxia (47%), cranial nerve palsy (33%), nystagmus (33%) and scoliosis (13%). Patients with CMI/SM showed ataxia in 51%, nystagmus in 18%, cranial nerve palsy in 18% and scoliosis in 18% of cases.

Abnormalities	**CMI**	**CMI/SM**	**CM/MMC**	**Total**
Head MRI	**17**	**43**	**13**	**73**
Compression of cerebellar cisterns	17	43	13	73
Tonsillar herniation of more than 5mm	16	39	10	65
Atlas assimilation	3	2	-	3
Reduced length of clivus	1	-	-	1
Syringomyelia	-	43	3	46
Kinking of medulla	2	3	2	7
Cerebellar hypoplasie	1	-	1	2
Basillar invagination	2	5	-	7
Compression of fourth ventricle	2	2	1	5
Arachnoidal cyst	3	1	-	1
Hydrocephalus	2	7	7	16
Syringobulbia	-	1	1	2
Dandy walker	-	1	1	2
Cine MRI measuring CSF velocity/flow at foramen magnum (n° of patients)	**1**	**5**	**-**	**6**
Decreased posteriory	1	5	-	6
Decreased anteriorly	1	3		4
Spine MRI	**17**	**43**	**13**	**73**
SM	-	43	3	46
Scoliosis or Kyphosis	2	8	7	17
Klippel-Feil syndrom/platybasy	1	1	2	3

Table 6. Preoperative MRI findings in cases of patients with Chiari malformation.

Table 6 provides a description of the MRI features of this series of patients with Chiari malformation. The most common findings were compression of the CSF spaces around the cerebellum in all patients. Tonsillar herniation of at least 5mm was observed in 94% and in 91% of CMI and CMI/SM patients respectively. Concomitant hydrocephalus was observed in 12% of CMI and in 16% of CMI/SM cases. Finally, arachnoidal adhesions binding the tonsils to the upper cervical cord were noted in 38% of CMI and 48% of CMI/SM patients.

Spinal abnormalities found to be associated to the malformation included syringomyelia; 63% (46 patients) of cases in the entire series of 74 admitted patients. Abnormal skeletal

curvatures such as scoliosis or kyphosis were detected in 2 CMI patients (12%) and in 8 CMI/SM patients (19%). Bony anomalies were observed in the cranio-vertebral junction in 6 CMI patients (35%) and in 8 CMI/SM patients (19%) that included basilar invagination and atlanto-occipital assimilation, block vertebrae of Klippel-Feil syndrome as well as the Dandy Walker syndrome. Other findings included kinking of the medulla, compression of the fourth ventricle, arachnoidal cyst, syringobulbie and cerebellar hypoplasy.

Of the patients who have undergone CINE-MRI, six have shown a decrease of CSF flow posterioly (in the cisterna magna and subarachnoid space poserior to the cerebellum) and in four cases a decrease anteriorly (the premedullary and prepontine spaces anterior to the brain stem).

The operative approach in our institution in case of Chiari malformation was as follows:

- in case of concomitant hydrocephalus priority is given to ventriculo-peritoneal shunting,
- posterior fossa decompression is performed for the patients without hydrocephalus or for the patients with hydrocephalus who have not improved after shunt procedure.

2.3 Prior surgical treatments in patients selected for operation

In the CMI group (15 patients) two patients had prior surgical treatment related to their disease. One patient underwent a cystoperitoneal shunting procedure after a left temporal arachnoidal cyst was detected; this was followed by multiple shunt revisions due to a shunt dysfunction. The posterior fossa decompression by this patient was performed in an aim to avoid a formation of syrinx. The second patient had hydrocephalus treated with a ventriculoperitoneal shunting which required a revision after shunt infection.

In the CMI with syringomyelia group (33 operated patients), five patients had prior surgical treatments; three patients underwent in the past syringosubarachnoid shunting, one patient syringosubarachnoid shunting and later PFD, and one patient had hydrocephalus treated with a ventriculoperitoneal shunting.

2.4 Operation procedure

Procedure	CMI (15 patients)	CMI/SM (33 patients)	CM/MMC (13 patients)	**Total (61 patients)**
Transoral odontoid resection	1	-	-	**1**
PFD with DG alone	11 (73%)	27 (82%)	5 (38%)	**43 (70%)**
PFD with DG combined with cystosubarachnoid shunt	1	-	-	**1**
PFD combined with resection of tonsils	1	-	-	**1**
PFD combined with VP shunt	-	1	-	**1**
Cystosubarachnoid shunt	-	1	1	**2**
Ventriculostomie	-	1	-	**-**
Ventriculoperitoneal Shunt	-	2 (6%)	6 (46%)	**8 (13%)**
Arachnoidal cyst fenestration	1	1	1	**3**

Table 7. Operative management of patients with Chiari malformation.

As noted in Table 7, 73% of the CMI group (11 patients) underwent a posterior fossa decompression with a dural graft. Other procedures included transoral odontoid resection (one patient), posterior fossa decompression combined with a cystosubarachnoid shunt due to arachnoidal cyst (one patient), PFD combined with a cerebellar tonsils coagulation (one patient) and posterior fossa decompression with arachnoidal cyst fenestration (one patient).

Elsewhere, in CMI with concomitant syringomyelia, 82% (27 patients) underwent posterior fossa decompression and dural graft, and 6% (two patients) a ventriculoperitoneal shunting. Other procedures were PFD combined with a ventriculoperitoneal shunting (one patient), cystoperitoneal shunting (one patient), PFD with an arachnoidal fenestration (one patient) and endoscopic ventriculostomie by occlusive hydrocehalus (one patient).

2.5 Surgical findings

A summary of surgical findings in this series is given in Table 8. Tonsillar herniation was found in all cases except one. The most common level of herniation in the CMI case was level of C2 (38%) and C1 (42%) in the CMI/SM case. Adhesions between the dura, arachnoid and tonsils were frequently observed in both cases of CMI/SM (48%) and CMI (38%). Vascular anomalies were noted in 8% of all cases, and various degrees of bone deformities were found at the cranio-vertebral junction in 62% of CMI and 52% of CMI/SM patients.

Surgical findings	CMI (13 patients)	CMI/SM (33 patients)	CM/MMC (5 patients)
Tonsillar descent	12	33	5
Below foramen magnum	3 (23%)	9 (27%)	
C1	3 (23%)	14 (42%)	2 (40%)
C2	5 (38%)	6 (18%)	-
C3	-	-	-
Level unspecified	1	4	3
Adhesion	5 (38%)	16 (48%)	-
Tethered cord	-	-	2
Dural Band	-	6 (18%)	-
Vascular anomalies	2 (15%)	1 (3%)	1
Skeletal abnormalities	8 (62%)	17 (52%)	5 (100%)
Arachnoid cyst	2 (15%)	-	1

Table 8. Surgical findings in cases of patients with Chiari malformation.

2.6 Operative Results

Morbidity and Mortality	**CMI (7/15 operated patients)**	**CMI/SM (17/33 operated patients)**	**CM/MMC (3/5 operated patients)**
Respiratory depression	4 (27%)	4 (12%)	-
CSF leak	5 (33%)	5 (15%)	3 (60%)
Headache	1 (7%)	8 (24%)	-
Wound infection	2 (13%)	4 (12%)	-
Worsening of symptoms	-	8 (24%)	-
Meningitis	2 (13%)	-	-
Hygroma	2 (13%)	3 (9%)	5

Table 9. Postoperative morbidity and mortality of patients with Chiari malformation.

- Postoperative morbidity and mortality are shown in Table 9.

There was no incidence of mortality in this series of patients. Seven CMI patients (47%) and 17 CMI and SM patients (52%) had postoperative complications. In the CMI case, the most frequent postoperative complication was CSF leakage. This occurred in five CMI patients (33%), followed by respiratory depression (usually in the first two days after operation) which occurred in the four of the 15 patients (27%). In addition, two patients who had lower cranial nerve involvement needed elective ventilation which lasted 24 hours.

In the CMI/SM patients, the most frequent postoperative complications were worsening of symptoms, which occurred in eight patients (24%), and headache also in 24% of cases. Other postoperative complains in the mixed series of CMI with or without SM, were one case of shunt infection which needed shunt replacement, one sepsis, one pneumonia and one lung embolism.

- Long-term progress

All patients have been reviewed in the outpatient clinic postoperatively. The period of follow up ranged from 5 months to 10 years with a mean of 4 years (Table 10).

Postoperative results		Foramen magnum compression			Central cord disturbance			Cerebellar syndrome		
		CMI	**CM/SM**	**CM/MMC**	**CMI**	**CM/SM**	**CM/MMC**	**CMI**	**CM/SM**	**CM/MMC**
N° of cases		14	32	10	11	30	6	6	10	3
Early Improvement %		100	81	70	91	70	50	83	70	33
Symptomatic only %		-	-	-	-	-	-	-	-	-
Symptomatic and clinical %		100	81	70	91	70	50	83	70	33
No change %		-	19	30	-	3	23	16	33	67
Worse %		-	-	-	-	7	-	-	-	-
Late Deterioration	n° patients	2	4	1	3	1	4	2	1	-
	percent	14	13	10	27	13	17	33	10	-
Improved at last review	n° patients	10	28	7	7	26	3	3	9	1
	percent	71	87	70	63	78	50	50	90	33

Table 10. Postoperative results at latest follow up examination of patients with Chiari malformation.

The symptoms and signs were divided into three groups:

- Foramen magnum compression presented a combination of motor and sensory deficits along with ataxia and lower cranial neuropathies and headache.
- Central cord syndrome presented a dissociated sensory loss, upper extremity weakness/wasting and long tract signs.
- Cerebellar syndromes presented primary symptoms of ataxia and/or nystagmus.

2.6.1 CMI patients

Early improvement of preoperative symptoms occurred in 91% among the CMI patients. The most favorable result in early improvement was noted among patients with foramen magnum compression (all 14 patients), 2 patients (14%) experienced late deterioration and 10 (71%) improved at last review.

Of the 15 CMI patients, 11 (73%) presented a central cord disturbance. Among them, 91% showed early clinical and symptomatic improvement, 27% experienced late deterioration and 63% improved at last review.

Among the CMI patients with cerebellar syndrome (40%), 83% showed clinical and symptomatic improvement, 33% experienced a late deterioration and 50% improved at last review.

2.6.2 CMI with SM

Early improvement was experienced by 73% of CMI/SM patients, while 81% of patients with foramen magnum syndrome experienced early symptomatic and clinic improvement, 19% felt no change and 4% experienced late deterioration (Table 10). In the long term, CMI/SM patients showed very good results with 87% of improvement, at last review, of the symptoms related to the foramen magnum compression.

Of the 33 CMI/SM patients, 30 (91%) presented central cord disturbances, 70% of those experienced early clinical and symptomatic improvement, 23% felt no change, while 7% felt worse and 13% experienced later deterioration. In the long term results, CMI with SM patients showed 78% of improvement of their central cord disturbances at last review. Good results were noted in the ten (30%) CMI and SM patients presenting a cerebellar syndrome. 70% of them showed an early improvement, 30% showed no change, while one patient experienced a late deterioration. Finally, 90% showed an improvement of their cerebellar syndrome at last review.

2.7 Postoperative changes in the syrinx

Among the 33 operated CM/SM patients, postoperative MRI findings from 27 patients were reported. Reports about changes of the syrinx size were indicated after posterior fossa decompression. The follow up period had a mean of 4 years and the MRI imaging demonstrated that:

- in 14 patients (52%) the syrinx reduced size,
- in 12 patients (44%) the syrinx expansion stabilized,
- in one patient (4%) the syrinx completely resolved.

2.8 Complications and operation revisions

2.8.1 CMI patients

In the CMI series of patients, three (23%) needed operation revisions. In one case, a shunt infection was manifested where the shunt needed to be removed after an infection with staphylococcus epidermis had been detected. One case of permanent headaches was reported.

After a posterior fossa decompression, this patient underwent a ventriculoperitoneal shunt 6 months later. The third case was that of a second posterior fossa decompression and arachnolysis with cerebellar tonsils resection. The patient could not improve mainly due to his myelon atrophy 10 years after his first decompression.

2.8.2 CMI/SM patients

In the CMI/SM series of patients, five (15%) needed operative revision. One case of lumbal canal stenosis 10 years after a posterior fossa decompression was reported. The patient underwent an osteoligamentaire decompression with good clinical results. Another case was that of a patient with cervical syrinx expansion 1 year after a posterior fossa decompression. The latter underwent an extensive posterior fossa decompression which stabilized the syrinx size and led to a good improvement at last patient's review (5 years later). In a third isolated case, two years after posterior fossa decompression and wound revision due to CSF leakage, MRI imaging showed an expansion of the syrinx. This patient successively underwent a syringosubarachnoid shunting and 10 years later an adhesiolysis. At the last review, the size of the syringomyelia has reduced. Two months after initial decompression, a fourth patient developed an intramedullary oedema with expansion of his cervical syringomyelia. A revision was undergone where adhesions in the fourth ventricle were released. At last review (5 months later), the syrinx size was stabilized but the patient did not show any improvement. In the fifth and final case, a wound revision due to CSF leakage and meningitis after a posterior fossa decompression were reported. The patient obtained an SSB shunt implant 2 years later in an aim to stabilize an expansive postoperative syringomyelia. The patient's clinical symptoms did not improve considerably; an adhesiolysis was then undergone 10 years later. At the last follow up, five months later, the patient showed satisfactory clinical improvement and his MRI imaging showed a decreased size of the syrinx.

2.9 Patients with Chiari malformation and Myelomeningocele (CM/MMC)

Between 1977 and 2006, 13 patients with a diagnosed Chiari malformation and Myelomeningocele were admitted at the neurosurgery department of the Tübingen university hospital. They consisted of six males and seven females with a mean age of 11.69 years, ranging from 1 day to 33 years old. Chiari II was documented in nine patients by MRI and operative findings, while three patients were documented as Chiari I and one patient as Chiari III. Their clinical findings and follow ups are summarized in Table 11.

There were ten patients (77%) with myelomeningocele and three patients (33%) with encephalocele. Most of them underwent a closure of their spina bifida within the first two days after birth. Elsewhere, a ventricular dilatation in various degrees was found in all the 13 Chiari and spina bifida patients. These children had each undergone a CSF shunt due to a progressive hydrocephalus. Six neonates needed shunting right after birth and this was usually combined with the closure of their dysraphic lesion. Five neonates were shunted in the first four weeks of life and one neonate after two months. Finally, a single patient developed hydrocephalus first at the age of 14 years and was then shunted.

All the admitted patients had a shunt inserted; the majority a VP shunt (12 patients) and one patient, suffering from Dandy-walker and Klippel-feil abnormalities, received a cystoperitoneal shunt.

The patients were in majority asymptomatic, except for three (23%) patients that were documented as Chiari II and who were found to present a brain stem compromise. Of those three patients, one presented concomitant syringomyelia and one presented syringobulbia. Respiratory signs and symptoms due to lower brain stem dysfunction were observed in these three patients; by one neonate at the age of two days, by the second patient at the age of four weeks and by the third at the age of 6 weeks. Stridor and apnea were the presenting signs. They were first associated with crying or feeding and later became continuous, leading to respiratory distress. Upper airway obstruction was managed initially with intubation in the three patients. Two patients later developed laryngeal stenosis where tracheostomy was performed. Additionally to a CSF shunt, one of the symptomatic patients also required a posterior fossa decompression.

At the latest admission, the mean age was 11.69 years. Two patients cited coughing or sneezing as the precipitating factor, while paraparesis and tetraparesis were the most common

symptoms. Progressive muscle weakness was observed in eight patients (61%) with five cases accompanied with an increase in muscle tone and deep tendon reflex. Four patients (32%) presented paraparesis and three (23%) presented tetraparesis. Urinary incontinence and voiding disorders were observed in more than half of the patients. Another common symptom was pain in the form of occipital headache. Other clinical manifestations such as nystagmus (31% of cases) and ataxia were frequently observed in older children. Cranial nerve palsies were observed in eight patients (61%) and auditive anomalies were observed in one.

MRI revealed hydrocephalus in seven cases (53%) and tonsillar herniation of at least 5 mm was present in ten patients (77%). Furthermore, syringomyelia was detected in three, syringobulbia in one and cord tethering in three cases. Other findings included arachnoidal cyst and cerebellar hypoplasia.

Seven children (54%) developed scoliosis; one a severe one with 120 degrees according to Combb. Skeletal abnormalities also comprised Dandy Walker and Klippel-Feil syndroms in two children.

Patient Nr/Gender Actual age	Diagnosis	Spina bifida	VP shunt	Brainstem Age	Other symptoms	Previous Treatment/ Nr of revisions	Actual Operation	Outcome
1/F 15 years	Chiari 3	ENC Closure 1st day	1st day	–	Dandy walker, Klippel-Feil. Scoliosis 120° Cerebellar atrophy	CYP shunt At birth	Ventral release	Good
2/M 7 years	Chiari 2	MMC 1st day	1st day	–	Paraparesis Incontinence	VP Shunt / 5 revisions	VP shunt revision	Good
3/F 10 years	Chiari 1 SM, A cyst	MMC 2nd day	1 month	–	Scoliosis, Omphalocele	VP/VA/LP shunt, 5 revisions	PFD 3 years later + VP shunt	Good SM↓
4/F 33 years	Chiari 1	MMC 1st day	14 years later	–	Paraparesis	VP/2 revisions	control	Good
5/M 21 years	Chiari 2	ENC 2 months	2 months	–	Ataxia, vomiting	VP shunt	Ventriculo-cisternostomie	Good
6/F 2 years	Chiari 2, SM	ENC 2nd day	1st day	Yes 2 days	Auditif, intestinal, Klippel-Feil Cardiocirculary Anomalies, severe scoliosis	PFD on 2nd day + VP shunt	VP shunt revision	Good SM↓
7/F 21 years	Chiari 2	MMC 1st day	1 month	–	Tetraparesis Ataxia, Incontinence. Scoliosis, Thethred cord	VP shunt 3 revisions cord release	PFD 18 years later + VP revision	Poor SM de novo
8/M 5 years	Chiari 2, Syringo Bulbie	MMC 1st day	3 weeks with Acute herniation	Yes 6 weeks	Herniation symptoms, incontinence, Cardiocirculary anomalies	VP shunt	PFD 1month later, tracheostomie	Poor
9/M 18 years	Chiari 2	MMC 1st day	1 month	Yes 4 weeks	Layringealstenosis Tetraparesis Incontinence Strabismus	VP shunt tracheostomy	VP revision	Good
10/F 23 years	Chiari 1	MMC 1st day	1st day	–	Tetraspastic, incontinence Cerebellar symptomatic	VP 4 revisions	VP free	Good
11/M	Chiari 2	MMC 1st day	1st day	–	Paraparesis Incontinence Tethered cord Dyslalie,scoliosis	–	VP	Good
12/F 31 years	Chiari 2	MMC 1st day	1st day, congenital	–	Diplopie, paraparesis, nystagmus	VP shunt	VP revision	No change
13/M 10 years	Chiari 2	MMC 1st day	2 weeks	–	Paraparesis incontinence Sezures, tethered cord, scoliosis	5 VP-shunt revisions	PFD 7years later, VA shunt	Good

Table 11. Synopsis of clinical findings and follow up summary of 13 patients diagnosed with Chiari and myelomeningocele.

2.10 Treatment and results

In this series of 13 patients, severe respiratory or swallowing dysfunctions, associated with poor feeding and failure to thrive with respiratory distress and aspiration, was considered an indication for urgent surgery in the infants. With the development of stridor, direct laryngoscopy was used to assess laryngeal function. If bilateral abductor vocal cord paralysis was present, ventriculoperitoneal shunt insertion was carried out. Moreover, VP revision was performed if hydrocephalus was not under optimal control. Cervical decompression was completed in those patients who had functioning shunts and who developed stridor despite shunting. In the older children, progressive spasticity and upper-extremity weakness, syringomyelia or severe scoliosis were the most frequent indications for surgery. 12 patients were treated in the past in our institution, mainly in the first days of their lives. Therefore, all initially had their dysraphic lesion repaired and all were shunted in an aim to control hydrocephalus. The exception was patient Nr. 4 who first received a VP insertion at the age of 14 years.

Two patients turned symptomatic; patient Nr. 9 and patient Nr. 6. The former showed, at the age of 4 weeks, stridor and apnea. A laryngoscopy confirmed the BAVP, which was successfully reversed after the patient received a tracheostomy and a VP shunt. Patient Nr. 6, in addition to receiving a VP shunt, underwent decompression as he showed brainstem compromise and potentially life-threatening symptoms in form of stridor and apnea at the age of 2 days. Later, this patient also showed other functional abnormalities of the brainstem in form of abnormal conduction in the auditory pathway.

At last admission, seven patients (54%) showed increased intracranial pressure as confirmed by MRI. After standard diagnostic and shunt device tests, five patients were decompressed; four posteriorly and one anteriorly. One of the seven patients had ventriculocisternostomy, one received a VP shunt, five had their shunt revised and one had a VP shunt removed.

2.11 A summary of the findings in the series of five decompressed patients

A summary of the surgical findings in this series of five decompressed patients is given in Table 11. Four patients were documented as Chiari II and one as Chiari I. Tonsillar herniation

was thus by definition present in all cases. The position of the tonsils was found in two cases at C-1 and was not specified in the other three. A tethered cord was noted in two patients, while an abnormal course of the PICA and an arachnoidal cyst were both revealed in a single but different patient. The presence or absence of caudal displacement of the medulla was rarely commented upon by the surgeon. Four of the five patients suffered from scoliosis of which two were severe. Evidence of syringomyelia was found in two patients and syringobulbie in a single one.

The most frequent postoperative complication was CSF leak. This was observed in three of the five patients (60%), which responded well to bed suturing. No cases of mortality occurred. Four patients in this series treated with posterior fossa decompression and one with ventral release have been reviewed in the outpatient clinic postoperatively. The period of follow up varied from one to seven years with a mean of four years. Three patients experienced a good outcome and two had their syringomelia decreased in size. Conversely, two patients showed a poor outcome where patient Nr. 7 experienced late deterioration and needed multiple VP revisions. Later he experienced expansion of the syringomelia de novo. In addition, patient Nr. 8 showed apnea and stridor, and needed a tracheostomy.

2.12 Long-term progress of 13 patients with spina bifida and Chiari

Early improvement of preoperative symptoms occurred in 10 patients (70%) and all showed early improvement of their clinical signs (Table 10). Despite their initial improvement, four patients subsequently deteriorated to their preoperative state and at last review, only two of them deteriorated further while one experienced no change. The patients showing late deterioration included patients Nr. 7 and Nr. 8. Patient Nr. 8 was documented as Chiari II with concomitant syringobulbia and who suffered acute herniation at the age of 3 weeks leading to the necessity of VP shunting. The patient experienced furthermore repeated severe respiratory disturbances despite a posterior fossa decompression at the age of 6 weeks. This resulted in a tracheostomy. Patient Nr. 7 was also diagnosed with Chiari II, was shunted at birth with multiple revisions and release of a thetered cord, and had an expansion of syringomyelia de novo.

The most favorable long term results were noted among patients with the foramen magnum compression.70% of them showed improvement at last review. Of the six patients presenting

central cord disturbances, four experienced late deterioration whereas five (62%) showed improvement at last review. In the three patients with cerebellar syndrome only one (33%) showed improvement at last review.

2.13 Summarizing figures

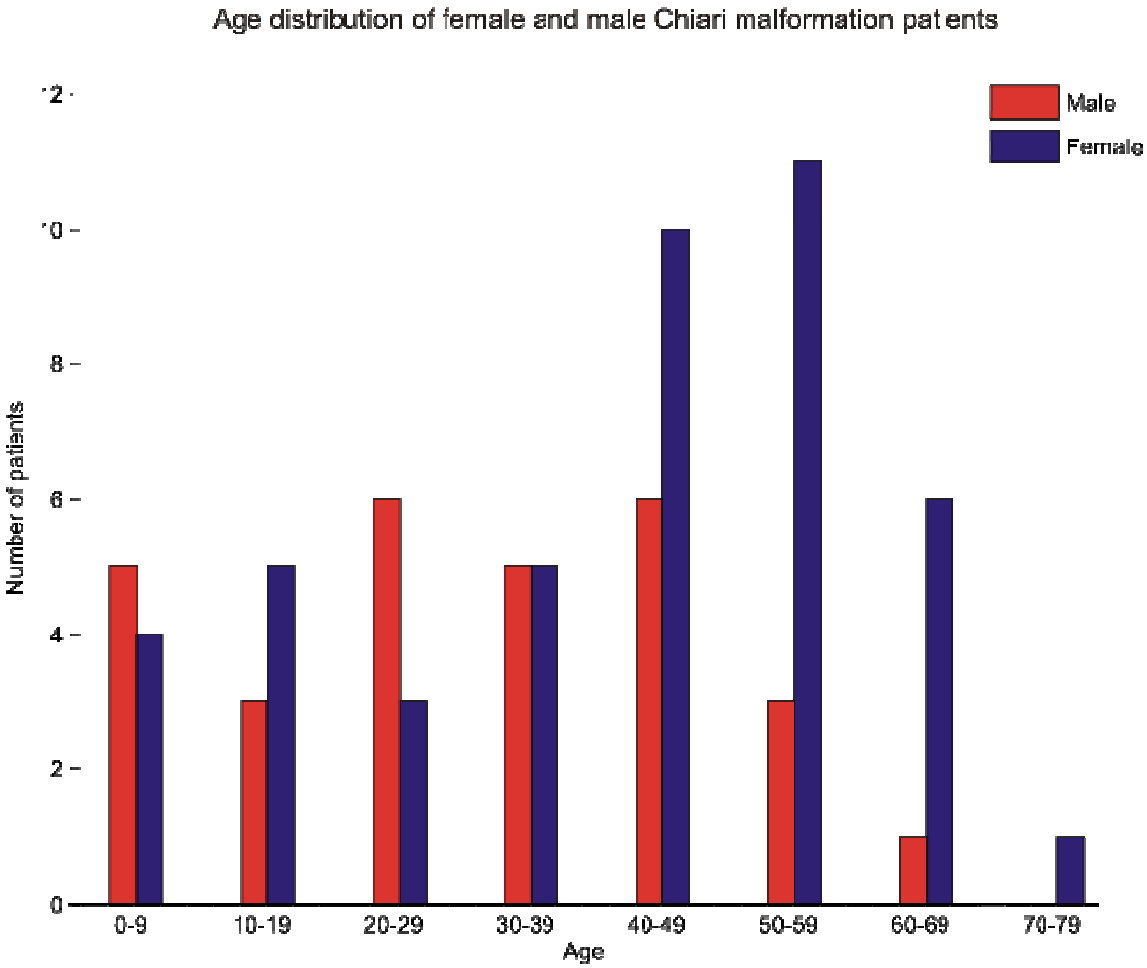

Figure 1. Age distribution of female and male Chiari malformation patients.

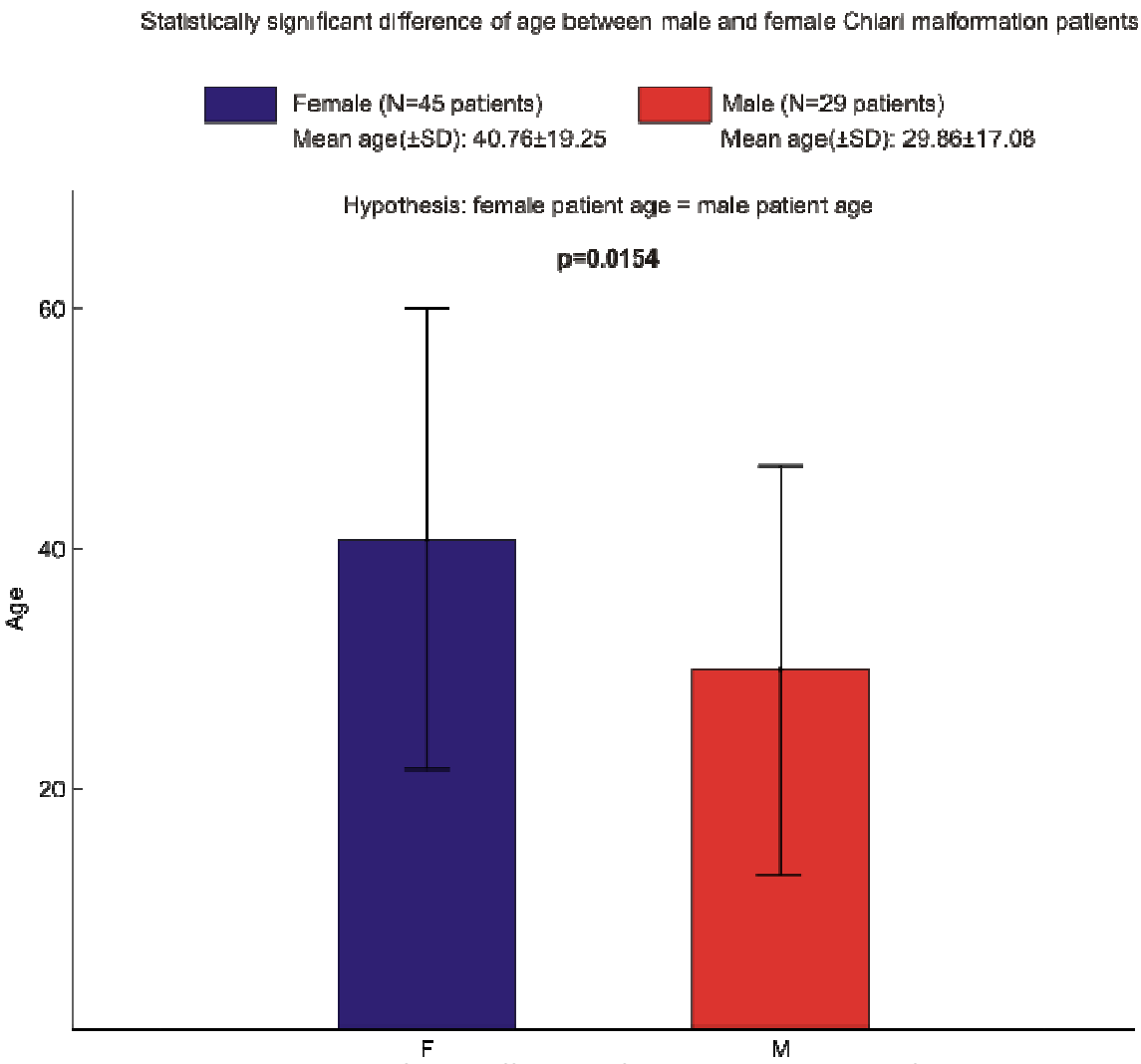

Figure 2. Statistically significant difference of age between male and female Chiari malformation patients.

The age distribution of male and female Chiari malformation patients is shown in Figure 1. Whereas the age distributions of the two sexes are comparable for patients younger than 40 years, the female patients outnumber the male patients for ages above this threshold. A statistical comparison of the mean ages of patients of the two sexes is depicted in Figure 2. The mean (±SD) age of female patients (40.76±19.25) is found to be larger, in a statistically significant manner (Student's t-test, p=0.0154), than that of the male patients (29.86±17.08). A plausible explanation for this discrepancy is revealed in the data shown in Table 2 where the CMI/SM category of the disease comprises more female than male patients, 29 and 14 respectively, and is also the category with the highest mean patient age. In other words, female Chiari patients seem to be older than their male counterparts because they are more

affected by the CMI/SM manifestation of the disease which characterizes predominantly the eldest patients.

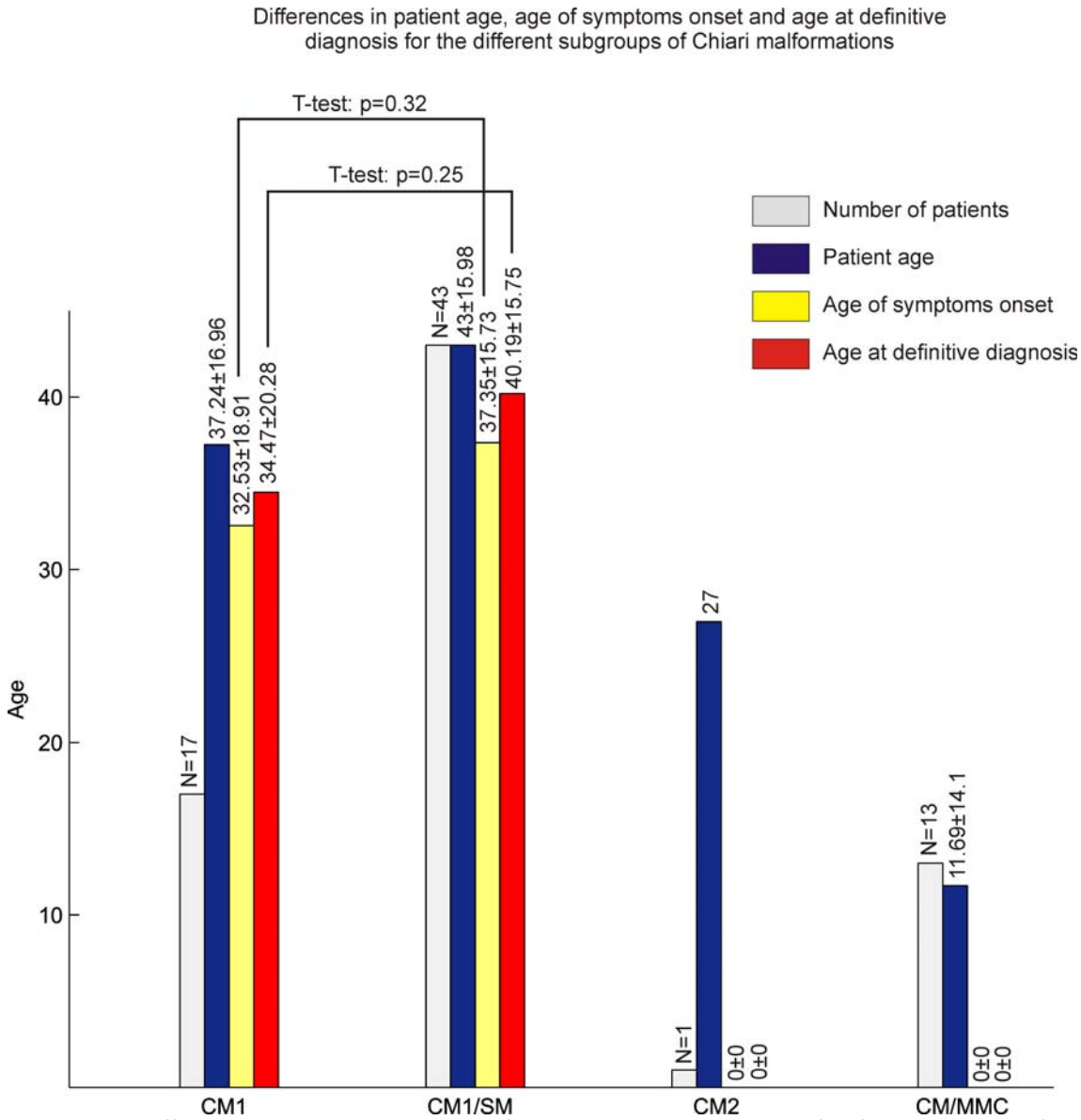

Figure 3. Differences in patient age, age of symptoms onset and age of definite diagnosis for the different subgroups of Chiari malformations.

Figure 3 summarizes the mean (±SD) ages of patients at the moment of clinical admission, at the onset of symptoms and at moment of definitive diagnosis for the four categories of the Chiari malformation. It is apparent that when comparing the CM1 and CM1/SM categories, the mean ages at symptoms onset and at moment of definitive diagnosis are greater in absolute terms in the CM1/SM case. A statistical analysis (Student's t-test) has

however revealed that these differences are not statistically significant at the p=0.05 level (see figure for the computed p-values). In addition, the time elapsed between the moment of symptoms onset and definitive diagnosis for the CM1 and CM1/SM categories are different in their mean values in absolute terms; they are of 1.94 and 2.84 years, respectively. It follows that for the CM1/SM patients it took on average 11 months longer than for their CM1 counterparts to be diagnosed after appearance of first symptoms.

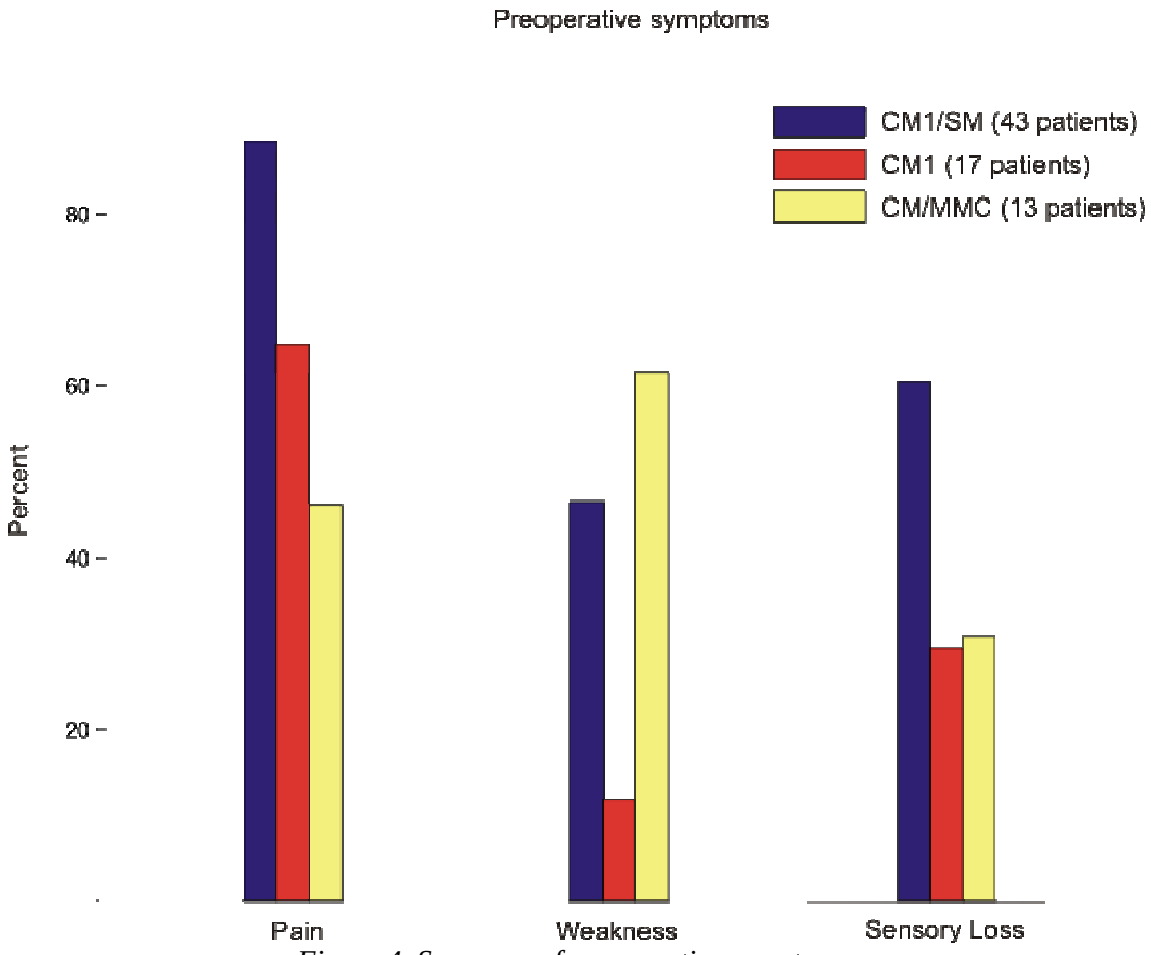

Figure 4. Summary of preoperative symptoms.

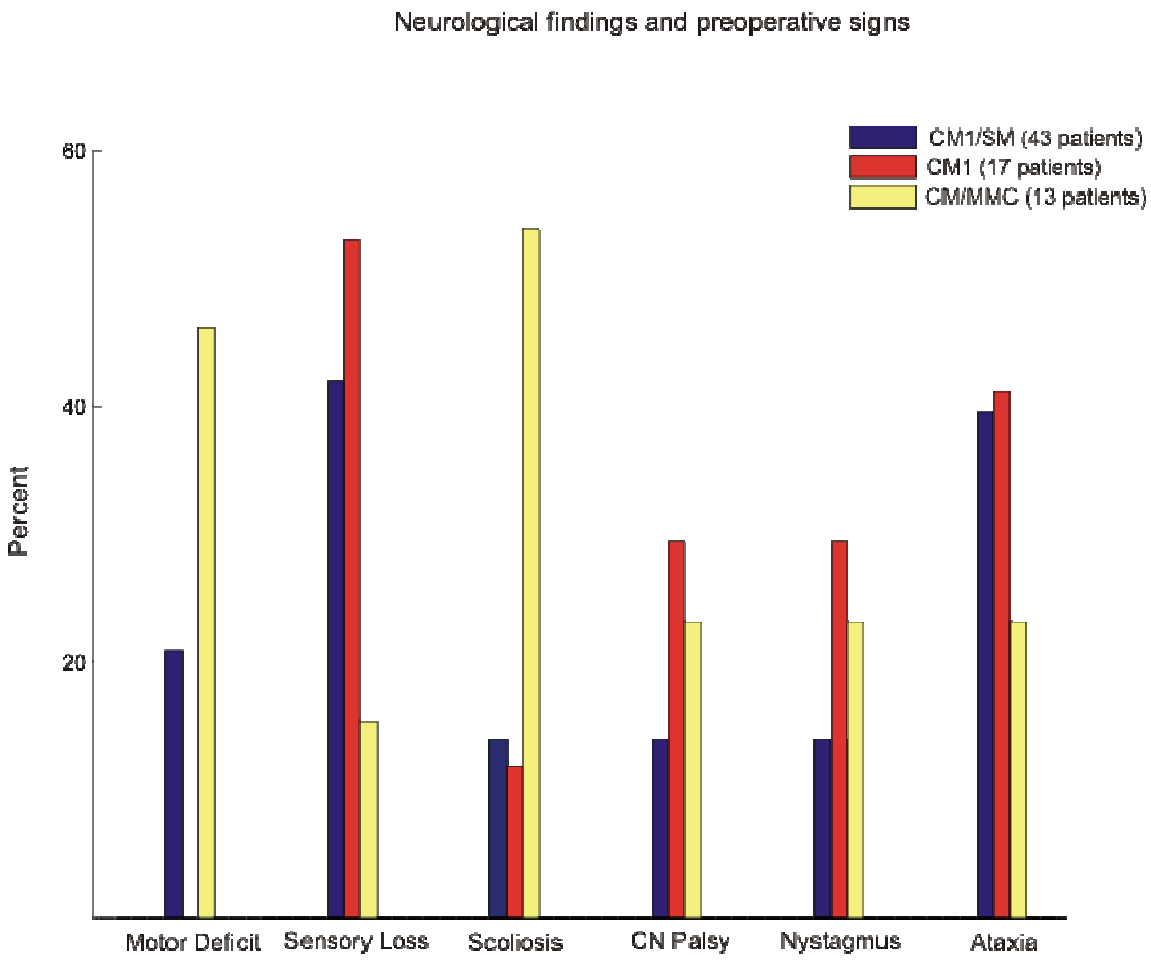

Figure 5. Summary of neurological findings and preoperative signs.

3 Discussion

The distribution by patient sex showed a female preponderance which corresponds to some previouse reports (32, 44).

The profile of clinical presentation was comparable with what is known about the clinical entity. 15 of our 74 patients (20%) were found to have associated craniocervical anomalies such as basilar invaginations or atlanto-axial fusions. The incidence of such anomalies was similar to other reported series of patients (40, 42) in which these abnormalities appeared on average to be present in every fourth patient. In these reports, the incidence of syringomyelia in patients with CMI was found to be between 20 and 75%, whereas in our own series the incidence was 64%. The most common symptom in our series that is related to the craniovertebral malformation is pain, and the earliest symptoms tended to be a gait disturbance, radicular pain or dysesthesia in one upper limb. Patients without syringomyelia showed fewer symptoms than those with syringomyelia. In our series, most of the patients without a syrinx presented with headache and neck pain, while patients with syringomyelia additionally showed manifestations of sensory and motor changes. Preoperative motor dysfunction was only present in cases of Chiari I malformation associated with syringomyelia; motor deficits were present in 9 patients, which is 15% of the entire patient group. This incidence is lower than in other reports (72).

There were no clear differences in the incidence of major symptoms between the here studied series and other published reports. There was however a major difference in the time from symptoms onset to moment of definitive diagnosis. The latter was on average 2.38 years, a relatively long period of time, which in this case is mainly due to pre MRI cases also included in this series of patients. Prior to MRI, the diagnosis of Chiari I malformation was made using myelography or CT. Such invasive investigations were generally reserved for patients who developed neurological symptoms and signs related to spinal cord or craniocervical junction. We found major differences between Chiari I and Chiari with concomitant syringomyelia. We noticed that in patients with syringomyelia the elapsed time from the onset of neurological symptoms until definitive diagnosis was greater. Whereas for Chiari I this interval is 1.93 years, patients with concomitant syringomyelia wait on average 2.84 years between the onset of symptoms and definitive diagnosis. We therefore suspect that during this long clinical course the strength of the muscles had been compromised causing deficits in their

development. By the time a patient has developed muscle atrophy, ataxia, nystagmus or trigeminal or dorsal column dysfunctions, or has been symptomatic for longer than 2 years, severe and permanent neurological dysfunctions have occurred and surgery is unlikely to return the patient to an asymptomatic state (46). Thus, it is assumed that the best time to perform surgical treatment is when patients exhibit any changes in neurological findings and that early surgical treatment for symptomatic syringomyelia associated with Chiari I malformation is beneficial for relieving neurological symptoms. Parameters such as the axial diameter of the widest syrinx, the longitudinal extent of the syrinx and the extent of the tonsillar herniation in MRI scans have shown not having prognostic value, and thus cannot be used as indication of when early interventional surgery to treat the lesion is necessary (48). Nevertheless, it was reported that sudden significant deterioration was observed for patients with syringomyelia especially with large syringes (18). MRI monitoring is necessary. On other hand now with the advent of MRI, many patients are now diagnosed in the early stage of the disease, when there are no or minimal neurologic deficits present or in some incidentally diagnosed cases, the patient can be asymptomatic. This was the case in seven patients in our investigated series (10%). In the cases of children patients, a significant number among them were diagnosed during the investigation of scoliosis with no or minimal neurological symptoms. Here also neurological examination monitoring is specially asked to avoid early surgeries and to help to identify young infants with brain stem impairment.

The operative approach in our institution in case of Chiari malformation was as follows: in case of concomitant hydrocephalus priority is given to ventriculo-peritoneal shunting, posterior fossa decompression is performed for the patients without hydrocephalus or for the patients with hydrocephalus who have not improved after shunt procedure. Even if there were some attempts in the past of SSB shunting, the surgeons in our clinic consider now the risk of the myelotomy unacceptable in a patient with otherwise little dysfunction, and assume that posterior fossa decompression alone is adequate. Some authors have discussed the use of subocipital craniectomy with and without duraplasty (23), tonsillar coagulation only (13), and direct shunting of the fluid cavity (63). Some have also reported that posterior fossa decompression without duraplasty prevents complications, but other series showed that the opening of the dura and widening the cisternal space with a graft duraplasty, in case of concomitant syringomyelia, makes the essential difference in surgical treatments of this condition, and may lead to a more reliable reduction in the volume of the syrinx (23). Additional maneuvers such as tonsillar coagulation and ventriculo-subarachnoid stent placement have all been reported with varying success.

In addition to numerous preoperative symptoms and deficits found in Chiari I malformation, numerous possible surgery related complications have been described (40). In our own series there were no cases of mortality and the CSF leakage rate (21%) was similar to the rates reported elsewhere. The risk of CSF leakage has to be accepted as a downside of the procedure. Our series also included two cases of meningitis which were successfully treated with antibacterial therapy. Furthermore, we report 12% of patients with a diminution of the syrinx, 14% with a stabilization of the syringomyelia and one patient (4%) with the syringomyelia completely resolved. It is known however that there is no significant correlation between the reduction in syrinx size in MRI images and the degree of clinical improvement (28). Parameters such as axial diameters, longitudinal extent of the syrinx and level of tonsillar herniation in MRI scans do not have prognostic value and therefore, irreversible neurological deficits may persist after surgery even with resolution of the syrinx (28).

Based on our results, presenting symptoms associated with good outcome were headache, cervical pain, mild scoliosis and sleep apnea. Those associated with a poor outcome included an increased duration of symptoms, muscle atrophy, ataxia and nystagmus. Patients with headache symptoms responded very well to a decompressive surgery, and 40 patients with preoperative headache experienced complete relief immediately after surgery. In the remaining patients, a longer period was required before the headaches resolved. At follow up examinations, only four patients reported persistent neck pains, two patients reported recurrent pain and another two reported significantly improved pain, whereas all others were pain free.

In our series of the 41 patients who presented with central cord disturbances, 30 had syringomyelia, hypesthesia and moderate dysesthesia in the upper extremities were present in 31 of the 41 patients, improvement or complete normalization of sensory symptoms was achieved in 83% of cases and in 17% of patients no change or late deterioration was demonstrated. In previous studies, authors have reported resolution or significant improvement of sensory symptoms in 70% (44) or even in over 90% (32) of cases.

Finally, presenting symptoms associated with a relatively worse outcome in our series included cerebellar syndromes such as ataxia and nystagmus. Only 65% of such patients with cerebellar syndromes showed improvement at last review.

It is known that after initial surgery patients may fail to improve or have recurrent symptomatology requiring further operation (13). In a particular studied series, up to 30% of the patients required more than one procedure (13). Different causes were suggested, ranging

from not opening the dura to making a large decompression. On the other hand, up to 20% of patients who initially responded well to surgery later presented a recurrence of similar pre-operative symptoms due to prominent scarring that impair the CSF flow at the level of the decompression. In comparison, our results showed eight patients (20%) that required more than one surgery; two due to recurrent symptoms, four due to development or expansion of syringomyelia and another two due to a lack of improvement after surgery.

Historically the major presenting symptoms for Chiari I malformation have consisted of weakness, pain, dissociated sensory loss and headache. This pattern held true in both the paediatric and the adult groups in our series. This typically adult presentation in a paediatric group has been also previously reported. The clinical picture of patients with Chiari malformation and myelomeningocele presents differently depending on the patient's age. Younger patients (up to 1 year old) most often present with stridor apnea and feeding difficulties. Older patients may present with nystagmus, oscilopsia, motor weakness, opisthotonus, mirror movement, Horner´s syndrome, or lower cranial nerve palsies (5, 10). In our series of 13 Chiari malformation and myelomeningocele cases including older children and young adults, a direct compression of the brain stem and cervical medulla led in two cases (15%) to syringomyelia producing a different clinical picture of upper extremity weakness and long tract signs. These patients responded favorably to posterior fossa decompression and cervical laminectomy and the cavity of the syrinx also decreased in size.
In comparison to older children, the combination of direct compression and vascular compromise leads to a much more devastating clinical picture in young infants. It is possible that in the third of myelodysplastics that become symptomatic before the age of three, there is a greater degree of brainstem dysmorphysm. Consequently, the brainstem is more susceptible to injury from compression and/or ischemia (10). During the 30 year period of our survey, three of 13 patients (23%) with a myelomeningocele, all defined as a Chiari II malformation type, presented a symptomatic state. The incidence of symptomatic Chiari II malformation was higher than that reported by others (6, 20, 31, 32, 34). The three mentioned patients were aged 2 days, 1 month and 6 weeks, respectively. The reason that some children manifest early and rapid brainstem compromise is still not clear, but may indicate that these patients have a particulary severe degree of cervicomedullary compression, a brainstem vascular supply that predispose them to ischemia, or intrinsic brainstem abnormalities that make them more vulnerable to secondary injury (8, 10, 11). Pathological studies on patients with myelomeningocele and Chiari malformation have shown disorganized brainstem nuclei, a

feature that explains the difficulty that myelodysplastic children often have with lower cranial nerve dysfunctions. After the onset of initial signs of brainstem compression, progressive deterioration often occurs precipitously (53).

Thus, early recognition of the presence and significance of brainstem and lower cranial impairment has major importance in our population of patients. The operative indication for neonates and young infants are still controversial. This reflects concerns regarding the risks of this procedure in young infants and the fact that postoperative results have often been disappointing.

4 Synopsis

Even though Chiari malformation has been a known disease since the 19th century, a general consensus on its correct definition has still not been reached. There is still much controversy regarding the best treatment paradigm mainly because of an unclear pathophysiology picture. The main definition streams and surgical approaches as well as their historical changes are reviewed in this work. While it is becoming well established that symptomatic Chiari I malformation should be treated to prevent further clinical deterioration, the best treatment paradigm is subject to debate. Despite the controversy of operation specifics, some principles are agreed on. There is a consensus that priority should be given to hydrocephalus before considering a decompression. Posterior fossa decompression is performed for patients without hydrocephalus or for patients with hydrocephalus who have not improved after a shunt procedure. There is also a consensus that craniectomy should be kept small and that intradural maneuvers, such as tonsillar coagulation or resection, are to be avoided. In the case of a concomitant syringomyelia syrinx, shunting procedures are not recommended as the initial approach. Instead, suboccipital craniectomy with duraplasty in most patients will be a sufficient treatment and the syrinx will resolve after the initial decompression.

A significant debate and variable results exist in the current neurosurgical literature regarding the evaluation of shunt function vs. Chiari decompression in patients with symptomatic Chiari II. In an aim to better identify the outcome of symptomatic and non-symptomatic patients with Chiari II, their evolution was here analyzed separately over the years. The surgical experience of patients afflicted with Chiari malformation in the last four decades at our institution was reviewed. A series of 74 patients in whom the diagnosis of Chiari malformation was confirmed and in which 61 patients underwent a surgical procedure was analyzed:

- 17 Chiari malformation Type I patients,
- 43 Chiari malformation Type I and Syringomyelia patients,
- 13 Chiari malformation and myelomeningocele patients (3 CM I, 9 CM II, 1 CM III),
- 1 Chiari malformation Type II patient.

.

Sex and age distributions, age of disease onset, prior surgical treatments, preoperative symptoms, neurological findings, radiological characteristics, operative procedures, outcomes

and complications were analyzed from the admission history, physical examinations and operative reports. The distribution of patient sex showed a female preponderance. The age of female patients was significantly greater than that of their male counterparts because they were more affected by the CMI/SM. This stems from the fact that in patients with syringomyelia the elapsed time from the onset of neurological symptoms until definitive diagnosis was longer. Regarding symptom manifestation, most of the patients in the series without a syrinx presented with headache and neck pain, while patients with syringomyelia additionally showed manifestations of sensory and motor changes.

The operative approach in our institution in the case of Chiari malformation was as follows. In case of concomitant hydrocephalus, priority is given to ventriculo-peritoneal shunting, while posterior fossa decompression is performed for the patients without hydrocephalus or for the patients with hydrocephalus who have not improved after the shunt procedure. In case of concomitant syringomyelia, the surgeons in our clinic assume that posterior fossa decompression alone is adequate. Most of the patients responded favorably to posterior fossa decompression and cervical laminectomy and in case of syringomyelia the cavity of the syrinx also decreased in size. Based on the reported results, presenting symptoms associated with good outcome were headache, cervical pain, mild scoliosis and sleep apnea. Those associated with a poor outcome included an increased duration of symptoms, muscle atrophy, ataxia and nystagmus. Postoperative complications included CSF leakage and meningitis. Some patients required more than one surgery due to recurrent symptoms, development or expansion of syringomyelia or to a lack of improvement after surgery.

The clinical picture of patients with Chiari malformation and myelomeningocele presents differently depending on the patient’s age. In older children, patients responded favorably to posterior fossa decompression and cervical laminectomy and the cavity of the syrinx also decreased in size. On the other hand, the operative indication for neonates and young infants in whom the combination of direct compression and vascular compromise can lead to a more devastating clinical picture are still controversial.

5 References

[1] A. O. Aboulezz, K. Sartor, C. A. Geyer, and M. H. Gado. Position of cerebellar tonsils in the normal population and in patients with Chiari malformation: a quantitative approach with MR imaging. *J Comput Assist Tomogr*, 9(6):1033–1036, 1985.

[2] J. Aboulker. [syringomyelia and intra-rachidian fluids. x. rachidian fluid stasis]. *Neurochirurgie*, 25 Suppl 1:98–107, 1979.

[3] B. Badie, D. Mendoza, and U. Batzdorf. Posterior fossa volume and response to suboccipital decompression in patients with Chiari I malformation. *Neurosurgery*, 37(2):214–218, Aug 1995.

[4] A. J. Barkovich, F. J. Wippold, J. L. Sherman, and C. M. Citrin. Significance of cerebellar tonsillar position on MR. *AJNR Am J Neuroradiol*, 7(5):795–799, 1986.

[5] R. A. Bhadelia, A. R. Bogdan, S. M. Wolpert, S. Lev, B. A. Appignani, and C. B. Heilman. Cerebrospinal fluid flow waveforms: analysis in patients with Chiari I malformation by means of gated phase-contrast MR imaging velocity measurements. *Radiology*, 196(1):195–202, Jul 1995.

[6] C. D. Bluestone, A. N. Delerme, and G. H. Samuelson. Airway obstruction due to vocal cord paralysis in infants with hydrocephalus and meningomyelocele. *Ann Otol Rhinol Laryngol*, 81(6):778–783, Dec 1972.

[7] M. Caldarelli, C. Di Rocco, C. Colosimo, G. Fariello, and M. Di Gennaro. Surgical treatment of late neurological deterioration in children with myelodysplasia. *Acta Neurochir (Wien)*, 137(3-4):199–206, 1995.

[8] Massimo Caldarelli and Concezio Di Rocco. Diagnosis of Chiari I malformation and related syringomyelia: radiological and neurophysiological studies. *Childs Nerv Syst*, 20(5):332–335, May 2004.

[9] P. W. Carmel and W. R. Markesbery. Early descriptions of the Arnold-Chiari malformation. the contribution of John Cleland. *J Neurosurg*, 37(5):543–547, Nov 1972.

[10] E. B. Charney, L. B. Rorke, L. N. Sutton, and L. Schut. Management of Chiari II complications in infants with myelomeningocele. *J Pediatr*, 111(3):364–371, Sep 1987.

[11] H. Chiari. Concerning alterations in the cerebellum resulting from cerebral hydrocephalus. 1891. *Pediatr Neurosci*, 13(1):3–8, 1987.

[12] J. Cleland. Contribution to the study of spina bifida, encephalocele, and anencephalus. *J Anat Physiol*, 17(Pt 3):257–292, Apr 1883.

[13] D. D. Cochrane, R. Adderley, C. P. White, M. Norman, and P. Steinbok. Apnea in patients with myelomeningocele. *Pediatr Neurosurg*, 16(4-5):232–239, 1990.

[14] A. D. Elster and M. Y. Chen. Chiari I malformations: clinical and radiologic reappraisal. *Radiology*, 183(2):347–353, May 1992.

[15] E. G. Fischer. Posterior fossa decompression for Chiari I deformity, including resection of the cerebellar tonsils. *Childs Nerv Syst*, 11(11):625–629, Nov 1995.

[16] R. R. Gacek. Localization of laryngeal motor neurons in the kitten. *Laryngoscope*, 85(11 pt 1):1841–1861, Nov 1975.

[17] W. J. Gardner and R. J. Goodall. The surgical treatment of Arnold-Chiari malformation in adults; an explanation of its mechanism and importance of encephalography in diagnosis. *J Neurosurg*, 7(3):199–206, May 1950.

[18] L. Genitori, P. Peretta, C. Nurisso, L. Macinante, and F. Mussa. Chiari type I anomalies in children and adolescents: minimally invasive management in a series of 53 cases. *Childs Nerv Syst*, 16(10-11):707–718, Nov 2000.

[19] J. N. Gilbert, K. L. Jones, L. B. Rorke, G. F. Chernoff, and H. E. James. Central nervous system anomalies associated with meningomyelocele, hydrocephalus, and the Arnold-Chiari malformation: reappraisal of theories regarding the pathogenesis of posterior neural tube closure defects. *Neurosurgery*, 18(5):559–564, May 1986.

[20] A. Goel and K. Desai. Surgery for syringomyelia: an analysis based on 163 surgical cases. *Acta Neurochir (Wien)*, 142(3):293–301; discussion 301–2, 2000.

[21] F. Goldstein and J. J. Kepes. The role of traction in the development of the Arnold-Chiari malformation. an experimental study. *J Neuropathol Exp Neurol*, 25(4):654–666, Oct 1966.

[22] P. A. Grabb, T. B. Mapstone, and W. J. Oakes. Ventral brain stem compression in pediatric and young adult patients with Chiari I malformations. *Neurosurgery*, 44(3):520–7; discussion 527–8, Mar 1999.

[23] R. I. Haroun, M. Guarnieri, J. J. Meadow, M. Kraut, and B. S. Carson. Current opinions for the treatment of syringomyelia and Chiari malformations: survey of the pediatric section of the American association of neurological surgeons. *Pediatr Neurosurg*, 33(6):311–317, Dec 2000.

[24] R. M. Hays, R. A. Jordan, J. F. McLaughlin, R. E. Nickel, and L. D. Fisher. Central ventilatory dysfunction in myelodysplasia: an independent determinant of survival. *Dev Med Child Neurol*, 31(3):366–370, Jun 1989.

[25] N. Hesz and M. Wolraich. Vocal-cord paralysis and brainstem dysfunction in children with spina bifida. *Dev Med Child Neurol*, 27(4):528–531, Aug 1985.

[26] P. C. Holinger, L. D. Holinger, T. J. Reichert, and P. H. Holinger. Respiratory obstruction and apnea in infants with bilateral abductor vocal cord paralysis, meningomyelocele, hydrocephalus, and Arnold-Chiari malformation. *J Pediatr*, 92(3):368–373, Mar 1978.

[27] B. J. Iskandar, C. McLaughlin, T. B. Mapstone, P. A. Grabb, and W. J. Oakes. Pitfalls in the diagnosis of ventricular shunt dysfunction: radiology reports and ventricular size. *Pediatrics*, 101(6):1031–1036, Jun 1998.

[28] Y. Iwasaki, I. Koyanagi, K. Hida, and H. Abe. Syringo-subarachnoid shunt for syringomyelia using partial hemilaminectomy. *Br J Neurosurg*, 13(1):41–45, Feb 1999.

[29] W. M. Kirsch, B. R. Duncan, F. O. Black, and J. C. Stears. Laryngeal palsy in association with myelomeningocele, hydrocephalus, and the Arnold-Chiari malformation. *J Neurosurg*, 28(3):207–214, Mar 1968.

[30] J. Klekamp, U. Batzdorf, M. Samii, and H. W. Bothe. The surgical treatment of Chiari I malformation. *Acta Neurochir (Wien)*, 138(7):788–801, 1996.

[31] P. J. Koehler. Chiari's description of cerebellar ectopy (1891). with a summary of Cleland's and Arnold's contributions and some early observations on neural-tube defects. *J Neurosurg*, 75(5):823–826, Nov 1991.

[32] M. D. Krieger, J. G. McComb, and M. L. Levy. Toward a simpler surgical management of Chiari I malformation in a pediatric population. *Pediatr Neurosurg*, 30(3):113–121, Mar 1999.

[33] Farhad M Limonadi and Nathan R Selden. Dura-splitting decompression of the craniocervical junction: reduced operative time, hospital stay, and cost with equivalent early outcome. *J Neurosurg*, 101(2 Suppl):184–188, Nov 2004.

[34] M. Marin-Padilla and T. M. Marin-Padilla. Morphogenesis of experimentally induced Arnold–Chiari malformation. *J Neurol Sci*, 50(1):29–55, Apr 1981.

[35] T. Matsumoto and L. Symon. Surgical management of syringomyelia–current results. *Surg Neurol*, 32(4):258–265, Oct 1989.

[36] Catherine A Mazzola and Arno H Fried. Revision surgery for Chiari malformation decompression. *Neurosurg Focus*, 15(3):E3, Sep 2003.

[37] D. G. McLone. Results of treatment of children born with a myelomeningocele. *Clin Neurosurg*, 30:407–412, 1983.

[38] D. G. McLone and P. A. Knepper. The cause of Chiari II malformation: a unified theory. *Pediatr Neurosci*, 15(1):1–12, 1989.

[39] J. Meadows, M. Kraut, M. Guarnieri, R. I. Haroun, and B. S. Carson. Asymptomatic Chiari type I malformations identified on magnetic resonance imaging. *J Neurosurg*, 92(6):920–926, Jun 2000.

[40] Arnold H Menezes, Jeremy D W Greenlee, and Kathleen A Donovan. Honored guest presentation: lifetime experiences and where we are going: Chiari I with syringohydromyelia–controversies and development of decision trees. *Clin Neurosurg*, 52:297–305, 2005.

[41] D. J. Mikulis, O. Diaz, T. K. Egglin, and R. Sanchez. Variance of the position of the cerebellar tonsils with age: preliminary report. *Radiology*, 183(3):725–728, Jun 1992.

[42] T. H. Milhorat, M. W. Chou, E. M. Trinidad, R. W. Kula, M. Mandell, C. Wolpert, and M. C. Speer. Chiari I malformation redefined: clinical and radiographic findings for 364 symptomatic patients. *Neurosurgery*, 44(5):1005–1017, May 1999.

[43] A. R. Morley. Laryngeal stridor, Arnold-Chiari malformation and medullary haemorrhages. *Dev Med Child Neurol*, 11(4):471–474, Aug 1969.

[44] I. Munshi, D. Frim, R. Stine-Reyes, B. K. Weir, J. Hekmatpanah, and F. Brown. Effects of posterior fossa decompression with and without duraplasty on Chiari malformation-associated hydromyelia. *Neurosurgery*, 46(6):1384–9; discussion 1389–90, Jun 2000.

[45] H. J. Nauta, E. Dolan, and M. G. Yasargil. Microsurgical anatomy of spinal subarachnoid space. *Surg Neurol*, 19(5):431–437, May 1983.

[46] Ramon Navarro, Greg Olavarria, Roopa Seshadri, Gabriel Gonzales-Portillo, David G McLone, and Tadanori Tomita. Surgical results of posterior fossa decompression for patients with Chiari I malformation. *Childs Nerv Syst*, 20(5):349–356, May 2004.

[47] M. Nishikawa, H. Sakamoto, A. Hakuba, N. Nakanishi, and Y. Inoue. Pathogenesis of Chiari malformation: a morphometric study of the posterior cranial fossa. *J Neurosurg*, 86(1):40–47, Jan 1997.

[48] S. Nishizawa, T. Yokoyama, N. Yokota, T. Tokuyama, and S. Ohta. Incidentally identified syringomyelia associated with Chiari I malformations: is early interventional surgery necessary? *Neurosurgery*, 49(3):637–40; discussion 640–1, Sep 2001.

[49] D. Pang and M. S. Dias. Cervical myelomeningoceles. *Neurosurgery*, 33(3):363–72; discussion 372–3, Sep 1993.

[50] S. Papasozomenos and U. Roessmann. Respiratory distress and Arnold-Chiari malformation. *Neurology*, 31(1):97–100, Jan 1981.

[51] L. S. Paré and U. Batzdorf. Syringomyelia persistence after Chiari decompression as a result of pseudomeningocele formation: implications for syrinx pathogenesis: report of three cases. *Neurosurgery*, 43(4):945–948, Oct 1998.

[52] J. K. Park, P. L. Gleason, J. R. Madsen, L. C. Goumnerova, and R. M. Scott. Presentation and management of Chiari I malformation in children. *Pediatr Neurosurg*, 26(4):190–196, Apr 1997.

[53] T. S. Park, H. J. Hoffman, E. B. Hendrick, and R. P. Humphreys. Experience with surgical decompression of the Arnold-Chiari malformation in young infants with myelomeningocele. *Neurosurgery*, 13(2):147–152, Aug 1983.

[54] Coburn DF Penfield W. Arnold-Chiari malformation and its operative treatment. *Arch Neurol Psychiatry*, 40:328–336, 1938.

[55] P. K. Pillay, I. A. Awad, J. R. Little, and J. F. Hahn. Symptomatic Chiari malformation in adults: a new classification based on magnetic resonance imaging with clinical and prognostic significance. *Neurosurgery*, 28(5):639–645, May 1991.

[56] I. F. Pollack, D. Kinnunen, and A. L. Albright. The effect of early craniocervical decompression on functional outcome in neonates and young infants with myelodysplasia and symptomatic Chiari II malformations: results from a prospective series. *Neurosurgery*, 38(4):703–10; discussion 710, Apr 1996.

[57] I. F. Pollack, D. Pang, A. L. Albright, and D. Krieger. Outcome following hindbrain decompression of symptomatic Chiari malformations in children previously treated with myelomeningocele closure and shunts. *J Neurosurg*, 77(6):881–888, Dec 1992.

[58] David Sacco and R. Michael Scott. Reoperation for Chiari malformations. *Pediatr Neurosurg*, 39(4):171–178, Oct 2003.

[59] Edgardo Schijman and Paul Steinbok. International survey on the management of Chiari I malformation and syringomyelia. *Childs Nerv Syst*, 20(5):341–348, May 2004.

[60] R. L. Sieben, M. B. Hamida, and K. Shulman. Multiple cranial nerve deficits associated with the Arnold-Chiari malformation. *Neurology*, 21(7):673–681, Jul 1971.

[61] Y. Takahashi, Y. Tajima, S. Ueno, T. Tokutomi, and M. Shigemori. Syringobulbia caused by delayed postoperative tethering of the cervical spinal cord - delayed complication of foramen magnum decompression for Chiari malformation. *Acta Neurochir (Wien)*, 141(9):969–72; discussion 972–3, 1999.

[62] F. Tognetti and F. Calbucci. Syringomyelia: syringo-subarachnoid shunt versus posterior fossa decompression. *Acta Neurochir (Wien)*, 123(3-4):196–197, 1993.

[63] R. Shane Tubbs and W. Jerry Oakes. Treatment and management of the Chiari II malformation: an evidence-based review of the literature. *Childs Nerv Syst*, 20(6):375–381, Jun 2004.

[64] W. P. Vandertop, A. Asai, H. J. Hoffman, J. M. Drake, R. P. Humphreys, J. T. Rutka, and L. E. Becker. Surgical decompression for symptomatic Chiari II malformation in neonates with myelomeningocele. *J Neurosurg*, 77(4):541–544, Oct 1992.

[65] J. L. Venes, K. L. Black, and J. T. Latack. Preoperative evaluation and surgical management of the Arnold-Chiari II malformation. *J Neurosurg*, 64(3):363–370, Mar 1986.

[66] Enrique C G Ventureyra, Hani Abdel Aziz, and Michael Vassilyadi. The role of cine flow MRI in children with Chiari I malformation. *Childs Nerv Syst*, 19(2):109–113, Feb 2003.

[67] S. L. Ward, R. A. Jacobs, E. P. Gates, L. D. Hart, and T. G. Keens. Abnormal ventilatory patterns during sleep in infants with myelomeningocele. *J Pediatr*, 109(4):631–634, Oct 1986.

[68] K. A. Waters, P. Forbes, A. Morielli, C. Hum, A. M. O'Gorman, O. Vernet, G. M. Davis, T. L. Tewfik, F. M. Ducharme, and R. T. Brouillette. Sleep-disordered breathing in children with myelomeningocele. *J Pediatr*, 132(4):672–681, Apr 1998.

[69] K. Welch, J. Shillito, R. Strand, E. G. Fischer, and K. R. Winston. Chiari I "malformations"–an acquired disorder? *J Neurosurg*, 55(4):604–609, Oct 1981.

[70] R. H. Wilkins and I. A. Brady. The Arnold-Chiari malformations. *Arch Neurol*, 25(4):376–379, Oct 1971.

[71] B. Williams. Surgery for hindbrain related syringomyelia. *Adv Tech Stand Neurosurg*, 20:107–164, 1993.

[72] J. H. Wisoff. Hydromyelia: a critical review. *Childs Nerv Syst*, 4(1):1–8, Feb 1988.