**Supplement**

**Pallidotomy for hemiballism**

In autumn 1955, only a few months after having started their stereotactic work, Orthner and Roeder chose the pallidum as surgical target for the treatment of hemiballism based on the pioneering work of Mettler, Carpenter and Whittier in non-human primates [1]. In a 38 year old patient with hemiballism since childhood they achieved almost complete resolution of the ballism with a two-staged bilateral pallidotomy. The beneficial effect was maintained 11 months after the second intervention as illustrated by serial photographies extracted from a film of the patient (Figure 1 in [2]). The patient who had been dependent for everyday activities became fully independent after surgery. The only side effect in this patient was a weight gain of 8 kg within a few months.

In a first procedure large parts of the middle and posterior portion of the pallidum were lesioned resulting in insufficient clinical benefit. Following personal advice from Spiegel and considering a publication by Tailarach [3], in the second procedure Roeder and Orthner eventually targeted the posterior pallidum and ansa lenticularis (cf. Figure 1). This represented the key operation for the overall clinical benefit. To our knowledge, this is the first report of a major long-term improvement of hemiballism by a surgical procedure not resulting in hemiparesis. It demonstrates early adjustments of the pallidal target, which was moved into the posteriorly located motor area of the internal pallidum already in the 1950ies.

The total lesion volume after the second intervention was estimated to be 760 mm3 [2]. In this report the authors included a post-mortem study of a previously treated patient suffering from Huntington's disease who had died from bronchopneumonia and circulatory failure 7 days after bilateral pallidotomy [2]. The lesion exhibited some edema and hemorrhagic transformation. The intention for including this post-mortem exam was to substantiate their estimation of lesion volumes, as in the case of the Huntington's disease patient the actual size of the lesion was in accordance with the calculated volume.

**String electrodes**

Stimulation and lesioning were made exclusively with string electrodes, although, rod (straight needle) electrodes had already become more popular at that time (cf. Figure 3 in [4]). The authors repeatedly emphasized the multiple disadvantages of rod electrodes: stimulation is applied with less precision and lower spatial resolution; thermolesions become too large; stun effects related to the size of the electrode may prevent proper intraoperative testing; and rod electrodes are unsuited to be adapted to complex targets, in particular the elongated and obliquely oriented pallidum [5, 6].

Since May 1961 the authors used new models of insulated string electrodes that had been developed together with Jenny and Wyss at the Physiological Institute in Zurich [7]. This allowed Roeder and Orthner to actually restrict lesioning to the thin and small bare tip of the electrode preventing unnecessary lesioning along the whole extruded electrode wire [7]; reviewed in [4]. In fact, the lesion outlined in Fig. 2 is much larger than lesions performed with insulated string electrodes used by the Göttingen group since May 1961. The volume of single lesions with insulated electrodes was, depending on contact length, as small as 18-32 mm3 [5, 8]. Lesion volumes with common rod electrodes were almost ten-fold larger (200-250 mm3) [9, 10].

Roeder and Orthner mentioned that clinical effects were even better with the new generation of electrodes [7]. However, since follow-up was below one year for patients operated with this new electrode type (since May 1961) these patients had been excluded from clinical evaluation [7] and, unfortunately, were not published thereafter. However, the improved features of the new electrodes were strengthened in later publications (e.g. [5, 6]), and these electrodes had exclusively been used by one of the authors of this paper (D.M.) for lesioning in Hamburg from 1972 until 1994 leaving no doubt about their outstanding properties (cf. Table 3 in [4]).

**Pallidotomy in oculogyric crisis**

In 1925, Gottfried Ewald (1888-1963) who later became head of the Neuropsychiatric Department at the Göttingen University had described oculogyric dystonia in postencephalitic parkinsonism and insisted on the particularly disabling nature of accompanying psychiatric symptoms such as obsessions, anxiety, dysphoria, and modifications in consciousness [11]. This certainly contributed to awareness and knowledge about this clinical picture that is also described in Roeder's textbook of neurology [12]. Nowadays it is encountered mainly as a side effect of neuroleptic treatment. The observation of improvement of oculogyric crisis representing a focal dystonia with pallidotomy was fortuitous and unexpected [6, 7, 13]. It has also been described by the Freiburg group [14], but other contemporary authors did not make the same experience [15–17]. Orthner and Roeder attributed this to differences in the surgical technique. The authors emphasized the improvement not only of motor symptoms of oculogyric crises, but also of the full accompanying stressful psychiatric comorbidity. By 1962 the team had operated 13 patients with postencephalitic oculogyric crisis that had been ongoing from 3 to 30 years. The mean follow-up after surgery was 5 years. The three patients who had bilateral surgery had been liberated completely from their oculogyric crises. Unilateral surgery led to full relief in 5 patients, to partial relief in 3 and no change in 2 patients [18]. The team also performed pallidal surgery, mainly bilateral, for other focal or generalized dystonia [6].

**Adverse events**

Since standardized reporting of clinical results is lacking in studies from the 1960ies complication rates are of particular relevance for an appraisal of clinical achievements. Pallidotomy exhibits peculiar risks and the meticulous case descriptions presented by Roeder and Orthner provide a valuable basis to carefully assess adverse events.

*Surgical complications*

From March 1955 until February 1967, Roeder and Orthner had performed 601 procedures. A total of 405 procedures (315 patients) were conducted for Parkinson's disease including 371 pallidotomies of which 82 were bilateral [5]. Three *post*operative deaths (4.5%) occurred in a series of 76 pallidotomies (8 bilateral) performed in 67 patients [13]. In this paper, all pallidotomies performed between May 1956 and November 1958 had been presented in great detail and in chronological order ([13]; cf. Fig. 3).In their series of bilateral pallidotomy published 1962 there were no intra- or postoperative deaths among 36 patients [7].

In Göttingen stereotactic lesioning was performed for several other indications. From March 1955 until June 1970, Roeder and Orthner had performed 115 procedures in 60 patients suffering from psychiatric disorders with two mortalities [8, 19]. A patient suffering from schizophrenia died 7 days after surgery from pulmonary embolism. Another patient had died 'soon after surgery' without giving further details. In a series of 10 patients treated for epilepsy from June 2, 1956 until December 10, 1963 one patient suddenly died from suspected pulmonary embolism 21 days post surgery [20]. There was no mortality in 16 patients (31 procedures) treated for pain syndroms in various brain targets from 1955 to 1964 [21] and in additional 9 patients (12 procedures) operated from 1965 to 1969 [22]. In 1974, Roeder and Orthner presented a series of 111 Parkinsonian patients (116 procedures; 5 bilateral) operated in the thalamus with two postoperative deaths[23]. One patient died 5 days after surgery from acute circulatory failure and was autopsied (Fig. 5). For the other case the cause of death, the point in time when death had occurred and whether a post mortem exam could be performed was not stated. In this paper the authors also presented the post mortem analysis of another patient who had died after ventrolateral thalamotomy ([23]; Fig. 5). From another publication we learned that surgery in this patient had been performed for torticollis and that death had occurred three week after surgery from pneumonia and pulmonary embolism [5]. In total, among 309 patients who have been included in publications there were eight (2.6%) postoperative mortalities.

Only one intracerebral hematoma was confirmed at autopsy (case #2 presented in [13]). Autopsy had also been performed in several other cases without the detection of a bleeding. It was reported that with the use of insulated string electrodes (involving smaller lesions) outcome had improved even more, and with increasing surgical experience it is unlikely that rates of mortality and hemorrhage had increased after the report from 1959. On the other hand, small hemorrhages being asymptomatic or leading to mild neurological deterioration could not be detected at that time. One cannot rule out selection bias in some of these studies, although, at least both pallidotomy series included consecutive patients of defined periods. Other selection bias may stem from the fact that only patients who had received a successful unilateral pallidotomy were likely candidates for a contralateral procedure. Roeder stated that in only one of 601 stereotactic procedures an *intra*operative mass hemorrhage resulted in death [5]. This hemorrhage had occurred *prior* to coagulation.

One has to bear in mind that rather imprecise aiming and lesioning techniques (often combined with scanty clinical evaluation) were common during the late 1950ies and early 1960ies. These approaches resulted in complication rates that were several fold higher than with proper stereotactic techniques. For example, Taarnhoij following Cooper's popular technique reported mortality rates of >12% and high rates of other severe complications [24]. Cooper himself stated among 650 cases a mortality rate of 2.4% but it is unclear whether this represents pure operative mortality or also includes the postoperative course [25].

Thus, it is worthwhile to compare the complication rates from Göttingen with those of the most successful stereotactic centers at that time. Spiegel and Wycis as well as Krayenbühl published mortality rates of approximately 2% [17, 26]. Svennilson who evaluated Leksell's patients operated until 1957 reported no intraoperative deaths among 81 patients [27]. Two patients died after discharge from the hospital. Among 123 patients operated in a later period by Leksell in the pallidum one patient (0.8%) had died from a suspected intracerebral hematoma 9 days after surgery [28]. Feinstein reported a mortality rate of 0.5% after 1645 procedures (500 patients) performed between 1955 and 1965 [29].

At the leading German stereotactic unit in Freiburg, mortality (until discharge from hospital) dropped from >2.5% in the 1950ies to <1% in the 1970ies ([30]. For 1402 cases operated in Freiburg between 1951 and Oct 22, 1962 the risk of hemorrhage was estimated at 1.8% [30]. The neurosurgeons from Freiburg attributed the initially higher rate of hemorrhages in the 1950ies to the properties of their first lesion generator. But even with use of the Coagulateur de Wyss (N.B. that was also used in Göttingen) complication rates had remained similar [31]. Mundinger and Riechert had registred some crackling sound suspicious of gas formation (so-called “popping”) and went to develop another lesions apparatus [30, 32].

Additional factors may have influenced the initially higher rate of hemorrhages in Freiburg. In a letter to Hugo Spatz, Orthner wrote on February 24, 1959 that Riechert had reported in a meeting in Brussel (probably: Premier Congrès International des Sciences Neurologiques, Bruxelles, July 21-28, 1957) that whenever the effect of lesioning was unsatisfactory he now tended to advance the probe with a heated and extruded string electrode with rotary movements until the desired effect was achieved. Orthner disapproved such maneuvers and explained how this will produce large and uncontrolled lesions and is accompanied by the risk of cutting into vessels increasing the risk of hemorrhages. Orthner also mentioned that one of his co-workers who had attended operations in Freiburg for several months had witnessed mass hemorrhages with fatal outcome. Orthner had learned that Riechert by pointing out to the risk of intraoperative mass hemorrhages [30, 33] warned K. Conrad (Director of the Department of Neurology, University-Hospital Göttingen since 1958) to introduce stereotactic procedures at his department. A few years later, during the 1960ies, in Freiburg the risk of hemorrhage and mortality dropped significantly to extraordinary low rates ([34] and cf. above).

Taken together, the safety of the Göttingen procedures compares very well to the most renowned centers at that time. Rates from these centers appear to be similar to those reported from leading centers in the modern era of pallidotomy blessed with MRI-guidance and other technical advances. In particular at the beginning of the second pallidotomy era the rates for mortality and hemorrhages were highly variable with some high rates even in experienced hands (reviewed in [35]). In reviews of the literature of modern pallidotomy by Alkhani and Lozano [36] and de Bie et al. [37] using different inclusion criteria for studies that mostly covered unilateral procedures, mortality rates were 0.4% and 1.2% ([36] and [37], respectively). The risk for *symptomatic* hemorrhages was 1.7% and 3.9% ([36] and [37], respectively) connoting a dark figure for the overall occurrence of hemorrhages. As in former times, bilateral pallidotomy has not been pursued by many groups in the modern stereotactic era. Iacono et al. reported about a large series of 126 patients of which 68 patients underwent bilateral pallidotomy [38]. There was no mortality and the risk for intracranial complications was 3.2%.

*Neurological adverse events*

In both pallidotomy series including bilateral lesioning there were no visual field defects reported [7, 13]. Later Roeder stated that in all Parkinsonian patients (n= 315) operated between March 1955 and February 1967 (including 371 pallidotomies) only a single case with a postoperative homonymic hemianopia was observed [5]. Visual field defects represent a well-known complication of pallidotomy and are routinely checked for after such procedures. Taking into account the meticulosity in which pallidotomized patients were evaluated including detailed description of other side effects it is fair to assume that other clinically detectable visual field deficits have not occurred. This extraordinary low rate of visual field defects is even more remarkable when considering that the authors often placed lesions into the ansa lenticularis in direct vicinity of the optic tract. Riechert reported six cases of hemianopia that eventually led them to start intraoperative stimulation with significant risk reduction [31]. In the 1990ies the occurrences of visual field defects were highly variable and were found to range between 0 and 40% with an average rate of 2% (1.5% permanent) [36] or 2.4% [37]. Among 259 patients Laitinen et al. had observed visual field defects in 4% of their cases, yet no such complication in their last 100 cases [39]. In Iaconos series of 126 patients including 68 patients with bilateral pallidotomy the rate for hemianopsia was 2.4% [38].

Among 18 *bilateral* pallidotomy cases symptoms attributed to inadvertent lesioning of the internal capsule, i.e. postoperative spasticity and weakness were observed in 3 cases [7]. In a later publication Roeder and Orthner reported about a patient who suffered from a stroke one month after surgery associated with hemiparesis (improving later), aphasia and cessation of residual tremor [5]. The rates for hemiplegia reported by other authors were similar [17, 26, 30]. Transitory pyramidal lesions and facial weakness have also been observed in a rather high proportion of patients operated by Leksell [27]. In the 1990ies the average rate for 'limb weakness' was 1.6% (0.9% permanent) with an additional rate of 3.7% (1.3% permanent) for facial weakness [36]. In another review the average rate for 'limb weakness' was 2.1% (0.3% permanent) with an additional rate of 6.0% (2.4% permanent) for facial weakness [37]. In Iaconos series of 126 patients including 68 patients with bilateral pallidotomy transient hemiparesis unrelated to hemorrhage was observed in only one case [38].

Obviously, according to the outcomes of the series of bilateral pallidotomy reported by Orthner and Roeder, dysarthria seems to be less of an issue compared to the frequency of severe dysarthria well known to be the major limitation of bilateral thalamotomies explaining the virtual absence of published bilateral thalamotomies and contributing to the success of bilateral VIM stimulation starting at the end of the 80ies [40]. Significant worsening of hypophonia, in particular following bilateral pallidotomy, was reported for about 10% of the patients [5]. In the 1990ies an average rate for dysarthria following pallidotomy was 3.2% (1.6% permanent) in addition to a rate of 1.3% for hypophonia [36]. De Bie reported rates for dys- and anarthria of 4.8% (3.9% permanent) in addition to a rate of 1.2% (0.3% permanent) for hypophonia [37].

There were other adverse events mentioned by Roeder and Orthner. Postoperative arterial hypotonia was seen in 20-30% of the patients [5]. They also observed weight gain and increased appetite and speculated that the rostral and dorsal margins of the lesions may have encroached on the small pallidohypothalamic bundle [7]. No seizures were observed.

*Psychiatric adverse events*

Roeder and Orthner had been trained in neurology but they were also experienced neuropsychiatrists. Both had been well aware of warnings from other centers about psychiatric adverse events following bilateral pallidotomy. Severe and long-lasting psychotic states described as disturbed consciousness, disorientation, dementia, apathy, stupor or coma had been reported following bilateral pallidal procedures [27, 41–45]. Hassler mentioned poor experiences with bilateral pallidal procedures in patients with hyperkinetic disorders, and for this reason he considered that bilateral pallidotomy should not be recommended for Parkinson's disease [43, 44]. Because the pallidum is receiving unspecific afferents from the thalamus, Hassler regarded the pallidum as part of the reticular activating system what he found supported by arousal reactions observed upon intraoperative electrical stimulation of the pallidum [43, 44]. He referred to cases in which delirant, disoriented or severely demented states as well as loss of initiative up to coma had been observed following bilateral pallidal procedures [43, 44].

Although being hesitant in the beginning, Roeder and Orthner eventually dared staged bilateral pallidal lesioning. However, in several of their first cases the authors had to witness unfavorable outcomes resembling those already described by their peers. The clinical courses for these cases exhibiting various degrees of apathy, that was referred to as drive disorder, apathy, and stuporous states, have been described in great detail [13]. In one patient drive disorder resolved completely (follow-up of 5 years). In another patient the stuporous state eventually vanished following electroconvulsive therapy, and two years later the patient travelled through the USA for several months (follow-up 4 years). In two patients the drive disorder persisted. In total, apathic symptoms were observed in 4 (two permanent) of 36 of the first patients having undergone bilateral pallidotomy [7]. Spiegel and Wycis pointed out to these cases from Göttingen and wrote: 'in some instances bilateral pallidotomy may even accentuate the diminution of initiative, as has also been observed by Orthner and Roeder' [26].

Notably apathy or psychiatric complications had not been observed in all the other patients operated on thereafter [7]. Roeder and Orthner stressed that bilateral procedures could be considered when performed with the necessary precision and caution, and they eventually lesioned the contralateral pallidum with more restraint, i.e. in general only two coagulations were performed [5, 7, 13]. They pointed out that lesioning should be restricted to the posterior pallidum, and they mentioned an area approximately 12 mm posterior to the anterior commissure as favorable. Later the nucleus itself was largely spared, and lesions were restricted to the ansa lenticularis (pallido-ansotomy) as supported by autopsy findings (cf. Fig. 5 vs. Fig. 3 and 4). This was facilitated with the introduction of insulated string electrodes in May 1961.

Roeder and Orthner concluded that post-pallidotomy apathic states observed in the beginning were due to too extended lesioning, and they argued that the less beneficial effects and higher rates of complications reported by other authors must be accounted for by a different approach and surgical technique (cf. Introduction; [5, 6]). Of note, when Hassler elaborated on such psychiatric complications in 1964 [44] he did not quote Orthner and Roeder who had already published their detailed experience with bilateral pallidotomy [7].

Even in the modern era of pallidotomy (almost exclusively unilateral lesioning) there were significant rates for psychiatric adverse events. Based on a literature review Alkhani and Lozano reported average rates for postoperative psychosis (0.5%) and confusion (2.6%), depression (0.9%), and impaired memory (1.3%; 0.9% permanent) [36]. In a similar review using different inclusion criteria for studies to be analyzed, De Bie reported rates for transient acute confusion or somnolence (3.9%), neglect (0.6%), changes in personality or behaviour (3.9%), transient depression (0.6%), dysphasia (0.9%), psychosis (0.9%), worsening of dementia (0.3%) [37].

For bilateral pallidotomy, de Bie included 5 studies with a total of only 20 patients and pointed out to complications in 14 patients (70%) including problems with speech, cognitive decline, visual field defects and depression [37]. Psychiatric adverse events were permanent in 12 patients. De Bie did not include Iacono's article from 1995 reporting about 68 patients with bilateral pallidotomy without the mentioning of psychiatric adverse events [38].

The total rates for permanent morbidities were highly variable in the modern age of pallidotomy [35–37]. Based on reviews of the modern literature *permanent* morbidities occurred with 14.3% and 13.8% [36, 37]. In particular at the beginning of the modern era of pallidotomy higher and sometimes alarming complications rates had been reported occasionally [35].

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