Long-term Outcome of Total and Near-Total Resection of Spinal Cord Lipomas and Radical Reconstruction of the Neural Placode: Part I—Surgical Technique

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OBJECTIVE: Partial resection of complex spinal cord lipomas is associated with a high rate of symptomatic recurrence caused by retethering, presumably promoted by a tight content-container relationship between the spinal cord and the dural sac, and incomplete detachment of the terminal neural placode from residual lipoma. Since 1991, we have performed more than 250 total/near-total resections of complex lipomas with radical reconstruction of the neural placodes. Sixteen years of follow-up have proven the long-term benefits of this technique. Part I of this series introduces our technique of total resection and reports the immediate surgical results. Part II will analyze the long-term outcomes of both total and partial resection and identify the factors affecting outcome.

METHODS: From 1991 to 2006, 238 patients (age range, 2 months–72 years) with dorsal, transitional, and chaotic lipomas underwent total or near-total lipoma resection and radical placode reconstruction. Eighty-four percent of the patients were children younger than 18 years and 16% were adults. The technique consisted of wide bony exposure, complete unhinging of the lateral adhesions of the lipoma-placode assembly from the inner dura, untethering of the terminal conus, radical resection of the fat off the neural plate along a white fibrous plane at the cord-lipoma interface, meticulous pia-to-pia neurulation of the supple neural placode with microsutures, and expansile duraplasty with a bovine pericardial graft. Elaborate electrophysiological monitoring was used.

RESULTS: Three postoperative observations concern us. The first is that of the 238 patients, 138 (58%) had no residual fat on postoperative magnetic resonance imaging; 81 patients (36%) had less than 20 mm^3 of residual fat, the majority of which were small bits enclosed by neurulation; and 19 patients (8%), mainly of the chaotic lipoma group, had more than 20 mm^3 of fat. There are no significant differences in the amount of residual fat among lipoma types, but redo lipomas are more likely than virgin (previously unoperated on) lipomas to have residual fat by a factor of 2 ($P = 0.0214$). The second concern is that the state of the reconstructed placode is objectively measured by the cord-sac ratio, obtained by dividing the sagittal diameter of the reconstructed neural tube by the sagittal diameter of the thecal sac. A total of 162 patients (68%) had cord-sac ratios less than 30% (low), 61 (25.6%) had ratios between 30% and 50% (medium), and only 15 (6.3%) had high ratios of more than 50%. Seventy-four percent of patients with virgin lipomas had low cord-sac ratios compared with 56.3% in the redo lipoma patients. The overall distribution of cord-sac ratio is significantly different between redo and virgin lipomas ($P = 0.00376$) but not among lipoma types. Finally, the incidence of combined neurological and urological complications was 4.2%. The combined cerebrospinal fluid leak and wound infection/dehiscence incidence was 2.5%. Both sets of surgical morbidity compared favorably with the published rates reported for partial resection.

CONCLUSION: Total/near-total resection of spinal cord lipomas and complete reconstruction of the neural placode can be achieved with low surgical morbidity and a high yield of agreeable postoperative cord-sac relationship. Some large rambling transitional lipomas and most chaotic lipomas are the most difficult lesions to resect and tend to have less favorable results on postresection magnetic resonance imaging.

KEY WORDS: Complex spinal cord lipoma, Cord-sac ratio, Reconstruction of neural placode, Surgical complications, Surgical technique, Total resection

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ABBREVIATIONS: CSF, cerebrospinal fluid; **DREZ**, dorsal root entry zone; **MRI**, magnetic resonance imaging

It is decidedly not the intention of this series of articles to resubmit the argument of whether asymptomatic spinal cord lipomas should be prophylactically treated. Before 2004, there were legitimate doubts about reports that allegedly "proved" the progressive nature of spinal cord lipomas by stressing the preponderance of deficits in older versus younger children (1, 18, 23, 25, 26, 29, 62) or by reconfiguring pseudo-regression curves using the ages at symptom onset rather than real outcome data (11, 23). However, in 2004, Kulkarni et al. (27), from Necker-Enfants Malades, Paris, published the definitive prospective study of a large cohort of children with untreated lipomas and showed beyond any doubt that asymptomatic lipomas carry a 10-year probability of deterioration of 43%. No clinician faced with these dire statistics in a pediatric disease would hesitate to treat. Ironically, the same Parisian group advised against prophylactic surgery because their own results of prophylactic partial resection (27, 56) showed an equally high rate of late deterioration as that of the untreated disease. The argument, should there be one, ought not to be whether asymptomatic lipomas should be treated, but what technique other than partial resection will unambiguously improve on the natural history of the disease, preferably by a wide margin.

There is no equivalent longitudinal study for untreated symptomatic lipomas. Traditionally, these are all referred for resection with the hope that surgery will halt neurological progression. The preferred technique seems by consensus to be partial resection of the lipoma (1, 6, 18, 20, 29, 42, 62), but despite wide acceptance of this practice, objective data from many large series do not support the opinion that partial resection adequately confers long-term protection against symptomatic recurrence. For example, Dorwood et al. (16) reported a 48% late deterioration rate with a mean follow-up of only 2.2 years. Colak et al. (12) reported a 10-year probability of symptomatic progression of 52%, but because their series contained 37% terminal lipomas, which have a much better prognosis than the other lipomas, the figure for dorsal and transitional lipomas must be even worse. Pierre-Kahn et al. (55) documented a 10-year deterioration rate of 46% with their mixed lipoma group, and Cochrane et al. (11) and Xenos et al. (64) similarly recorded frequent late deterioration. These disturbing results put in question whether leaving behind residual lipoma and its broad, raw, sticky bed promotes scar formation and consequently incurs firmer tethering and thus does more harm than no surgery with the lipoma's original smooth pial surface left unviolated, or, conversely, whether more aggressive removal of a lipoma plus other measures designed to minimize recurrent tethering would give better long-term results than partial resection.

The need for an alternative operation did not, however, occur to the senior author (DP) until 1991, who had by then performed 116 partial resections of conus lipomas using the technique described by others (4, 18, 41, 42, 55, 60, 62), only to discover that partial resection in our hands was associated with an alarming frequency of symptomatic recurrence. That prompted us to develop and later adopt the then unorthodox technique of total resection of the lipomas followed by meticulous reconstruction of the neural placode and expansile dural grafting. We are now in a position to compare 2 radically different techniques and philosophies of surgical treatment practiced consecutively by 1 surgeon over a span of 26 years. The result is the current study. It is semiprospective. The results of partial resection before 1991 came from a retrospective review of records; after 1991, we consolidated our protocol for total resection and began collecting data prospectively.

The study, which excluded terminal lipomas (caudal lipomas by Chapman's [8] nomenclature), aimed to show the following: 1) total/near-total resection of dorsal and transitional lipomas is feasible in most cases with very few complications, 2) total/near-total resection of lipomas with reconstruction of the neural placode and expansile duraplasty can minimize the probability of retethering and give a better long-term outcome than partial resection or no treatment, and 3) partial resection, by engendering new scar and at the same time exposing the raw, adherent cut surface of the residual lipoma, may in fact accelerate progression of symptoms compared with nonsurgical treatment.

Part I of this study introduces the technique of total/near-total resection of lipomas and complete reconstruction of the neural placode. Part II analyzes the long-term outcomes of both the total and partial resection techniques and attempts to identify factors that affect outcome.

PATIENTS AND METHODS

Patients

The total/near-total resection group included patients of all ages diagnosed with dorsal and transitional lipomas, as defined by Chapman (8) in 1982, and chaotic lipomas, a new type defined below. Terminal (caudal in Chapman [8]) lipomas are excluded because they are simple to resect, their prognosis is much better than that of other varieties, and their management poses no controversy (1, 9, 11, 56, 64).

The designation total/near-total resection denotes complete detachment of the lipoma and neural placode from the dura, total or near-total removal of the intradural lipoma, pia-to-pia dorsal closure (neurulation) of the neural placode with microsutures, and expansile graft duraplasty using bovine pericardium (Endura; Integra Inc., Plainsboro, NJ) to ensure a capacious dural sac. (The term *neurulation* is used here and in subsequent context out of convenience to evoke the process of dorsal rolling-up of the neural placode and the edge-to-edge apposition and later fusion of the opposing pial margins, albeit by artificial means. It should in no way be associated with the natural embryological event of neurulation.)

From 1991 to 2006, 238 patients with dorsal, transitional, and chaotic lipomas had total or near-total resection. Their ages were between 2 months and 72 years, with a mean age of 4.8 years. Two hundred two (84%) were children aged 2 months to 18 years (mean age, 3.9 years) and 36 (16%) were adults aged 18 to 72 years (mean age, 30 years). There were 115 males and 123 females. In this group, there were 185 transitional lipomas, 35 dorsal lipomas, and 18 chaotic lipomas. One hundred fifty-eight virgin lipomas (66%) were never operated on

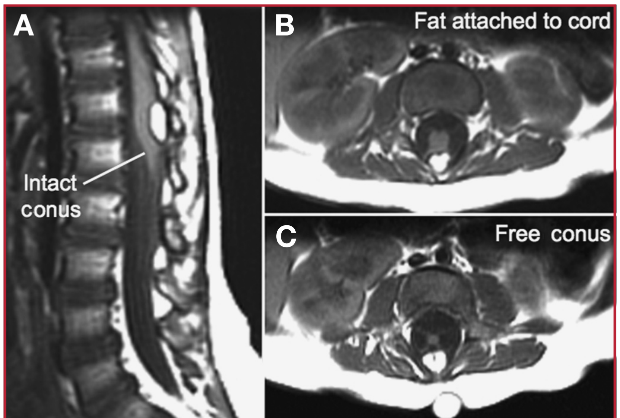

FIGURE 1. *Dorsal lipoma on magnetic resonance imaging (MRI).* **A**, *sagittal image showing an intact conus caudal to the lipoma stalk. Axial images showing the site of the lipoma attachment to the cord (***B***) and the free conus just caudal to the level of the lipoma attachment (***C***).*

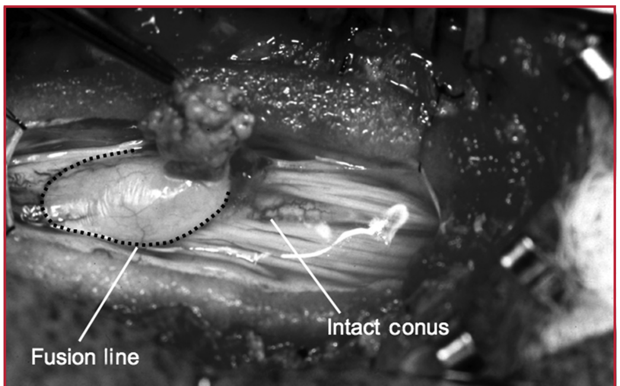

FIGURE 2. *Dorsal lipoma. Intraoperative photograph showing a neat oval fusion line around the lipoma-cord interface on a horizontal plane. Note the intact conus and caudal sacral roots.*

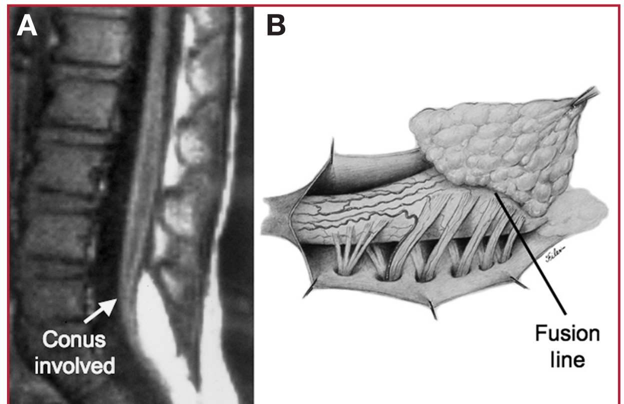

FIGURE 3. *Transitional lipoma.* **A**, *sagittal MRI scan showing that the lipoma begins dorsally but involves the entire conus. The ventral side of the neural placode is free of fat.* **B**, *the plane of the fusion line begins dorsally and then cuts obliquely toward the tip of the conus. The array of dorsal root entry zone (DREZ) and dorsal roots is also forced to slant dorsoventrally.*

before, and 80 redo lipomas (34%) had at least 1 previous attempt at partial resection.

Anatomic and Neuroimaging Classification of Spinal Cord Lipoma

In the literature, the nomenclature of the types of spinal cord lipomas is imprecise and inconsistent. For the purpose of this article, we are defining the types of lipomas as follows, based loosely on Chapman's (8) original classification.

Dorsal Lipoma

The lipoma-cord interface is entirely on the dorsal surface of the lumbar spinal cord, sparing the distal conus (Figs. 1 and 2). The junctional demarcation between the lipoma, cord, and pia, the *fusion line*, can always be traced neatly along a roughly oval track, enclosing the entire lipoma dorsomedially and separating fat from the dorsal root entry zone (DREZ) and dorsal nerve roots laterally (Fig. 2). The lipoma therefore never contains nerve roots. The lipomatous stalk runs through an equally discrete dorsal dural defect to blend with extradural fat. The intact but sometimes elongated conus often ends in a thickened filum terminale.

Transitional Lipoma (Intermediate Type in Chapman [8])

The rostral portion of this type is identical to that of a dorsal lipoma, with a discrete fusion line and easily identifiable DREZ and dorsal nerve roots. Unlike the dorsal type, however, which always spares the conus, the transitional lipoma then plunges caudally to involve the conus as the plane of the fusion line cuts ventrally and obliquely toward the tip of the conus, similar to making a slanting, beveled cut on a stick (Fig. 3). The lipoma-cord interface created may be undulating and tilted so that the neural placode is rotated to 1 side or even spun into a parasagittal edge-on orientation. The lipoma may therefore be markedly asymmetrical, its involvement with the cord biased to 1 side, and obscuringly massive, but the neural tissue is always ventral to it and the DREZ and nerve roots are predictably localizable lateral and ventral to the fusion line and therefore do not course through the fat (Fig. 4). There may or may not be a discrete filum. The dorsal dural defect extends to the caudal end of the thecal sac and may be much larger on the biased side. This latter variant corresponds to the dorsolateral lipoma described by Chapman (8) and others (10).

Chaotic Lipoma

This previously undescribed type is so named because it does not follow the rules of either the dorsal or transitional lipoma. It may begin dorsally in an orderly fashion as in a dorsal or transitional lipoma, but its caudal portion is ventral to the neural placode and does engulf neural tissue and nerve roots (Fig. 5). The fusion line may be distinct rostrally but quickly becomes blurred distally, and the location of the DREZ and nerve roots is less predictable. The moniker chaotic depicts the sometimes confusing blend of the ventral fat and neural placode and the often impossible task of separating fat from neural tissue at surgery (Fig. 6). Chaotic lipomas are uncommon but are characteristically seen with sacral agenesis.

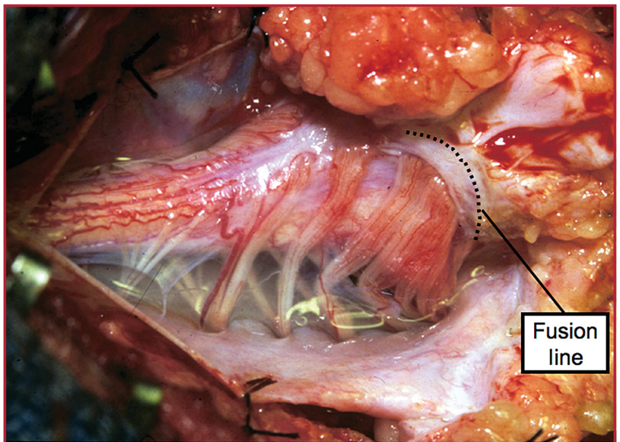

FIGURE 4. *Transitional lipoma. Intraoperative photograph showing a massive lipoma but a very distinct dorsoventral fusion line separating fat from the DREZ and dorsal roots, which always lie lateral and ventral to the fusion line. The ventral side of the placode is always free of fat in a regular transitional lipoma.*

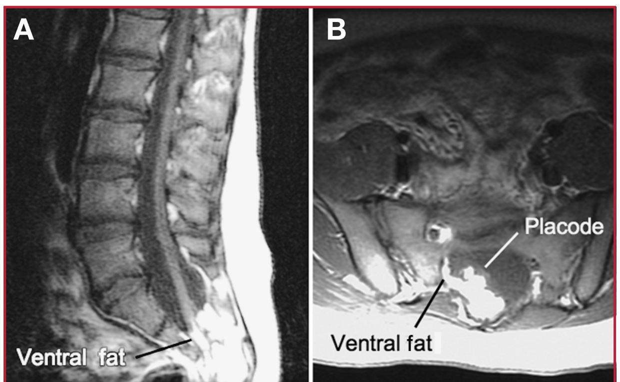

FIGURE 5. *Chaotic lipoma.* **A**, *sagittal MRI scan showing ventral as well as dorsal fat in relation to the neural placode. Note sacral agenesis with only 2 visible sacral segments.* **B**, *axial MRI scan showing ventral fat and an extremely irregular lipoma-fat interface.*

The literature (1, 56) describes one other lipoma type, the lipomyelomeningocele, in which part of the distal conus extends along side the fat through the dorsal bony defect into the extraspinal compartment, dragging with it a small collar of cerebrospinal fluid (CSF) sac (Fig. 7). The basic structure is most commonly that of a transitional lipoma but occasionally a dorsal one. Accordingly, we choose to classify this type as either a transitional or dorsal lipoma with the descriptive qualifier of extraspinal extension.

Surgically Relevant Embryology

Embryogenesis of Dorsal and Transitional Lipomas

In the embryo, a progressive disparity exists between the spinal cord and the vertebral column as a result of the faster growth rate of the latter (14, 17, 28, 61). The caudal end of the cord ascends gradually from opposite the coccyx in the 30-mm human embryo to the L1–L2 level at birth (3, 21, 28, 61). Proper ascent of the cord requires a well-formed neural tube and a smooth pia-arachnoid covering. If a dorsal defect exists in the dura (duraschisis) and neural tube (myeloschisis) during early development, mesodermal elements from the surrounding mesenchyme will enter the dural sac and form an attachment with the sliding neural tube in the form of a fibrofatty stalk, resulting in its entrapment. This theory features a fundamental defect in neural tube closure during primary neurulation (secondary neurulation does not involve dorsal neural fold closure) and thus applies only to the dorsal and transitional lipomas (see below). It is compatible with the observation that these 2 types of lipomas are always associated with spinal dysraphism.

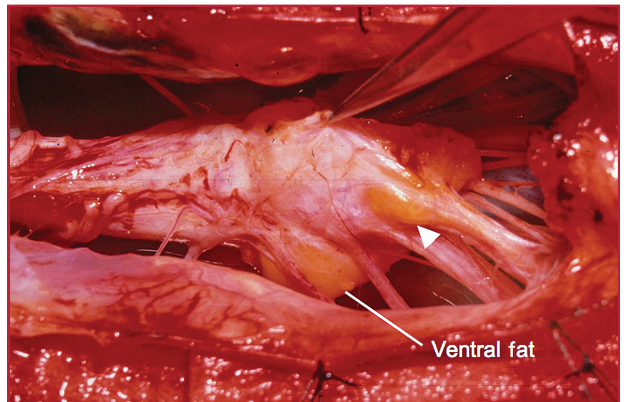

FIGURE 6. *Chaotic lipoma. Intraoperative photograph showing fat ventral to the placode and on one of the sacral roots (arrowhead). Note the absence of a discrete fusion line.*

FIGURE 7. *Lipomyelomeningocele with the lipoma stalk, cerebrospinal fluid sac, and part of the conus extending out of the spinal canal through a dorsal defect.*

Several theories have been proposed to explain the embryological error leading to the mesodermal invasion of the neural tube in the genesis of the lipomatous stalk. McLone et al. (7, 40, 43) think that the error lies in *premature disjunction* between the cutaneous and neural ectoderms, i.e., the separation of one from the other occurs before the converging neural folds fuse with each other. This allows the paraxial mesenchyme to roll over the still gaping neural folds and enter the central canal. Once contact between the mesenchyme and ependymal neuroectoderm is made, further closure of the neural tube is permanently prevented and a segmental dorsal myeloschisis is created (Fig. 8, A and B). An alternative theory claims that there is a primary insufficiency of

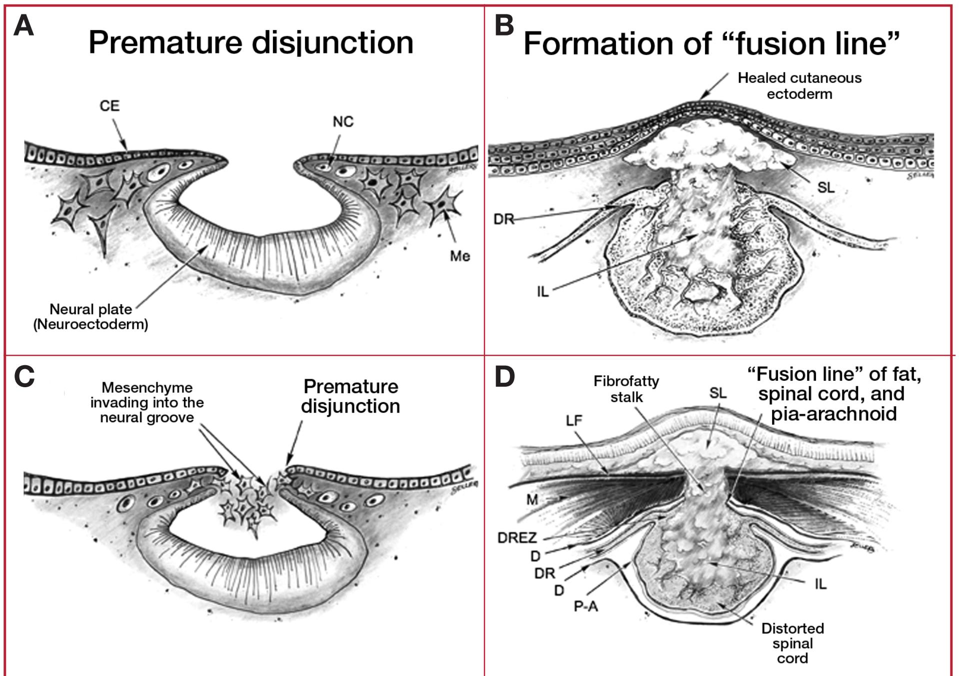

FIGURE 8. *Embryogenesis of a dorsal lipoma, a pure primary neurulation defect.* **A** *and* **B**, *premature disjunction before complete closure of the neural plates allows migration of mesenchymal cells into the neural groove to be in contact with the ependymal surface.* **C** *and* **D**, *formation of the fusion line between the lipoma, the cord, and the pia-arachnoid. The dorsal root entry zone (DREZ) and dorsal root (DR) are always lateral to the fusion line and thus not entangled in fat. CE, cutaneous ectoderm; NC, neural crest; Me, mesenchyme; SL, subcutaneous lipoma; DR, dorsal root; IL, intramedullary lipoma; D, dura; P-A, pia-arachnoid; M, muscle; LF, lumbodorsal fascia. Modified from Pang D: Spinal cord lipomas, in Pang D (ed):* Disorders of the Pediatric Spine. *New York: Raven, 1995, pp 175–201 (54).*

the paraxial mesoderm in providing the chief extrinsic forces that normally impel dorsal bending and convergence of the neural folds (30-34, 36), causing a delay in neural fold fusion (35). Ectodermal disjunction, being an epochal event with its own set time, would then precede neural folds fusion in the case of delayed fusion. The result will be similar to that of premature disjunction. Last, faulty fusion of the neural folds caused by a metabolic disturbance of the cell membrane-bound glycosaminoglycans, which are vital to cell-cell recognition and adhesion (39, 44, 47, 63), could likewise reverse the temporal relationship between disjunction and neural fold fusion.

Experimental studies show that the pluripotential mesenchyme forms derivatives according to the inductive properties of the adjacent neuroectoderm (Fig. 8C) (13, 22). McLone and Naidich (40) postulate that the ependymal side of the neural tube induces the mesenchyme to form fat, muscles, collagen, and occasionally bone and cartilage. The outer surface of the neural tube, in contrast, induces the mesenchyme to form meninges, but no dura can now form over the dorsal opened portion of the neural tube. The dural defect, therefore, surrounds the junction between neural tissue and an intramedullary lipoma. Through this dorsal dural defect, the intramedullary lipoma links up with the extramedullary, extracanalicular adiposity to complete the lipomatous stalk, by which the cord is now tethered to the subcutaneous tissues. In like manner, deficiencies in the overlying myofascial layers (from myotomal mesoderm) and neural arches (from scleromesoderm) also neatly surround the lipomatous stalk (Fig. 8D).

Within the neural tube, the intramedullary fat and muscles fuse with the developing alar and basal plates. Because the dorsal root ganglions develop from neural crest cells at the outer aspect of the neural fold lateral to the site of failed fusion, the dorsal nerve roots grow outward ventrolateral to, but never traverse, the lipomatous stalk. The DREZ must correspondingly lie very near, but always lateral to, the exact junctional boundary between the lipoma and the spinal cord. This boundary, called the fusion line, is of tremendous surgical significance (Fig. 8D) (49, 51, 53). In the meantime, the cutaneous ectoderm, long detached from the neuroectoderm, heals over in the dorsal midline to form healthy skin over the subcutaneous lipoma.

The genesis of the dorsal lipoma perfectly exemplifies mistimed disjunction during primary neurulation. Its fibrofatty stalk always involves cord segments above the conus, which forms from secondary neurulation. Furthermore, failure of primary neural tube closure seems to be segmental, and normal closure takes place as usual immediately after the abnormal event. This square pulse nature is illustrated by the fact that the sharp fusion line between fat, the spinal cord, and the pia-arachnoid can be neatly traced circumferentially around the lipomatous stalk, which goes through an equally "crisp" dorsal dural defect (Fig. 2) (48, 51, 53). Dorsal lipomas therefore result from a segmental closure abnormality involving only primary neurulation. It is interesting that dorsal lipomas were found in less than 15% of spinal cord lipomas in our series, an incidence that roughly parallels that of the rare segmental myelomeningoceles, in which the "suspended" non-neurulated placode is considered an extreme form of segmental primary neurulation failure.

In transitional lipomas, the myeloschisis involves much more than an isolated segment of the primary neural tube. Even though its rostral part resembles the dorsal lipoma, the involvement of the whole of the caudal spinal cord means that not only primary but also secondary neurulation has been profoundly disturbed by the mesodermal invasion. This is supported by the observations that in many transitional lipomas, the filum is incorporated into the distal fat, and often within the lipomas are empty spaces resembling the terminal ventricles of the secondary neural tube. Also, although the rostral part of the transitional lipoma is always dorsal and aptly reflects premature disjunction of primary neurulation, the distal part sometimes involves both the dorsal and ventral aspects of the conus, a situation compatible with misguided mesenchymal inclusion during the much less orderly events of secondary neurulation. Intramedullary mesenchyme may migrate within the neural tube after invasion and travel caudally across the boundary from the primary

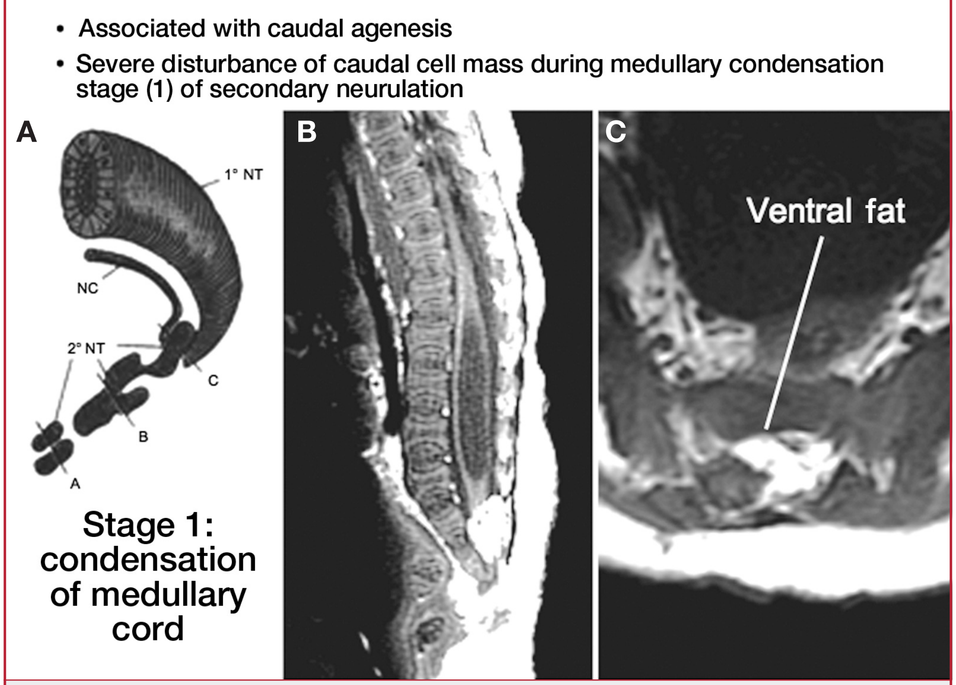

FIGURE 9. *Embryogenesis of chaotic lipomas.* **A**, *basic error probably occurs with the inclusion of abnormal lipogenic mesenchymal cells into the caudal cord during condensation stage (stage 1) of secondary neurulation, with the formation of the medullary neural cord, thereby generating fat tissue throughout the substance of the mature neural placode.* **B** *and* **C**, *dorsal and ventral fat and associated sacral agenesis. 1° NT, primary neural tube; 2° NT, secondary neural tube; NC, notochord.*

to the secondary neural canal since the 2 neural canals are probably always in continuity (59). In fact, the hypothesis that the rostral part of the transitional lipoma arises from aberrant primary neurulation (involving only the dorsal cord) and the caudal lipoma arises from abnormal condensation of the secondary neural cord (affecting more ventral aspects of the conus) provides at least 1 explanation for the dorsoventral obliquity of the lipoma-cord interface.

Embryogenesis of Chaotic Lipomas

Chaotic lipomas do not quite fit into either the dorsal or transitional schema. They often do not have a distinct dorsal part with the symmetry of a dorsal lipoma, and the lipoma-cord interface is irregular and ill-defined, with fat running through the neural placode to the ventral side in large and unruly measures. Even in the context of the less orderly transitional lipoma, the interplay between the lipoma and the cord in this type of lesion seems to be in constant chaos.

This degree of anatomic unpredictability in chaotic lipomas and its strong association with caudal agenesis (82% in our series) suggest that the embryogenetic error occurs during the early stage of secondary neurulation as part of the general failure of the caudal cell mass (Fig. 9) (45, 46). Secondary neurulation comprises 3 distinct stages: 1) condensation of neural material from the caudal cell mass caudal to the primary neural tube to form the solid neural cord, 2) canalization of this neural cord into intramedullary cavitations that coalesce into a single large secondary central canal (46, 58, 59) and integration of this cavitated secondary neural cord with the primary neural tube, and 3) retrogressive differentiation of the terminal neural cord into the thin filum terminale (28, 59). It is possible that formation of the chaotic lipoma in the background of caudal agenesis (50) involves the entanglement of the lipogenic mesenchymal stem cells with cells from the caudal cell mass during aberrant condensation of the secondary neural cord, resulting in an inseparable mixture of neural tissue and fat, with nerve roots projecting haphazardly.

Intraoperative Electrophysiological Monitoring

Intraoperative monitoring has become sine qua non in lipoma surgery (52, 54). In truth, we use it less as a monitor than an expositor because we are more concerned with using electromyography to accurately identify the motor roots and detect functional spinal cord within fibrofatty muddles. The muscles commonly used were the sartorius (L_1), rectus femoris (L_2, L_3), anterior tibialis (L_4, L_5), extensor hallucis longus (L_5), and gastrocnemius (S_1). Half-inch long, 25- to 27-gauge needle recording electrodes and input gains of 50 to 80 µV were selected to enable maximum capturing of far-field evoked action potentials of the indexed muscle without undue artifacts. Smaller needle electrodes were inserted directly through the anal verge to record activities of the external anal sphincter (S_2–S_4). All stimulations and recordings were done with the Cadwell Cascade Intraoperative Monitoring System (Cadwell Laboratories, Inc., Kennewick, WA) using the Cascade Software Version 2.0.

For nerve root and direct spinal cord stimulation, we used a concentric coaxial bipolar microprobe (Kartush Concentric Bipolar; Medtronic Xomed, Inc., Jacksonville, FL) (Fig. 10). This microprobe generates extremely focused and confined current spread at its 1.75-mm tip and thus works best at precise localization of small functioning neuron-axonal units. Larger double-pronged bipolar electrodes and, worse, monopolar electrodes, which in essence convert the spinal cord into a giant volume conductor, are undesirable because they cause unwanted recruitment of adjacent depolarizable tissues. Stimulating currents from 0.5 to 1.5 mA are used depending on target impedance. The stimulation frequency is usually set at 10 per second. This allows spontaneous random firing caused by nerve irritation from surgical manipulation to be distinguishable from the rhythmic evoked contractions.

To monitor L4–S1 spinal cord conduction, we used standard somatosensory evoked potentials with stimulating needle electrodes placed near the posterior tibial nerve behind the medial malleolus and near the common peroneal nerve over the fibular neck. Pudendal somatosensory evoked potentials for monitoring S2–S4 cord segments can be used with disc electrodes affixed to the dorsum of the

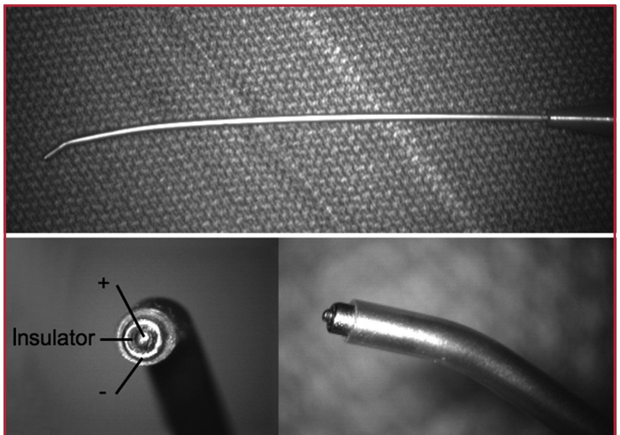

FIGURE 10. *Concentric coaxial bipolar microprobe stimulator in which the concentric cathode and anode are separated by a coaxial insulator. Tip diameter is approximately 1.75 mm.*

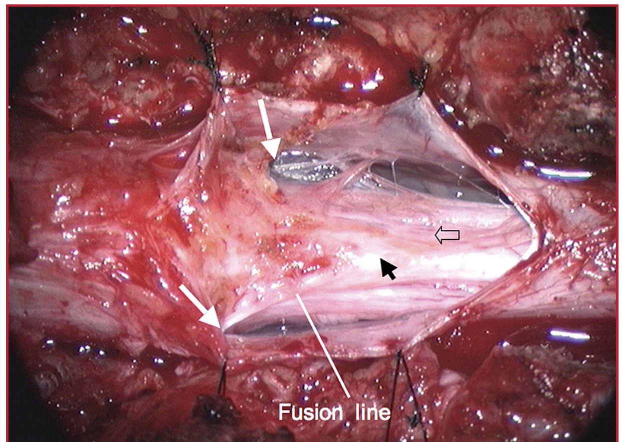

FIGURE 11. *Exposure of the rostral lipoma showing the normal cord to the right and the swath of yellow fat indicating the beginning of the lipoma (small arrow). The large arrows locate the far lateral adhesion points (the crotches) between the flanges of the lipoma and the inner dura. The rostral starting point of the fusion line is also indicated (open arrow).*

penis or on the periclitoral skin, but the evoked cortical tracings in infants tend to be disorganized, unstable, and extremely susceptible to inhalation anesthetics, which considerably limits the value of pudendal somatosensory evoked potentials in children younger than 1 year of age.

Surgical Technique of Total/Near-Total Resection

Step 1: Exposure

The skin and soft-tissue incision should go straight through the subcutaneous lipoma if one is present. Removing this will leave behind a large subdermal space into which CSF could collect under tension and consequently hinder wound healing. Frequently, a discrete fatty stalk connects the subcutaneous with the intraspinal lipoma through a defect in the lumbodorsal fascia. This stalk is continuous with the spinal cord and cannot be tugged on during fascial dissection.

The upper extent of the bony exposure should include 1 level above the rostral end of the lipoma. This reveals for proper orientation the last normal set of nerve roots and DREZ before starting lipoma resection. The lower extent of the bony exposure needs only to include 1 cm or so beyond the end of the neural placode and not of the lipoma. The distal fat sometimes goes far below the neural placode to fill the caudal dural sac, but that portion should be left behind after complete detachment from the conus (see below); not only will this isolated distal fat cause no harm, but it serves well as an end plug if the bottom of the CSF sac is tenuous.

Wide laminectomy is essential to afford full access to the lateral edges of the dural sac (see below). Visualization of the normal dura rostral to any lipoma gives a depth perspective as to how far out neural tissue and CSF sac might have extruded beyond the plane of the dura. The heavy bulk of extradural fat could then be safely cut off to make room for intradural dissection and lighten the tug on the conus.

Step 2: Detachment of the Lipoma from the Dura

The dura rostral to the lipoma is opened in the midline. For a dorsal lipoma, the dural incision is carried circumferentially around the discrete lipoma stalk and then down the middle again to expose the conus. For a transitional lipoma, the dura is cut close to the lipoma edge on each side as far caudally as possible, although the 2 side incisions seldom meet distally. The dural edges are then tautly and widely retracted with sutures. This is a crucial maneuver because full lateral exposure of the intradural span, made possible by the generous bone removal, reveals the "crotch" where the far lateral fringe of the lipoma attaches to the inner surface of the dura (Fig. 11).

Next, the fusion line is identified where the pia, spinal cord, and lipoma join in a continuous furrowed border that travels rostral–caudally outlining the entire attachment of the lipoma stalk to the cord. In a dorsal lipoma, the fusion line forms a neat complete oval or circle from side to side, usually on a leveled horizontal plane, often bilaterally symmetrical and always sparing the conus below (Figs. 1 and 2). In a transitional lipoma, the rostral fusion line starts distinctly enough but then edges ventrally toward the tip of the conus and tends to wander laterally and asymmetrically, often becomes sheltered by the overhanging fat, and never meets its mate from the other side at the caudal end (Figs. 3 and 4).

True to the events of embryogenesis, the DREZ and dorsal nerve roots are always lateral to the fusion line, and at the rostral end of the fatty stalk of both lipoma types, this orderly arrangement can be depended upon to occur on both sides, thus presenting a convenient place to start the dissection. In most transitional lipomas, however, the more caudal nerve roots are quickly hidden from view by the overflowing fat that tends to fuse with the dura at a far lateral point (Fig. 12, top). Hence, the term *crotch dissection*, which depicts the key step of grasping the overhanging fat and pulling it medially under tension against the tagged dural edge, then sharply separating the fat-dura attachment with the dissecting scissors (Figs. 12, bottom, and 13). It is absolutely requisite to lean the round curve of the scissors firmly against the inner lining of the dura while cutting this attachment to avoid blindly injuring the nerve roots that project from the cord slightly medial to the crotch and lie just deep to the fat. The hidden roots should spring into view wherever the detached fat is pulled back and can be gently coaxed away from the dura by blunt dissection toward the exit foramina (Fig. 14). At the same time, the free CSF space ventral to the dorsal nerve roots and the fat-free, pia-covered

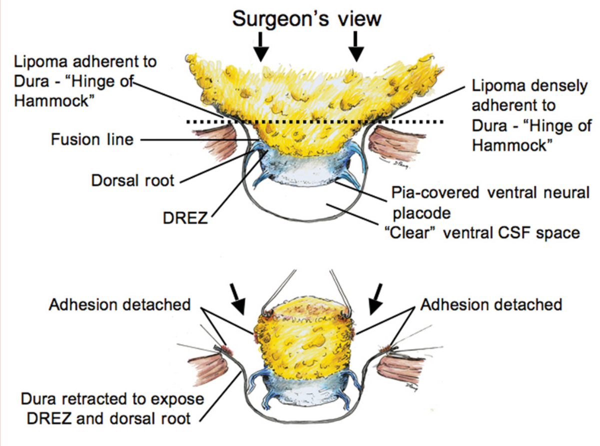

FIGURE 12. *Depiction of the relationship between the lipoma, the neural placode, nerve roots, and the dural sac in an axial slice. Upper, the lipoma-cord assembly is suspended at the dural edge at far lateral adhesion points like a hammock against side hinges. The dotted transverse line that joins the 2 side hinges divides the assembly into a dorsal disorderly fibrofatty half that completely blocks the surgeon's view and a much more orderly ventral half containing the important anatomic landmarks of the fusion line, dorsal root entry zone (DREZ), dorsal roots, the fat-free ventral placode, and the pristine ventral cerebrospinal fluid (CSF) space. Lower: after detaching the far lateral adhesion points (the hinges) by careful crotch dissection and folding-in of the fatty mass, the ventral anatomic landmarks can now be visualized.*

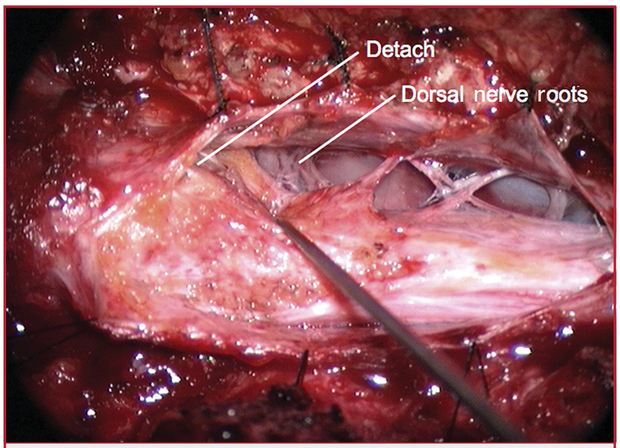

FIGURE 13. *Step 2 of the surgical technique: crotch dissection sharply detaching the far lateral adhesion points between the fringes of the lipoma and the inner dura to unhinge the hammock of the lipoma-cord assembly. Note revealing of the proximal sets of dorsal roots with just the beginning efforts of unhinging the hammock.*

ventral surface of the neural placode, hitherto hidden by the overhang, now "pop" into view (Fig. 15).

It is clear from this description that in each successive axial slice, all lipomas large or small, dorsal or transitional, are roughly divided by a

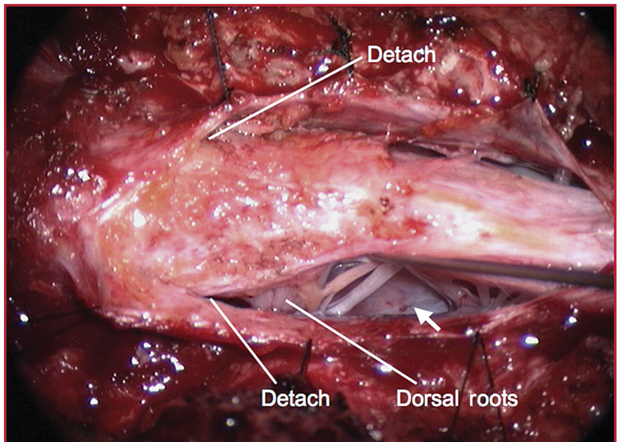

FIGURE 14. *Exposure of the pristine ventral cerebrospinal fluid space (arrow), nerve roots, and fat-free ventral side of the neural placode.*

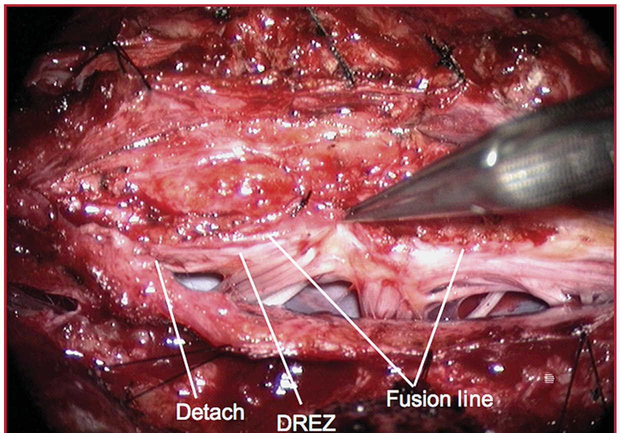

FIGURE 15. *Exposure of all relevant anatomy vital to the next stage of the actual resection of the lipoma: the fusion line, dorsal root entry zone (DREZ), dorsal roots, ventral side of the placode, and free cerebrospinal fluid space, in dorsal-ventral order.*

transverse line joining the points of the far lateral fat-dura attachment on each side, where the lipoma-cord assembly is in effect suspended like a hammock against 2 lateral dural hinges over an uncluttered ventral CSF pool. Dorsal to this transverse line is the visible but disorderly, massive, and unrevealing fat and ventral to this line is the orderly fusion line, the DREZ, dorsal nerve roots, the neural placode, and the ventral CSF space, but all initially rendered invisible to the surgeon by the overhanging fat (Fig. 12, top). The purpose of the crotch dissection is therefore to release this suspension so that the hammock of the neural placode and nerve roots can be folded inward enough to be identified and preserved during the next phase of lipoma resection (Fig. 12, bottom).

This laborious but indispensable step of crotch dissection is carried all the way caudally (Fig. 15) until all the useful nerve roots are identified and the entire neural placode, with a profusion of the lipoma still

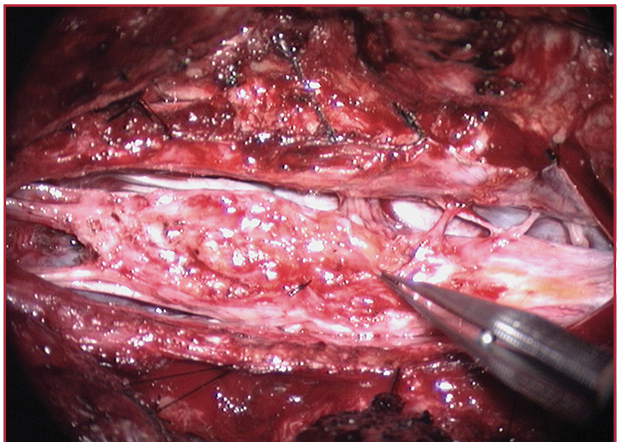

FIGURE 16. *Complete bilateral detachment of the adherent hinges and terminal untethering; the neural placode now sinks into the basin of the dural trough.*

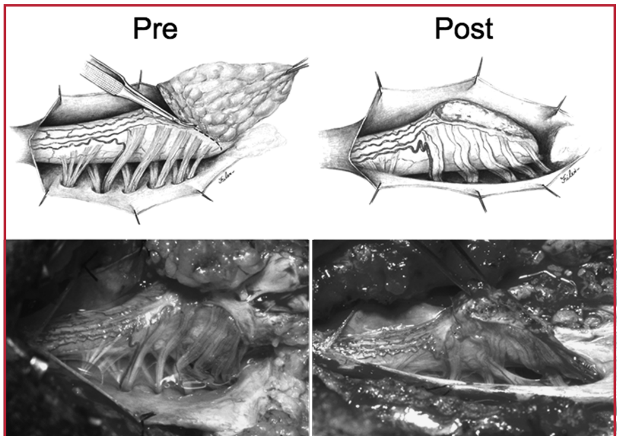

FIGURE 17. *Basic technique for transitional lipoma resection: resection on an asymmetrical and oblique fusion line along an occasionally undulating lipoma-cord interface plane, showing pre- and postoperative images.*

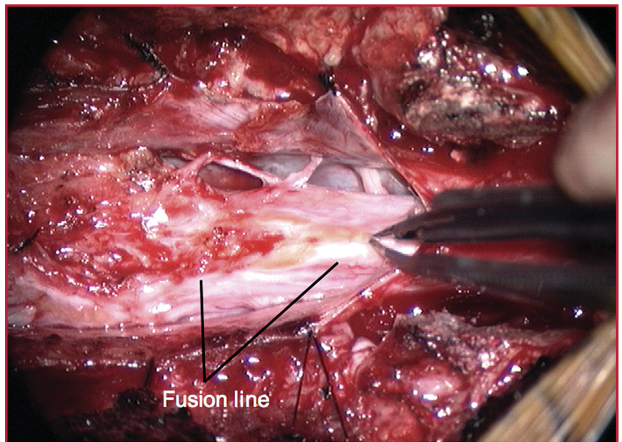

FIGURE 18. *Step 3 of the surgical technique: resection of lipoma begins at the rostral end of the fat, at the semilunar edge showing just a small yellow swelling (at the points of the bipolar microforceps). Note the rostral fusion line and first pairs of dorsal roots.*

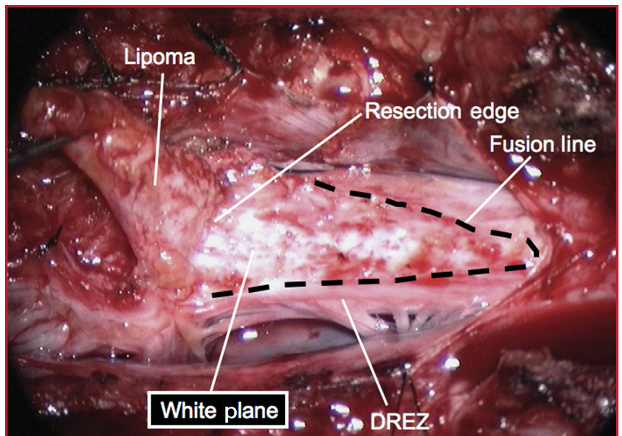

FIGURE 19. *The white plane of thin glistening fibrous netting separating fat from the spinal cord, bounded always by the fusion line. Note the detached rostral portion of the lipoma lifted away from the white plane to show the resection edge. DREZ, dorsal root entry zone.*

attached, is completely unsuspended from the dura and has literally fallen to the basin of the dural trough (Fig. 16).

Step 3: Lipoma Resection

Resection of the lipoma begins at the rostral end where the anatomic relationships between fat, the DREZ, and the dorsal nerve roots are clearly decipherable (Figs. 17 and 18). Sharp dissection with microscissors is used to locate a thin but distinct silvery white plane between the fat and the cord at the demilune of the rostral fusion line (Fig. 19). It takes some determination, for the initiate, to cut into this traditionally forbidden place, seemingly straight into the spinal cord right at the fusion line, but with experience, this white plane can be found in every case. We strongly discourage using the CO_2 laser because it chars the surface (thus no more white plane) and negates the tactile feedback through the microscissors on which the surgeon depends to differentiate between cutting through the grittiness of fibrous fat and the formless softness of spinal cord. Bleeding on the white plane can be handled with the ultrafine irrigating bipolar cautery (0.2-mm tips) and a very low current setting. The cold irrigation mitigates against sticking, but more importantly, it dissipates heat rapidly from the cord. Minimal cauterization is used on the DREZ to avoid postoperative dysesthesia.

As long as all the activities are rendered medial to the fusion line, thus also medial to the DREZ and the dorsal nerve roots, dissection along the white plane can be conducted safely all the way to the end with no damage to the cord or nerve roots (Figs. 20 and 21). In a dorsal lipoma, this is a simple feat because the white plane is basically hor-

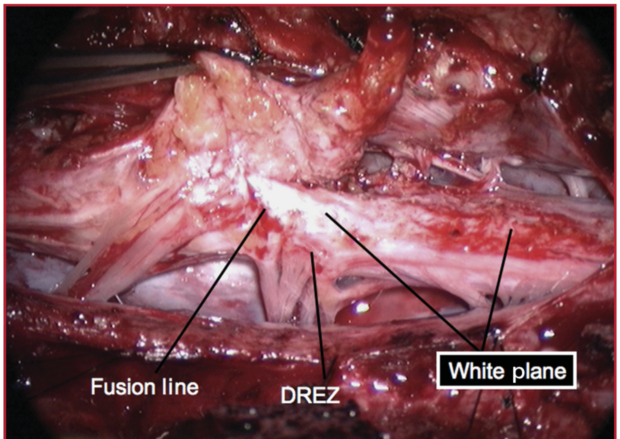

FIGURE 20. *At the outer margin of the white plane, dissection is kept strictly on the fusion line, thus reliably sparing the slightly more lateral dorsal root entry zone (DREZ) and dorsal roots.*

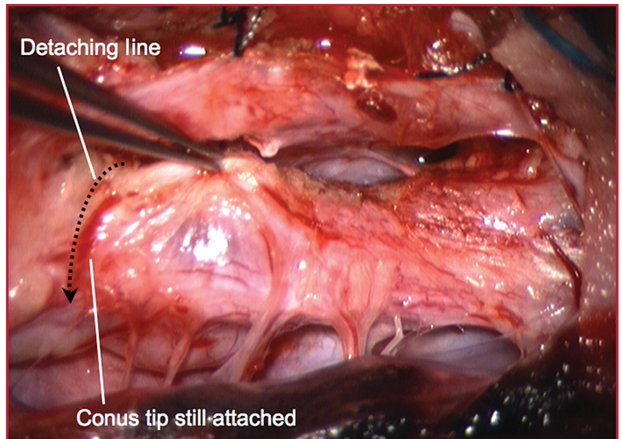

FIGURE 22. *Terminal disconnection of the neural placode from the residual caudal lipoma stump after identification of 2 healthy pairs of anal sphincter motor roots.*

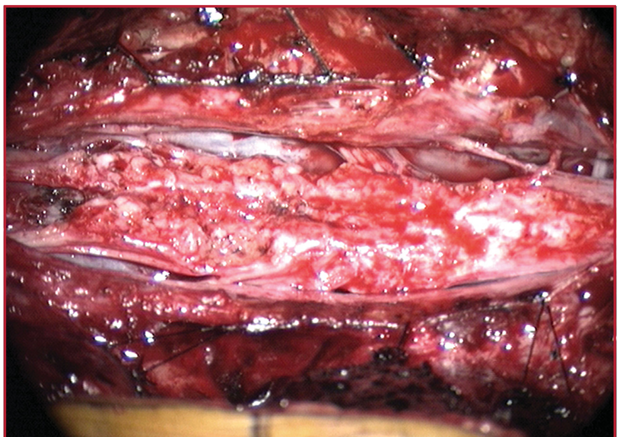

FIGURE 21. *Completed resection of the lipoma, leaving a thin, supple, purely neural placode free of all adhesions.*

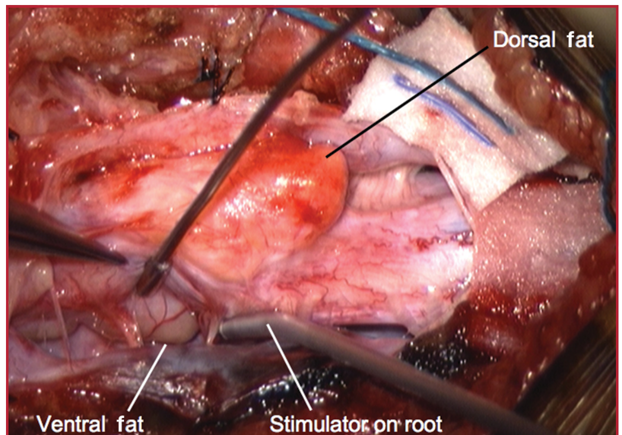

FIGURE 23. *Chaotic lipoma. Note ventral pia-covered fat medial to ventral nerve roots (being stimulated by concentric microprobe), and dorsal fat perched on the dorsal side of the placode.*

izontal and flat, the 2 banks are symmetrical, and the caudal end well defined rostral to the conus so that a complete circumscribed attack on the fat is possible from multiple angles. In a large transitional lipoma, navigating the white plane is more difficult because it always slopes ventrally, often undulates, and 1 side may be tilted so steeply that the corresponding DREZ and nerve roots are shifted ventrally and the placode so rotated that its ventral surface now faces the side. Such a white plane is almost turned vertically on edge, its orientation confusing unless one remembers the transverse line concept dividing one "clean" ventral hemisphere from the "messy" dorsal one.

The white plane sometimes seems never ending in large transitional lipomas and the caudal thecal sac is thronged with fat admixed with suspicious strands. This is when systematic stimulation and identification of the ventral nerve roots become invaluable in localizing the termination of the *functional* spinal cord. As soon as 2 to 3 pairs of sphincter-activating sacral roots are identified, any tissue distal to the last pair can be considered nonessential and be cleanly cut across to consummate the final liberation of the placode (Fig. 22). A good chunk of the now isolated distal fatty stump should be excised to prevent reconnection with the terminal placode.

In chaotic lipomas, electrophysiological determination of the functional extent of the neural placode may be the only way to achieve final untethering; the caudal fat-cord-fibrous jumble can only be sorted out functionally and not anatomically by direct stimulation of the placode and the projecting nerve roots. The handling of the white plane on the dorsal side of a chaotic lipoma is the same as with the other lipoma types, but the billows of fat on the ventral side of the placode should be left alone and its smooth pial surface left unviolated (Figs. 23 and 24). It is always the dorsal and never the ventral

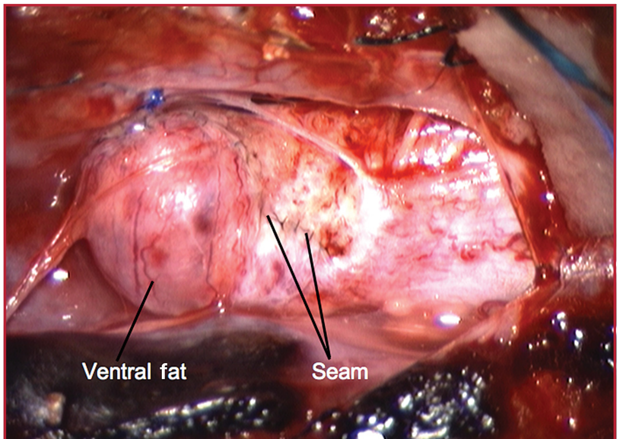

FIGURE 24. *Chaotic lipoma. The caudal placode is pulled up dorsally widthwise to be neurulated with the more proximal pial edge to form the seam, displaying the unviolated pia-covered ventral fat as a blunt stump.*

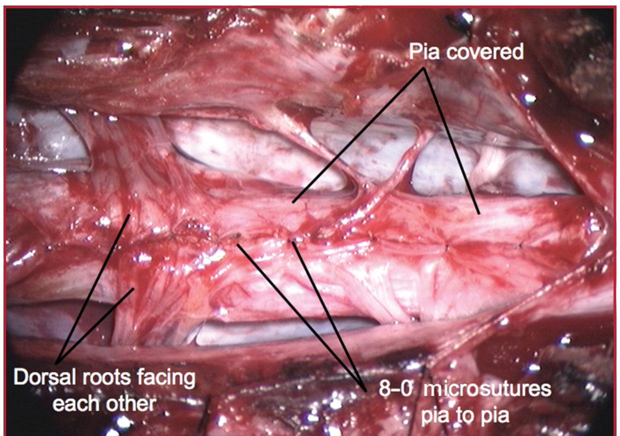

FIGURE 25. *Step 4 of surgical technique: pia-to-pia neurulation with 8-0 nylon sutures tied with inverted knots. The reconstituted neural tube is now completely covered by the pia and the dorsal root entry zones on each side are once again facing their opposite number near the midline.*

part (unless iatrogenically invaded) of the lipoma that actually tethers the spinal cord.

Step 4: Neurulation of the Neural Placode

Total resection of the dorsal fat and thorough unhinging of the placode convert a bulky, transfixed lipoma-cord complex into a free-floating, thin, supple, purely neural plate (Fig. 21), eminently suitable for pia-to-pia, midline dorsal closure with interrupted 8–0 nylon sutures without strain on or strangulation of the neural tissue (Fig. 25). It is helpful to leave a narrow cuff of pia along the cut edges of the white plane to accommodate the sutures, which are tied with inverted knots. Neurulation thus transforms a broad, wafery, sticky sheet into a trim, sturdy, pia-covered tube bearing a single seam, evocative of the natural neurulation process (Fig. 26).

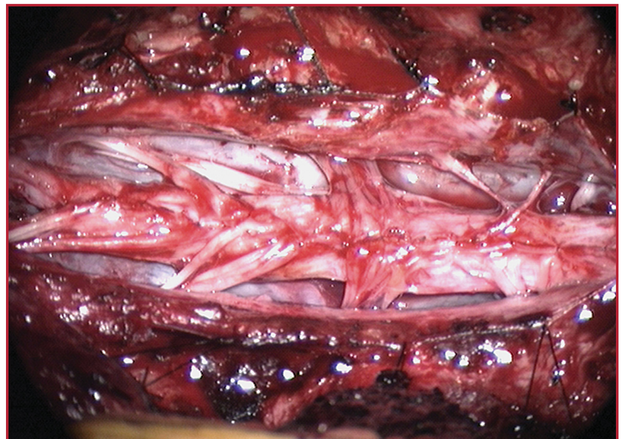

FIGURE 26. *Completed neurulation.*

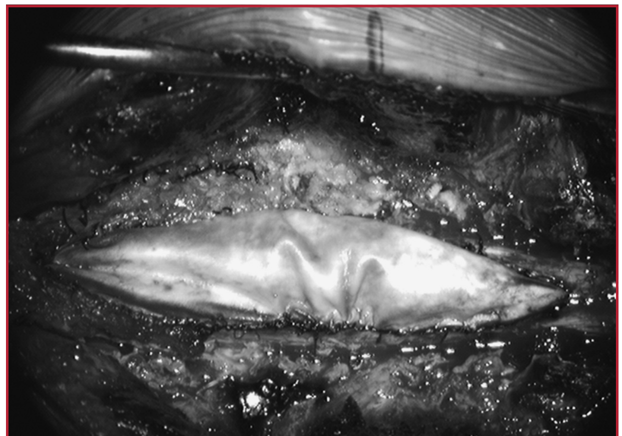

FIGURE 27. *Step 5 of surgical technique: completed expansile graft duraplasty with bovine pericardium.*

Step 5: Expansile Graft Duraplasty

The argument for a graft dural closure comes from our belief that if the neurulated placode could slosh about in ample CSF within a capacious sac, the likelihood of reattachment to the dura would be diminished. Thus, we prefer a slightly full-bodied yet texturally compatible (to infant dura) material, such as bovine pericardium that can maintain its shape, to a filmy, soft graft such as autologous fascia lata, which may swell and ebb with respiration and body movements and thus collapse on the cord. The bovine graft is carefully measured and shaped to prevent having inward folds. Running Prolene sutures are used to achieve water-tight closure, confirmed with Valsalva maneuver (Fig. 27).

RESULTS

Three elements of the aftermath of surgery concern us, including: 1) the amount of residual fat on the placode, which measures

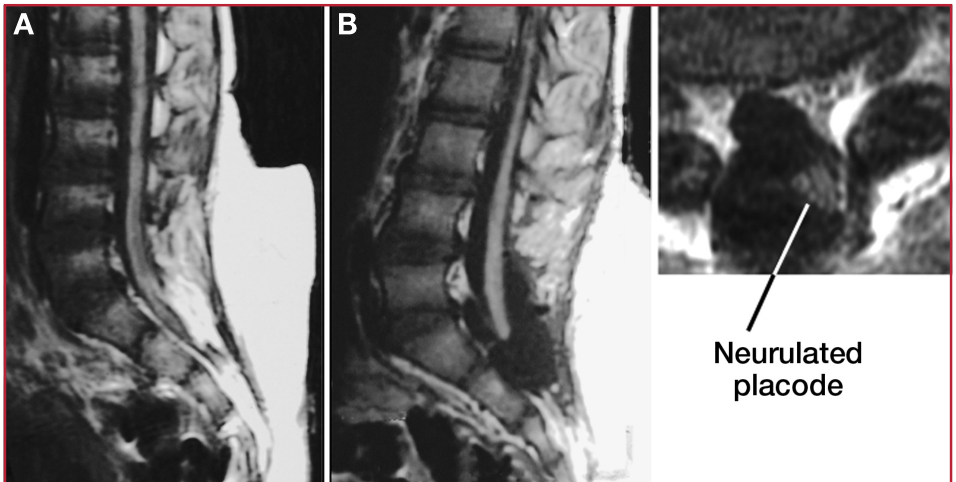

FIGURE 28. *Pre- (A) and postoperative (B) MRI of a transitional lipoma with no residual fat after total lipoma resection. Note the neurulated oblong-shaped, fat-free neural placode within a large dural sac.*

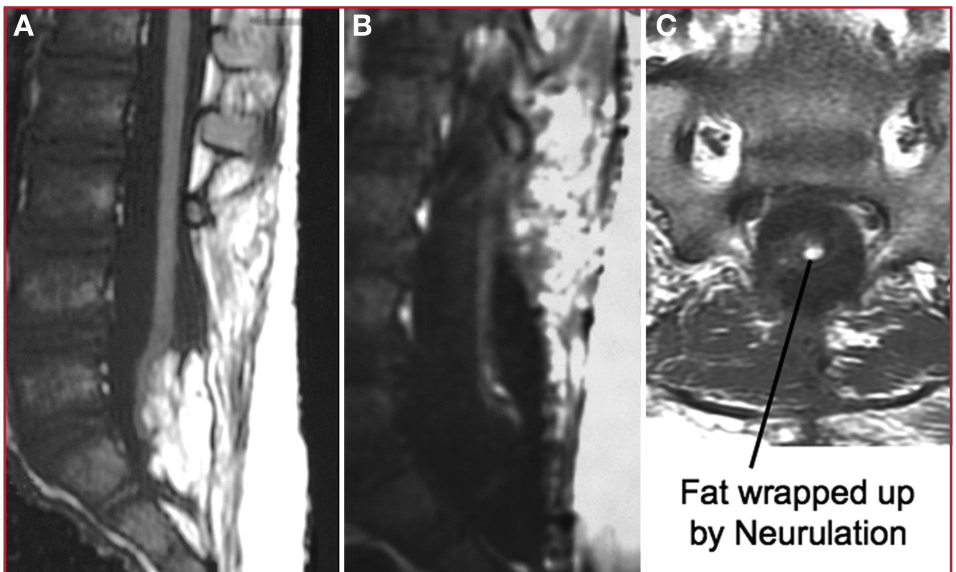

FIGURE 29. *Pre- (A) and postoperative (B) MRI of a complex transitional lipoma with a very small amount (<20 mm³) of residual fat after resection. C, axial MRI scan showing that the small round piece of fat is wrapped up within the roundly neurulated neural placode and therefore not exposed on the surface.*

the reality of our claim of total/near-total resection; 2) the state of reconstruction of the neural placode, which best translates the attainment of our goal of preventing retethering; and 3) complications, which ultimately decides on censure or sanction.

Residual Fat

The amount of residual fat was judged on postoperative magnetic resonance imaging (MRI) at 3 months. One hundred thirty-eight patients (58%) had no residual fat (Fig. 28). Eighty-one patients (36%) had less than 20 mm^3 of fat; the majority of these were small bits of fat wrapped up within the reconstructed neural tube by the neurulation (Fig. 29). Nineteen patients (8%) had more than 20 mm^3 of residual fat; all of these were either on the ventral surface or through the substance of the placode (Fig. 30). Fourteen of these patients had chaotic lipomas.

Although cases with more than 20 mm^3 of residual fat are more likely chaotic lipomas, χ^2 analysis of the overall series does not show a statistically significant correlation between the amount of residual fat and lipoma type. However, redo lipomas are more likely to have residual fat than virgin lipomas (66% versus 34%, $P = 0.0214$) (Fig. 31).

State of Reconstruction of the Neural Placode

The state of placode reconstruction is evaluated on 3 premises: the completeness of terminal detachment of the placode, the roundness of the neurulation, and the cord-sac ratio.

Complete detachment of the terminal end of the placode from fibroadipose tissue was accomplished in every case. A gap of at least 8 to 10 mm was created to prevent distal resticking by removing enough of the distal lipoma stump. Sometimes definite ascension of the detached neural tube was seen on the postoperative MRI (Fig. 32).

Meticulous pia-to-pia neurulation was achieved in every case to give the placode the smooth, rounded tubular shape (Fig. 33), except in some chaotic lipomas where the neurulated product was more oblong than round because of the residual fat. Sometimes the fishtail-shaped flap of the caudalmost neural placode had to be folded dorsally widthwise to complete the concealment of the raw lipoma bed. On postoperative MRI, this

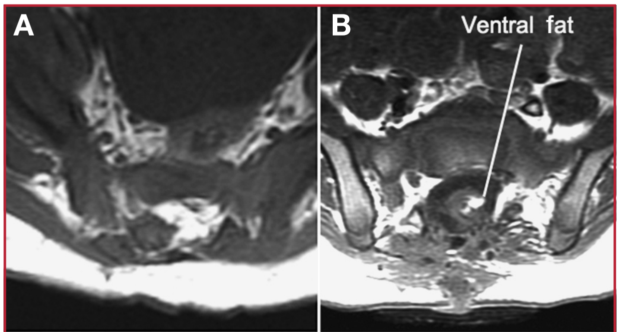

FIGURE 30. *Pre- (A) and postoperative (B) axial MRI of a chaotic lipoma showing massive dorsal and ventral fat filling the spinal canal before resection and greatly reduced fat quantity after resection, but a slightly larger amount (>20 mm³) of residual fat than usual, partially wrapped up within the neurulated placode except for a small ventral bit.*

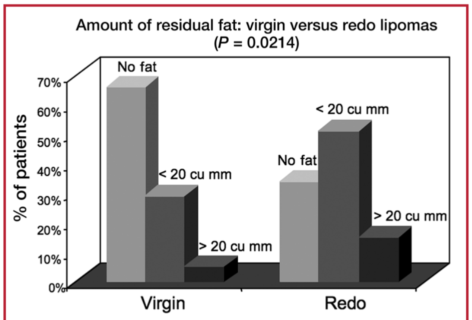

FIGURE 31. *Bar graph comparing the amounts of residual fat in virgin and redo lipomas after total/near-total resection. Redo lipomas are associated with a greater tendency to have residual fat in both the <20 mm³ and >20 mm³ categories. The difference between virgin and redo lipomas is statistically significant (*P *= 0.0214).*

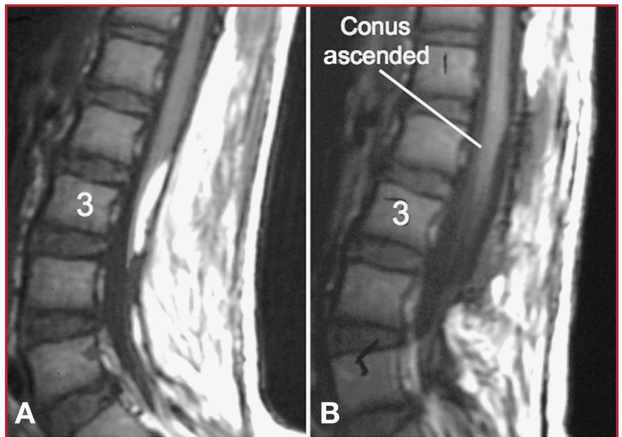

FIGURE 32. *Pre- (A) and postoperative (B) sagittal MRI of a transitional lipoma showing ascension of the conus after complete lipoma resection and distal untethering.*

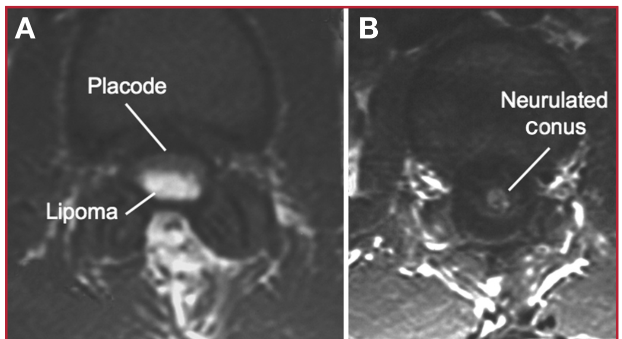

FIGURE 33. *Pre- (A) and postoperative (B) axial MRI of a transitional lipoma showing a smooth, rounded, reconstituted neural tube after complete resection of the lipoma and pia-to-pia neurulation.*

latter procedure conferred a characteristic stubby-stump look to the free-floating placode (Fig. 34).

The cord-sac ratio is created to assess the looseness or degree of freedom of the reconstructed placode within the newly formed dural sac. It is the ratio of the diameter of the cord to the diameter of the sac on postoperative axial MRI at the bulkiest portion of the reconstructed segment, where it enjoys the least commodious occupancy. The ratios are grouped into low (<30%) in the loosest sacs, medium (between 30% and 50%) in moderately loose sac, and high (>50%) in the tightest sacs. In the total group of 238 patients, 162 (68%) had low cord-sac ratios, 61 (25.6%) had medium ratios, and only 15 (6.3%) had high ratios (Fig. 35).

Among the 158 patients with virgin lipomas, 117 (74%) had a cord-sac ratio less than 30%, 36 (22.8%) had a ratio of 30% to 50%, and 5 (3.2%) had a ratio more than 50% (Table 1). Among the 80 patients with redo lipomas, the corresponding distribution of the 3 cord-sac ratios were 45 (56.3%) for low ratios, 25 (31.2%) for medium ratios, and 10 (12.5%) for high ratios (Fig. 36; Table 1). The virgin lipoma group thus had a higher preponderance of low cord-sac ratios compared with the redo lipoma group. The difference in distribution of cord-sac ratio between the 2 groups was significant ($P = 0.00376$).

The distribution of the cord-sac ratio among the 3 lipoma types is shown in Table 2. Although chaotic lipomas are twice as likely to end up with a more than 50% cord-sac ratio compared with dorsal and transitional lipomas, the overall distribution of cord-sac ratio is not significantly different among the lipoma types (between chaotic and dorsal, $P = 0.4252$; between dorsal and transitional, $P = 0.7462$.)

Complications of Total/Near-Total Resection

A detailed analysis of the postoperative complications for total/near-total resection will be reported in part II of this study.

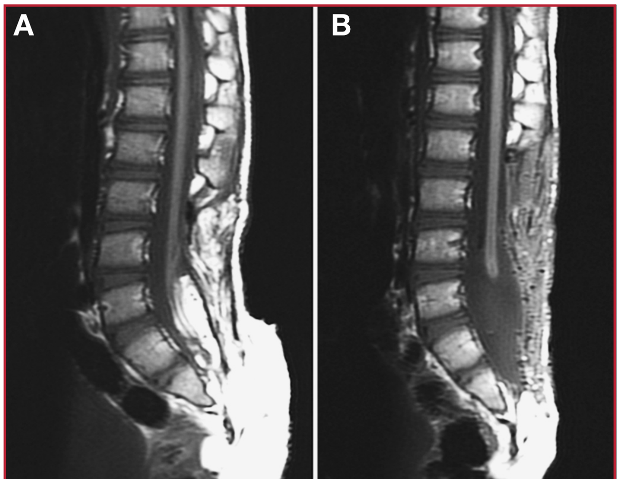

FIGURE 34. *Pre- (A) and postoperative (B) sagittal MRI of a transitional lipoma showing a blunt, stubby stump look to the terminal conus after widthwise dorsal folding of the caudal placode flap at neurulation. Note the large capacious dural sac.*

TABLE 1. Cord-sac ratio in virgin and redo lipomas

		Cord-sac ratio		
	Total no.	<30%	30%–50%	>50%
Virgin lipomas	158	117 (74%)	36 (22.8%)	5 (3.2%)
Redo lipomas	80	45 (56.3%)	25 (31.2%)	10 (12.5%)

An abbreviated account is shown in Table 3. Ten patients (4.2%) experienced neurological deterioration from surgery. The most common neurological symptom was dysesthetic pain in 1 or both legs (10 patients); only 4 patients (1.7%) had new motor weakness and 5 patients (2.1%) also had some sensory loss. Five of the 10 patients with neurological changes also had deterioration in bladder function, either voiding dysfunction or incontinence. All told, the combined neurological-urological complication rate is 4.2%. Patients with redo lipomas are 4 times more likely to have neurological-urological complications.

Four cases of CSF leak or pseudomeningocele were seen, 3 of which were the result of redo surgery. Six patients (2.5%) had wound problems, but wound problems are 5 times more likely to develop in redo lipomas than in virgin lipomas. The one case of bovine graft rejection had recurrent pseudomeningocele that ultimately required autologous fascia lata grafting. This child also developed severe arachnoiditis in the lumbosacral nerve roots. Thus, the overall surgical complication rate for total/near-total resection was 5.4%.

DISCUSSION

The rationale for total lipoma resection is based on 3 hypotheses: 1) the high rate of symptomatic recurrence after partial resection is caused by retethering; 2) retethering is promoted by 3 factors, a tight content-container relationship between spinal cord and dural sac, a large sticky, raw surface of residual fat, and incomplete detachment of the terminal neural placode from the residual lipoma; and 3) total resection can eliminate the factors conducive to retethering and thus reduce the probability of symptomatic recurrence.

The object of surgery is therefore to create conditions that will minimize retethering. The first condition relates to the fact that the normal spinal cord exhibits intradural motions to gravity and postural changes on ultrasonography and dynamic imaging (5, 15). Decreasing the content-container ratio and increasing the degree of freedom of the cord within the dural sac must lessen resticking by limiting sus-

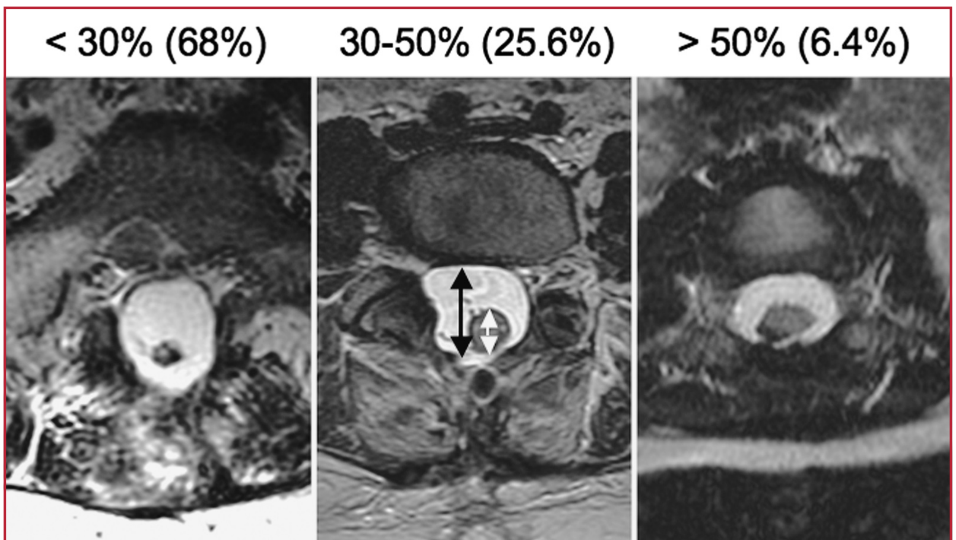

FIGURE 35. *Cord-sac ratios in the postoperative axial MRI after total/near-total resection of a lipoma. This ratio was obtained by dividing the sagittal diameter of the most bulbous portion of the postneurulated neural placode by the sagittal diameter of the dural sac. In our series, 68% of the patients had very loose sacs with cord-sac ratios <30%, 25.6% had intermediate ratios of 30% to 50%, and 6.4% had ratios greater than 50% with the least commodious cord-sac relationship. Cord-sac ratio estimates the degree of freedom of motion of the postneurulated spinal cord within its container sac.*

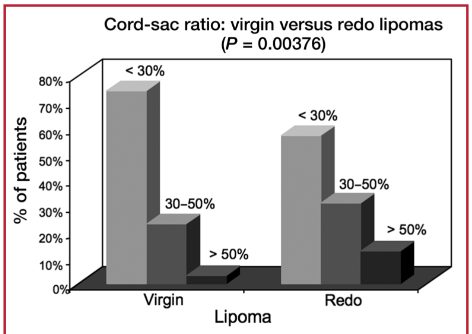

FIGURE 36. *Bar graph comparing cord-sac ratios in virgin and redo lipomas after total/near-total resection. There are more intermediate and high (30%–50% and <50%) cord-sac ratios among patients with redo lipomas compared with virgin lipomas, implying redo lipomas are more likely to end up with a tighter cord-sac relationship. The difference is significant (P = 0.00376).*

TABLE 2. Cord-sac ratio in different lipoma types

Lipoma type	Total no.	Cord-sac ratio		
		<30%	30%–50%	>50%
Transitional	185	126 (68.1%)	48 (26%)	11 (5.9%)
Dorsal	35	25 (71.3%)	8 (23%)	2 (5.7%)
Chaotic	18	11 (61%)	5 (28%)	2 (11%)

TABLE 3. Neurological, urological, wound, and miscellaneous complications of total/near-total resection of lipoma at 3 months[a]

Complications	Virgin lipomas, no.	Redo lipomas, no.	Total
Neurological			
Neuropathic pain	2	8	10 (4.2%)
Loss of sensation	1	4	5 (2.1%)
New weakness	0	4	4 (1.7%)
Total neurological	2	8	10 (4.2%)
Urological/bowel			
Worsened voiding function/ incontinence	1	3	4 (1.7%)
Required CIC	1	2	3 (1.3%)
Bowel incontinence	0	2	2 (0.8%)
Total urological/bowel	1	5	6 (2.5%)
Combined neurological-urological	2	8	10 (4.2%)
Miscellaneous/wound			
CSF leak	1	1	2 (0.8%)
Pseudomeningocele	0	2	2 (0.8%)
Graft infection	0	1	1 (0.4%)
Wound infection	1	2	3 (1.3%)
Wound dehiscence	0	1	1 (0.4%)
Bovine graft rejection	0	1	1 (0.4%)
Total miscellaneous/wound	1	5	6 (2.5%)
Overall complications		13 (5.4%)	

[a] CIC, clean intermittent catheterization; CSF, cerebrospinal fluid. Results for virgin and redo lipomas are separately tabulated.

tained contact between the cord and the dura, this sustained contact being intuitively a necessary condition preceding the formation of fibrous adhesions. To do this, the cord bulk must be drastically reduced. For large, rambling virgin lipomas, this means resection of all or most of the fat down to the thin, supple neural placode. For redo lipomas, the hard, grasping cicatrix must also be removed. The aim is to render the thinnest, most pliant neural placode possible that can be atraumatically neurulated without distortion or strangulation to form a slender, round tube. The raw, sticky lipoma bed is simultaneously concealed within the tube and the sac is enlarged by a capacious dural graft. Finally, total resection also enhances the chances of terminal untethering.

Technical Points

Resection of Fat and the White Plane

Our data show that total or near-total resection of spinal cord lipomas can be done in more than 90% of cases. Regarding the 36% of patients with some residual fat seen on MRI, it should be pointed out that 20 mm^3 of fat is a very small amount indeed ($<2.7 \times 2.7 \times 2.7$ mm), no more than a miniscule dot on 1 or 2 successive MRI slices. In most cases, the fat is adherent to the DREZ and had been invaginated out of mischief during neurulation. In the 8% of patients with more than 20 mm^3 of residual fat, the fat is usually part of the ventral component of a chaotic lipoma and has been intentionally left pia-covered and therefore harmless.

The size of the lipoma is not an important determinant of the completeness of resection. Much more relevant is the configuration of the lipoma-cord interface, which contains the white plane. The white plane is a filmy netting of relatively compact collagen fibers. It may be extremely contorted and asymmetrical in some transitional lesions. It occasionally sends hillocks of fibrous septae into the fat. These formal irregularities are usually toward the middle or caudal part of the lipoma, which makes the rostral end the safest place to first engage this plane, where the anatomy is predictable. There is no better way than to cut into the tongue of the rostral lipoma to find the glistening fibers beneath the first few globules of yellow fat. Once the plane is located, one can follow it with sharp dissection by feeling the grittiness through the microscissors and by spotting the glistening white stripes between yellow fat and pink spinal cord. The CO_2 laser (20, 29, 41) chars the dissection path and negates the enormous benefits of both the tactile and the visual cues.

With large dorsolateral transitional lipomas, the lipoma-cord interface can look almost vertical on axial MRI, with the lipoma always facing the side of the worse neurological deficits. Access to the DREZ of the ventral (down) side can be awkward unless the hammock is first unhinged, and the placode is swung back to a more horizontal position. On the more involved side, festoons of overhanging fat may obscure the emergent dorsal roots to give the false impression that they course through and not underneath the lipoma. In most cases, the overhang can be readily teased and lifted off the knee-turn of the dorsal rootlets to allow these to be traced under the veranda of fat into the true DREZ, at which site the white plane can once again be picked up. In general, a sinuous and severely rotated white plane makes it more likely to leave behind residual fat.

Unlike Arai et al. (1) and Chapman (9), who thought lipomyelomeningocele was a more treacherous lesion with a poorer prognosis, we have not found this to be the case as long as one is keenly aware of the extruded and thus more vulnerable extraspinal part of the placode during scything of the lipoma. Once the fat is off, the ensuing steps of reconstruction of these lesions are no more troublesome than for the regular lipomas. We also do not agree with Kulkarni et al. (27) and Chapman (8) that lipomas in adults are more difficult to resect. Allowing for slightly more abundant de novo adhesions in adult lesions, the prosecution of a virgin adult lipoma should be as orthodox as for a virgin lipoma in an infant.

Redo Lipomas

Redo lesions are associated with a higher rate of residual fat and a higher cord-sac ratio. When the fat layer is infiltrated by heavy cicatrix from previous surgery, the cementing hold to the surrounding dura is much more tenacious and harder to detach, and the bright yellow of virgin fat is lost to a gray dense concretion much harder to distinguish from the white plane. The dissection often stops short of the white plane to prevent cutting too deeply, and the result is a stiffer slab of residual scar-studded fat that not only augments the bulk of the placode, but also makes it awkward to fold at neurulation. The presence of this unyielding fat scar at the DREZ often leads to gouging, which may well be the cause of postoperative dysesthetic pain in redo patients. The wound complication rate also is higher than in virgin lipomas. Overall, it is our distinct impression that redo lipomas, irrespective of size, portray a much grimmer picture at surgery than virgin lipomas.

Terminal Untethering

Incomplete terminal untethering of the placode predictably ends in recurrence of symptoms (9, 55, 64). Both Pierre-Kahn et al. (55) and Xenos et al. (64) reported unsuccessful caudal detachment in 20% of their cases and correlated it with poor outcome. We attribute two possible explanations for the surgeon's hesitation to perform the final disconnecting cut. Often with very large transitional lipomas, the distal neural placode is buried in fat, and unless visualization is improved by substantial removal of fat, safe untethering cannot be done. Also, nerve twigs are sometimes seen issuing in pairs from the distal placode beyond where it dives into the caudal fat, making it seem impossible to complete the detachment without sacrificing functional cord. This assumption turns out to be spurious. We found that as long as 2 or 3 anal sphincter-activating roots, presumably S_2 to S_4, are identified and preserved on each side of the placode, there should be no loss of function if the terminal cut is made just caudal to these roots. The small nerve twigs within the discarded stump that did not stimulate are probably coccygeal roots and therefore vestigial in humans and have no essential function (8).

Reconstruction of the Neural Placode and Dural Sac Grafting

Thorough lipoma and scar resection and terminal untethering impart the optimal bulk, texture, and maneuverability to the neural placode for tensionless neurulation. Like McLone et al. (41), we believe that well-executed neurulation reduces the adhesive surface on the placode to a single seam and duly minimizes the probability of its interacting with the dura. Pierre-Kahn et al. (56) were only able to neurulate 17% of their patients because of bulk, and others (62) had a similar experience. In our partial resection group, less than 30% were neurulated. MRI in the unneurulated patients vividly display a fat-sated dural sac with cord-sac ratios exceeding 80% to 90%, and at surgery, the broad surface of the exposed lipoma is archly glued to the dorsal dura. In contrast, we were able to comfortably neurulate all our patients after total/near-total lipoma resection. No adverse effect has been noted with even the snuggest knitting together of the pial edges.

We found autologous fascia lata too soft and clinging to be used as graft material, as Pierre-Kahn et al. (56) did, but eschewed synthetic substances such as GORE-TEX or Silastic because of their propensity to leak CSF. Bovine pericardium is supple enough to match up with infant dura, yet sufficiently full-bodied to maintain an inflated shape in any posture. Even with recumbency, it is not likely to collapse inward on to the cord. All postoperative MRI showing inflated sacs was performed with the patient supine.

Chaotic Lipoma

These are the most treacherous lesions. They can be recognized on preoperative MRI by the presence of ventral fat medial to the ventral nerve roots and by their association with sacral agenesis (Fig. 5). Although the types of lipoma on the whole are not significantly correlated with the postoperative cord-sac ratio, chaotic lipomas compared with the others are more likely to show conspicuous residual fat on MRI. The strategy for chaotic lesion is knowing when to stop excavating deeper after the dorsal portion of the lipoma has been removed to enable neurulation. In general, if the ventral fat is judged not amenable to total excision and neurulation, then its pial surface that had hitherto laid freely against the adjacent ventral dura should be left unsullied to avoid creating new adhesions (Fig. 24).

Complications

Our combined neurological-urological deterioration rate after total/near-total resection is 4.2%, which compares favorably with rates in the literature, which range from 0.6% to 10% (1, 2, 11, 18-20, 24, 26, 29, 37, 38, 41, 56, 57, 62, 64) and average 3% to 7%. Almost all published series involve partial resection using techniques more conservative than ours. Among the patients with neurological problems, only 1.7% had weakness; almost all others had neuropathic pain, which, we suspect, was caused by close encounters of the DREZ and dorsal roots with heat from the electrocautery. Most minor bleeding on the cord can be stopped with gentle tamponade and Gelfoam, and if electrocoagulation has to be applied, only the ultrafine microtipped, irrigating bipolar cautery is used with very low current intensity.

Our extremely low rates of CSF leaks (0.8%) and wound complications (1.3%) are much better than those in almost all the published series (of partial resection), which report CSF leak rates of 2% to 47% (11, 18, 24, 26, 29, 41, 56, 62, 64) and wound dehiscence and infection rates of 2% to 26% (18, 20, 24, 29, 41, 56, 62, 64). Our good results are owed to the following technical stipulations.

1) There must be enough bony exposure caudally so that a cuff of healthy dura past the lowest extent of the lipoma can be made available for graft anastomosis. The graft should never be sewn to the web of fat at the remaining lipoma stump.
2) Absolute watertight closure of the graft with Prolene must be achieved and challenged by Valsalva maneuvers at pressures of 30 to 35 cm H_2O or higher.
3) Synthetic or organic tissue glues are used if there is even a suggestion of a leak.
4) In large sacral lesions, there are often gaping muscle and fascial defects that cannot be primarily approximated. In these cases, we use paramedian relaxing incisions on the flanking lumbodorsal fascia to facilitate sliding midline closure of the myofascial edges.
5) The large subcutaneous lipoma is never removed at the time of intraspinal surgery. The creation of this immense dead space will encourage collection of CSF, which may turn into an enlarging pseudomeningocele and ultimately threaten skin flap viability.

CONCLUSION

Total and near-total resection of complex spinal cord lipomas can be done with very low neurological, urological, and wound complications. By the means described, we can effectively and very substantially reduce the cord-sac ratio and the adhesive surface on the postsurgical spinal cord, the 2 main factors distinguishing total from partial resection. Whether this technical accomplishment improves recurrence-free survival in lipoma patients will be the subject of part II of this study.

At this end of a 16-year long passage of perfecting this technique, we have come to believe that the surgeon's mind set counts most in ultimately determining success or failure. The surgeon, when preparing to perform total resection, must be wholly committed to achieving the final ideal result, and be willing to endure long hours of repetitive micromotions in whittling away fat, of incising endless adhesions perilously close to the spinal cord, of incessantly tapping bands and would-be nerve roots with stimulating probes, of fidgeting with 8–0 sutures, and at the finale, slavishly treading ritualistic steps of graft and soft-tissue closures, very often working against physical exhaustion, dissolving concentration, and grueling monotony. He or she must always keep in focus the visage of the goal: turning the pliant neural placode into a slender, unfettered tube finally laid to rest within a capacious dural sac. Any swerving from this uncompromising course will beguile him or her unhappily into parlaying for a partial resection. It is that stubborn tenacity of purpose and near-obsessive adherence to details, practicable by many, not technical wizardry gifted to so few, that finally win the day.

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COMMENTS

Dr. Pang has contributed much to our understanding and treatment of closed neural tube defects. With this article, the first of 2 parts, Pang et al. add still more.

A common term used to describe the form of closed neural tube defects under discussion is "spinal cord lipoma." A lipoma is a benign tumor composed of fat cells that can enlarge by increasing the number of cells. The spinal cord "lipomas" under consideration are hamartomas. The size of the fatty component can enlarge only by increasing the volume of a fixed number of cells, something that can occur when a patient adds weight disproportionate to growth. It would seem better to refer to this entity as a lipomatous malformation rather than a lipoma.

Pang et al. compare their current results to those wherein they made no attempt to effect a pial-to-pial closure of the plaque and remaining lipomatous tissue once the spinal cord was untethered. One wonders whether a less radical resection of the lipomatous tissue with a pial-to-pial closure would produce the same results as are being reported in this study. I have not been as aggressive in removing the fatty tissue but have performed a pial apposition for a number of years. Although we have not reviewed our series for some time, when we did, our reoperation rate was in the vicinity of 5% and correlated mostly with the size of the abnormal subcutaneous fat collection, the larger size presumably reflecting a more extensive malformation.

Pang et al. have certainly set the bar much higher as to the extent of resection of the lipomatous tissue associated with this form of closed neural tube defect, without concomitantly increasing the risk. Whether such an extensive resection is needed, and whether others can achieve the same results as Pang et al., remains to be seen.

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I thoroughly enjoyed reading and learning from this exhaustive report of Dr. Pang's extensive experience with the operative management of spinal lipomas. The reader should appreciate the meticulous attention to anatomic detail from which he has been able to derive important general principles relating to surgical technique. In my view, the most important contribution has been to clarify the relationship between the relatively straightforward dorsal lipomas and their more complex transitional counterpart. Both share a "white plane," which demarcates the interface between lipoma and conus. The significance of this is that this plane lies just behind the root entry zone in transitional lipomas, just as it does in their dorsal counterpart. Moreover, the limit of the dural defect is circumferentially fused along the external line of this plane as well. This means that if one uses the white plane for orientation during dissection, it will be possible to safely untether transitional lipomas, regardless of the volume of lipomatous tissue and the degree of rotational distortion of the lipoma-conus complex. It also means that virtually the entire bulk of lipoma can been removed, allowing "surgical neurulation" of the placode and maximal reduction of the cord-to-sac ratio at the time of dural closure.

Experience, meticulous attention to anatomic detail, and patience are required to operate successfully and safely on the more complex spinal lipomas, even using the techniques described in this article. As the authors aptly express, it also "takes some determination, for the initiate, to cut into this traditionally forbidden place, seemingly straight into the spinal cord. . . ." In this context, they also emphasize the essential importance of using state-of-the-art neurophysiological monitoring during surgery, a measure with which I wholeheartedly agree.

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