Brachial plexus neurotization with donor phrenic nerves and its effect on pulmonary function

WOLF LUDEMANN, M.D., MICHAEL HAMM, M.D., ULRIKE BÖMER, M.D., MADJID SAMII, M.D., AND MARCOS TATAGIBA, M.D.

Departments of Neurosurgery and Pulmonology, Medical School Hannover; and Department of Neurosurgery, Nordstadt Hospital, Hannover, Germany

Object. To examine possible side effects of neurotizations in which the phrenic nerve was used, pulmonary function was analyzed pre- and postoperatively in patients with brachial plexus injury and root avulsions.

Methods. Twenty-three patients with complete brachial plexus palsy underwent neurotization of the musculocutaneous nerve, with the phrenic nerve as donor material. Patients who suffered lung contusions as part of the primary injury were excluded from this study. In 12 patients (five left-sided and seven right-sided neurotizations) pre- and postoperative functional parameters were compared and additional body plethysmography was performed more than 12 months postsurgery.

Of the 23, no patient experienced pulmonary problems postoperatively. Nonetheless, pulmonary functional parameters showed a vital capacity in percent of the predicted value of 9.8 ± 6.3% (mean ± standard deviation [SD]) in all patients examined, which was a significant reduction (p = 0.0002).

In right-sided phrenic nerve transfers this reduction was significant, at 14.3 ± 3.3% (mean ± SD), whereas left-sided transfers showed a nonsignificant reduction of 3.6 ± 3.5% (mean ± SD). The observed decrease in vital capacity (VC) correlates with the maximal inspiratory pressure (Pimax) as an indication of clinical significance.

Conclusions. When the right phrenic nerve is used as a donor in neurotization of the musculocutaneous nerve, the patient incurs a higher risk of reduced pulmonary VC. If possible, the left phrenic nerve should be preferred. The Pimax has to be determined preoperatively to avoid any further decrease in the already reduced pulmonary function due to the initial injury.

Key Words • phrenic nerve • neurotization • brachial plexus injury • pulmonary function • donor nerve

For treatment of brachial plexus injury with nerve root avulsion a number of nerves have been used for neurotization, including the intercostal, accessory, and the hypoglossal nerves, the contralateral brachial plexus nerve roots, and the motor branches of the cervical plexus. The sheer number of different treatment options clearly indicates that there is no ideal one. In general, the appropriate donor nerve should provide good functional results with minimal deficit.

Phrenic nerve avulsion was used to treat pulmonary diseases in the beginning of the twentieth century, and a number of anatomical and clinical studies were performed at that time. The diaphragmatic paresis resulting from this procedure was supposed to improve the chance of cure in pulmonary tuberculosis without chemotherapy. Interestingly and contrary to our goals, incomplete paresis of the ipsilateral diaphragm has been a major cause of treatment failure with this approach.

Use of the phrenic nerve as the donor for neurotization procedures was first mentioned in 1948. A major series on phrenic nerve neurotization was published in 1996 and in it comparatively good motor function was reported. It has been shown that pulmonary functional parameters were not affected by the procedure in the long term. In our study we examine pulmonary function after phrenic nerve neurotization to investigate whether any resulting deficit is detectable and acceptable.

Clinical Material and Methods

Between 1980 and 1999, a total of 507 nerve transfers for traumatic brachial plexus injury were performed in the Neurosurgical Departments of Nordstadt Hospital and the Medical School Hannover. Neurotization with the phrenic nerve as a donor was performed only in patients with clinical, electrophysiological, and radiological evidence of complete brachial plexus palsy and root avulsions. Root avulsion was determined using preoperative magnetic resonance imaging, myelography, and postmyelographic computerized tomography of the cervical spine, and, in several cases, dorsal inspection made possible by hemilaminectomy. Neurotization was performed with a combined supra and infraclavicular approach, with direct connection in five cases. The use of a sural autograft (mean length 11.1 cm, range 4–20 cm) was necessary in 18 patients.

We retrospectively analyzed 19 of 23 patients who had undergone neurotization, with the phrenic nerve as donor material. The patient follow up ranged from 12 to 42
months; four patients were lost to follow-up review. The mean age of the patients at surgery was 25 ± 5.6 years (mean ± SD, range 15–37 years). Ten patients were regular smokers.

Examinations consisted of pre- and postoperative determination of pulmonary functional parameters including VC, VC%, FEV₁, and FEV₁%. In the follow-up period, Pimax, FRC, and TLC were also assessed. The FRC and TLC were compared with predicted values according to the guidelines of the European Respiratory Society.13 Seven patients were excluded because they had severe lung contusions. Surprisingly, three of those seven showed remarkable improvement of pulmonary function—up to 15% VC—in the late follow up after surgery, despite phrenic nerve transfer. Thus, the improvement should be attributed to a slow recovery from the lung contusion.

Of the remaining 12 patients who were analyzed, in seven we had used the right phrenic nerve for neurotization and in five we had used the left phrenic nerve for the procedure. All patients underwent neurotization of the musculocutaneous nerve with the ipsilateral phrenic nerve.

Statistical evaluation included the Student t-test with paired and unpaired comparisons. Probability values less than 0.05 were considered significant.

Results

Biceps muscle strength reached Grade 4 in 58% of the patients, and only one had a disappointing result (Table 1). The seven patients who were excluded attained similar results, with Grade 4 in four and Grade 3 in three cases. No correlation between the length of the transplanted nerve and final muscle strength was observed.

Preoperative VC ranged from 4.1 to 5.95 L, with a mean of 4.98 L and postoperative VC ranged from 3.69 to 5.96 L, with a mean of 4.64 L. In the patients injured on the right side, the preoperative VC was 4.74 ± 0.49 L (mean ± SD), and postoperatively this was reduced to 4.26 ± 0.46 L. In the patients injured on the left side, the preoperative VC was 5.31 ± 0.64 L, and postoperatively this was reduced to 5.16 ± 0.73 L.

Values for VC showed a significant reduction of 14.3 ± 3.3%, ranging from 11 to 19% after right-sided neurotization (p = 0.0003); whereas the patients with left-sided neurotization had a nonsignificant reduction of 3.6 ± 3.5%, ranging from 1 to 8% (Figs. 1 and 2).

Preoperative FEV₁ ranged from 3.6 to 5.4 L, with a mean of 4.34 L, and postoperative FEV₁ ranged from 2.98 to 5.27 L, with a mean of 3.82 L. In the patients injured on the right side, the preoperative FEV₁ was 4.09 ± 0.43 L (mean ± SD), which was reduced to 3.52 ± 0.39 L postoperatively. In the patients injured on the left side, the preoperative FEV₁ was 4.68 ± 0.61 L, which was reduced to 4.24 ± 0.8 L postoperatively. No difference was found between the right- and left-sided FEV₁ in VC%, with a right-sided mean reduction of 7% (range 2–15%) and a left-sided reduction of 7% (range 0–18%).

### TABLE 1

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Mos of FU</th>
<th>Side of Neurt</th>
<th>VC% Preop</th>
<th>VC% Postop</th>
<th>Diff</th>
<th>Biceps Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>25</td>
<td>lt</td>
<td>94</td>
<td>95</td>
<td>-1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>26</td>
<td>lt</td>
<td>95</td>
<td>93</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>28</td>
<td>lt</td>
<td>90</td>
<td>82</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>31</td>
<td>lt</td>
<td>73</td>
<td>70</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>32</td>
<td>lt</td>
<td>91</td>
<td>85</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>24</td>
<td>rt</td>
<td>84</td>
<td>73</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>25</td>
<td>rt</td>
<td>80</td>
<td>64</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>27</td>
<td>rt</td>
<td>87</td>
<td>76</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>30</td>
<td>rt</td>
<td>95</td>
<td>76</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>36</td>
<td>rt</td>
<td>85</td>
<td>74</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
<td>36</td>
<td>rt</td>
<td>103</td>
<td>88</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>41</td>
<td>rt</td>
<td>109</td>
<td>92</td>
<td>17</td>
<td>3</td>
</tr>
</tbody>
</table>

* All nerve transfers shown were between the phrenic and musculocutaneous nerves; all others were deleted. Abbreviations: diff = difference; FU = follow up; neurot = neurotization.
Postoperative TLC showed significant differences between the sides, with 6.02 ± 0.68 L (mean ± SD, range 5–7.17 L) on the right side and 7.08 ± 0.62 L (range 6.63–8.1 L) on the left side. The values in percentage of predicted TLC values showed no significant difference, with 86% (range 69–115%) on the right side and 91.8% (range 83–100%) on the left side.

Postoperative FRC showed no significant difference between the sides, with 3.38 ± 0.63 L (mean ± SD, range 2.93–4.58 L) on the right side and 3.89 ± 0.42 L (range 3.42–4.5 L) on the left side. Likewise, the percentage of predicted FRC values showed no significant difference, with 104% (range 80–142%) on the right side and 112% (range 97–127%) on the left side.

Postoperative Pi max showed a significant difference between the sides, with 80.32 ± 14.6 cm H₂O (mean ± SD, range 61–107 cm H₂O) on the right side and 103.49 ± 20.4 cm H₂O (range 74–125 cm H₂O) on the left side (p = 0.04). Regression analysis between Pi max and a postoperative decrease in VC% showed a tendency toward a negative correlation without statistical significance (p = 0.1).

Despite these results, clinically speaking, no patient experienced breathing problems and none realized restrictions during physical activity. Only one patient showed right-sided hemidiaphragmatic palsy on postoperative chest x-ray films. No patient had left-sided hemidiaphragmatic palsy.

**Discussion**

The contribution of each phrenic nerve and hemidiaphragm to total ventilation is still unknown. Animal studies are of limited value because of anatomical and physiological differences among species. Significant reduction of pulmonary function has been reported, however, after accidental right phrenic nerve injury, during thoracic tumor surgery, and in a nerve crush for intractable hiccups. In contrast with these observations, patients in our study were young and their preoperative pulmonary function was not compromised, because patients with previous lung contusions were excluded.

Our results demonstrate a less than severe but significant reduction of pulmonary functional parameters after transection of the right phrenic nerve. Left phrenic nerve transfer did not cause significant reduction of VC. The reduction observed after right phrenic nerve neurotization was nonsymptomatic, however, and significant hemidiaphragmatic paresis was present in only one patient after surgery. These findings may confirm previous observations of the absence of pulmonary reduction following phrenic nerve transfer after 2 years of follow up. Furthermore, in previous reports, pulmonary capacity decrease after 1 year of observation was not examined for differences according to the side treated. According to our reading, only five of 180 patients in the earlier study showed persistent limitations of diaphragmatic movements.

The value of phrenic nerve transfer has also been demonstrated in the aforementioned study, with 84.6% of the patients regaining muscle strength of Grade 3 or greater. This is in accordance with our findings, in which there was only one disappointing functional result. It underlines the value of the phrenic nerve as donor material in neurotization of other nerves. Major advantages of using the phrenic nerve as donor material are as follows: 1) predominance of motor nerve fibers in the nerve fascicles; 2) direct coaptation with other nerves, that is, the musculocutaneous nerve.

**Fig. 2.** Box plot showing the decrease in VC% according to the European Respiratory Society’s guidelines. The difference between left- and right-sided transfers is statistically significant. *p < 0.01. The gray circle is an outlier.

**Fig. 3.** Box plot showing postoperative Pi max in cm H₂O after left- (li) and right-sided (re) phrenic nerve transfer. The difference is not significant. The white circles are outliers.

**Fig. 4.** Scatterplot showing the regression curve of the difference between pre- and postoperative VC% and the postoperative Pi max. The regression curve follows the equation: Y = 105,508 − 1579 * X; R² = 0.248; p = 0.1.
times possible, making autologous sural nerve grafting unnecessary; 3) the surgical procedure is an easy one to perform in contrast with other nerve transfer procedures; and 4) phrenic nerve transfer could be used in combination with other donor nerves.

In comparison with our results, in other studies muscle strength was reported to be Grade 3 or more in 21% of patients after hypoglossal nerve transfer. For intercostal nerves the best results included functional elbow flexion in 64 to 87%. Intercostal nerve transfer is a time-consuming procedure and carries the risk of pleural injury. Accessory branch transfer resulted in 72.5% of patients with Grade 3 or more, and the use of contralateral brachial plexus ventral roots led to functional results in seven of nine cases.

Anatomical and physiological considerations are possible explanations for the significant reduction of VC observed only after right phrenic nerve transfer. Pulmonary capacity on the right side is greater than on the left side, which has only two lobes and in which the heart occupies space. Phrenic nerve variations may be involved; problems in severing the phrenic nerve to produce hemidiaphragmatic paresis in studies conducted at the beginning of the twentieth century prompted interest in anatomical studies of this nerve. These authors reported more caudal and even thoracic nerves adding branches to the phrenic nerve, and thus recommended tearing the phrenic nerve out of the thoracic cavity by using clamps to ensure paresis. Current studies, however, could not confirm the findings of thoracic accessory branches. Cervicobrachial accessory phrenic nerves that were not divided during surgery could be an explanation for functional differences, but anatomical dissections in rabbits showed more cervical accessory phrenic nerves on the right side (43%) than on the left side (28%).

A physiological explanation of the right-sided decrease could be dominance of the right phrenic nerve in the innervation of the diaphragm, but there are no reports in the literature describing these findings. In contrast, magnetic stimulation in neonates has been more effective on the left side, with no statistical significance.

Functional pulmonary parameters are variable and dependent on the patients’ cooperation and motivation, especially immediately following the operation. Nevertheless, the observed difference between right and left and the correlation with $P_{E}$ support a more significant reduction of VC after right phrenic nerve transfer. Nonetheless, the data presented here should be confirmed with further studies. Although no patient showed clinical evidence of pulmonary impairment, asymptomatic pulmonary problems might become apparent with aging and continued smoking. In conclusion, we recommend a thorough pulmonary examination, including determination of $P_{E}$ before phrenic nerve transfer. Also, if possible, the left phrenic nerve should be used for neurotization.

References

20. Yamada S, Peterson GW, Soloniuk DS, et al: Coaptation of the C5 and C6 roots resulted in 72.5% of patients with Grade 3 or more.

Address reprint requests to: Wolf Luedemann, M.D., International Neuroscience Institute, Alexis-Carrel-Strasse 4, 30625, Hannover, Germany. email: Luedemann. Wolf@MH-Hannover.de.

Manuscript received April 4, 2001. Accepted in final form October 24, 2001.