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# Spiralometry: Computerized Assessment of Tremor Amplitude on the Basis of Spiral Drawing

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**Abstract:** Spiral drawing has been used for the assessment of the impact of therapy on motor performance in various movement disorders (e.g. in Parkinson's disease, especially for tremor and hypokinesia). Nevertheless, there are only few guidelines available providing some kind of standardized interpretation. The published protocol with the highest standard is that of Bain and Findley. Kinetic tremor assessed by spiral drawing is not quantified by alternative approaches so far and is not even considered by most rating scales. However, kinetic tremor is quite common and represents a significant impairment in the everyday life of parkinsonian patients. More complex instrumental methods for the quantification of kinetic tremor have not been practical as they, e.g., require relatively expensive equipment or have an unfavourable effort/benefit ratio. We pursued an alternative approach, where we scan drawn spirals to a computer-algorithm that calculates the tremor amplitude. Our standardized method can be applied without difficulty in patients needing only paper and pencil. The evaluation is fully automated, and therefore, it is appropriate for the assessment of therapeutic efficacy in very large populations. The objectivity of the approach represents a significant advantage. In the actual paper, we present how we analyzed the original spirals published by Bain and Findley to validate our computerized assessment. We found a highly significant connection between both methods (explained variance: 88.9%). © 2010 Movement Disorder Society

**Key words:** Spiralometry; tremor; kinetic tremor; drawing; spiral

Special rating scales are customarily used to assist the evaluation of the therapeutic efficacy and the progress of neurodegenerative disorders. In addition, there are a variety of instrumental approaches for quantification of motor performance. Such assessments have the advantage of relatively higher objectivity in comparison with clinical ratings scales. On the other hand, most of these instrumental methods have not been adequately standardized.

Writing and drawing tests are examples of a simple approach which investigators have used for a long time in the assessment of fine motor changes in movement disorders. The most prominent example of this approach is spiral drawing. The evaluation of drawn spirals usually focuses on hypokinesia, which, in the opinion of many authors, is reflected in reduced spiral pitch.

Spiral drawing as assessment of tremor is recommended by the Movement Disorder Society.[1] It is also used in the assessment of akinesia in Parkinson's disease (PD),[2] tremor in multiple sclerosis,[3] and essential tremor,[4–9] as well as for evaluating the therapeutic effect of deep brain stimulation.[10] In each of these cited works, all spirals are assessed by visual evaluation. However, this processing has never been strictly standardized, and there are no clear guidelines regarding judgment and interpretation. The published protocol with the highest standard for evaluation of tremor through spiral drawings (=spir(al)ography) is that of Bain and Findley,[11] who classified 37 representative spiral drawings with varying degrees of tremor into 11 stages (0–10).

Spiral drawing examines only kinetic tremor that is most often neglected by clinical investigators. It is a sub-form of action tremor defined by its appearance during voluntary movements. The combination of resting, postural and kinetic tremor ("tremor triad") is the

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most frequent constellation in PD.[12] In many patients, kinetic tremor has a major negative impact on fine motor performance—especially upon writing.

There is a variety of rating scales for the assessment of tremor, and the common PD scales include tremor questions, but these are all restricted to the evaluation of resting tremor and postural tremor.[8,13–19] There are also a number of instrumental approaches for analysis of drawing tests, including spiral drawing such as digitizing tablets[20–22] or electromyography.[9,23] The latter helped to derive some relevant parameters for the evaluation of tremor severity. However, most instrumental methods require relatively specialized and expensive equipment with more or less complicated examination. In addition, for established instrumental tests, patients, staff and test arrangement have to be brought together. Because, furthermore, almost all published techniques are not sufficiently standardized, none of these methods have been adopted for routine use so far but remained to be isolated applications in specialized centres.

Our current investigation therefore addresses the question of whether the paper and pencil version of the spiral drawing test could be developed into a standardized assessment method. We derived a novel algorithm for this purpose, enabling the measurement of tremor amplitude on the basis of scanned spiral drawings. The aim of this analysis is the cross validation of our new objective metric measurement ("spiralometry"), applying the Bain and Findley rating scale ("spirography") as standard.[11] Main objective of this article is the comparison between the expert tremor rating[11] and tremor amplitude from our computerized analysis.

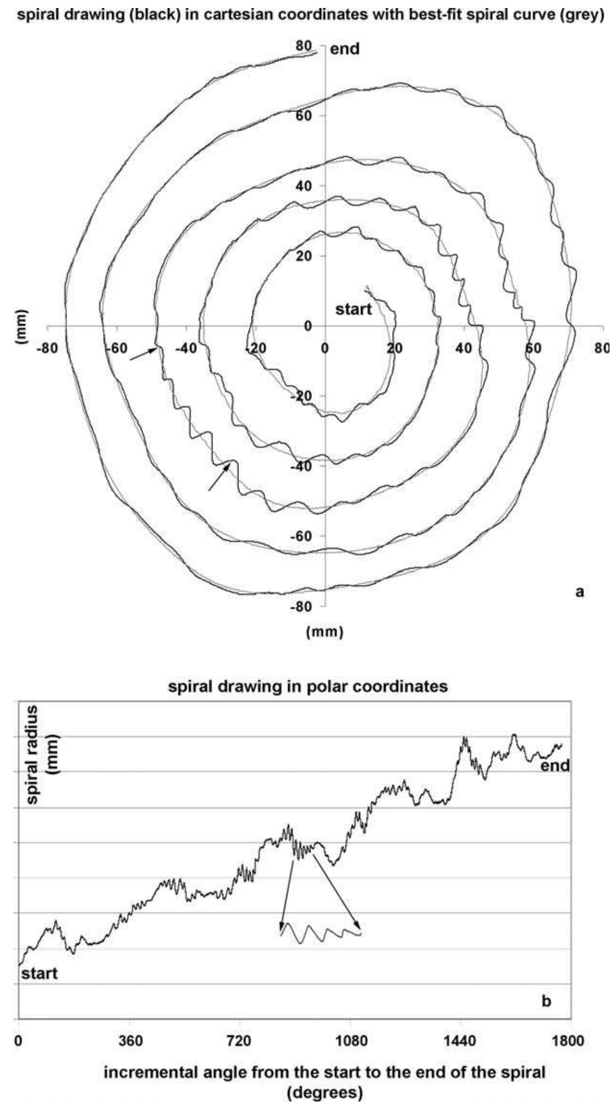


**FIG. 1.** (a) Spiral drawing by a PD patient with moderate kinetic tremor of the right hand (Cartesian coordinates). The grey line shows the best-fit spiral-curve following the deviations from an ideal mathematical spiral leaving the shorter tremor oscillations. (b) The identical information as above in polar coordinates. Long ranging movements represent the deviation from Archimedean spiral, tremor signal is stretched between the 2 arrows for didactical reasons (Comment: tremor amplitude of this drawing = 5.8 mm in original scaling). Arrowheads mark the identical position on a and b.

## MATERIALS AND METHODS

### Preceding Development of the Method

The following details (including Figs. 1–3) about our preceding technical development and methodological background are summarized to provide a basic understanding of history and rationale of our technique. It has to be emphasized that at the moment, spiralometry is exclusively focused on quantification of tremor-amplitude, regardless of clinical diagnosis and independently of tremor genesis. Although our method as designed for use prospectively with patients is very simple in data acquisition (paper and pen), it was developed with considerable expenditure and is highly sophisticated concerning further data handling and evaluation in particular.

For feasibility analysis and the development of our algorithm, we used modelled spirals with mathematically simulated tremor. Examples of those model spirals are shown in Figures 2 and 3. Sense and amplitude of spiral rotation as well as frequency and amplitude of simulated tremor were varied. Resulting patterns were printed and scanned and evaluated exactly the same way as patients drawings.

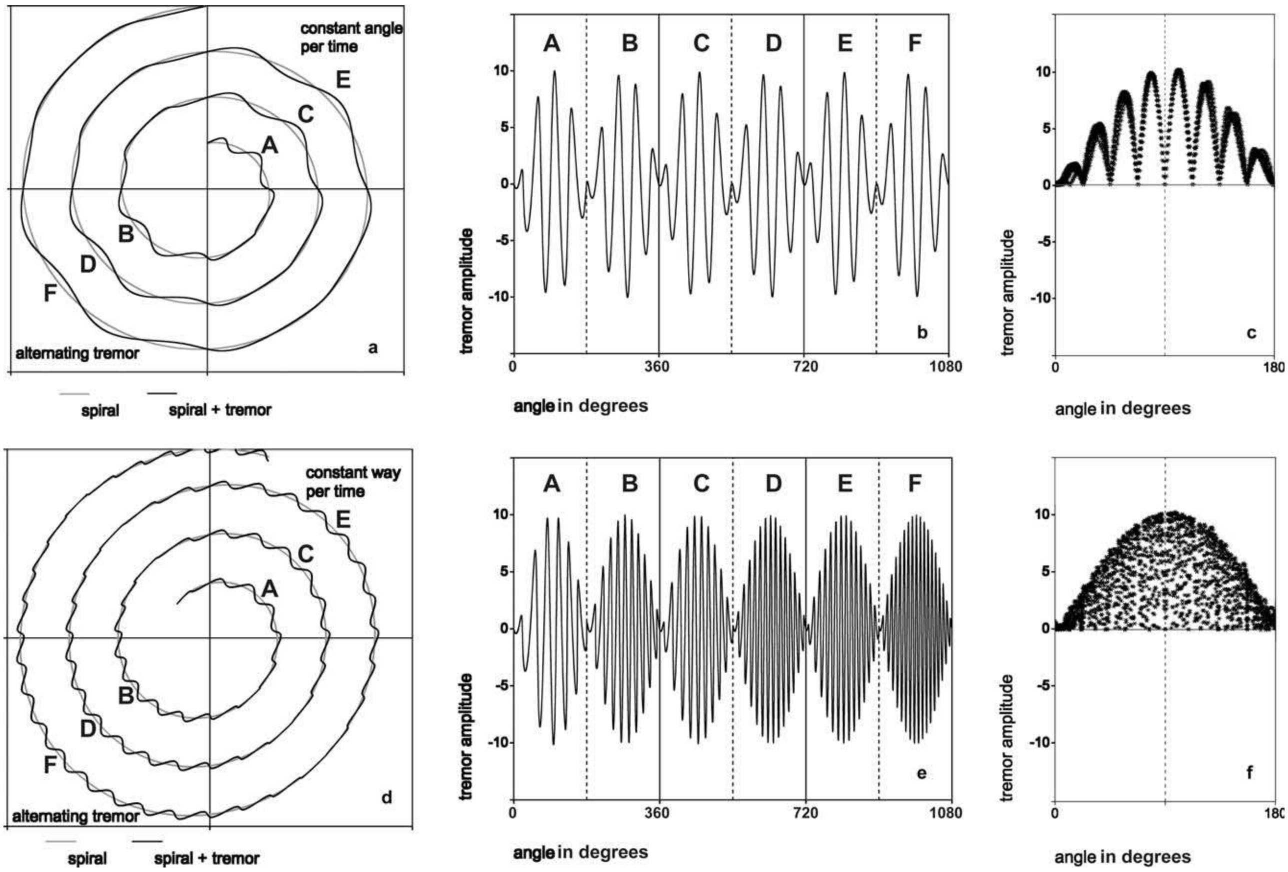


**FIG. 2.** Models of spirals with mathematically simulated tremor. (a) Spiral with modelled constant angular drawing speed. (b) The corresponding tremor signal (mm) after subtraction of the 'best-fit spiral-curve' printed as a function of continuous rotation angle (angular degrees). (c) The rectified tremor amplitude (absolute value) as a function of polar angle 0 to 180° (superimposition of all all segments of 180° length as marked "A" to "F" in b). Tremor amplitude is determined as the maximum of the envelope within this window. Characters A to F mark the identical segments in a and b. (d)–(f) Spiral with modelled constant linear drawing speed (description as above).

In addition, we analyzed spiral drawings from about 200 unselected tremor patients. Furthermore, *we* compared spiral-drawings (paper-pen test = static information) of a subgroup of patients with parallel measured signals from infrared videometry (Qualisys, 3 camera system = time series) for a better understanding of the relationship between movement pattern and drawing shape. We also implemented the metric calibration of videometric data into our algorithm.

The algorithm for spiral evaluation was continuously improved in this "learning" phase. Special attention was given to different tremor patterns (flexion-extension vs. rotatory) and to exceptions of tremors as well as of drawings (like intersections and interruptions). The most frequent tremor which is visible during spiral drawing is a flexion-extension tremor pattern (e.g., Fig. 1). Thereby, the tremor is logically only evident in those parts of the spiral where the oscillation is perpendicular to the drawing direction; e.g. in right hand drawing, the tremor is at maximum visible in the upper right and lower left quadrant of the coordinate system. Rotatory wrist tremor is rare during drawing and produces a consistent rosette pattern (Fig. 3).

## Principle of Spiralometry Technique

Spiral drawings are scanned using a Hewlett-Packard scanner (HP Scanjet 7400C) with automatic paper feed; settings were "black and white" and 300 dpi (dots per inch). Output format was "bitmap" (BMP-files) where curves can be identified stepwise as black neighboured pixels on base of their relative coordinates.

Our image analysing software is programmed with Visual Basic 6.0; tremor amplitudes are evaluated with SPSS 11.5.

The main steps of our evaluation are illustrated in Figures 1 to 3 and sequentially listed in Table 1: From

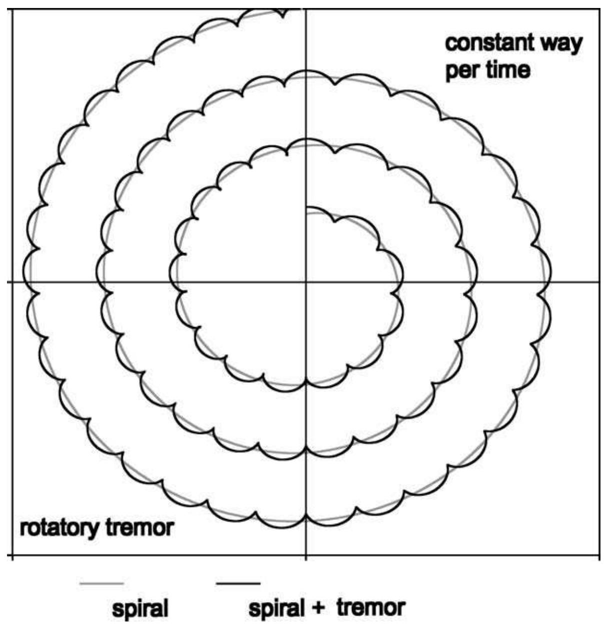


**FIG. 3.** Modelled spiral with mathematically simulated rotatory wrist tremor with rosette pattern.

the patient's drawing the "best-fit spiral curve" is calculated with an interpolation process ("moving window"-technique with parameters optimized to follow long drawing turns, working similar to a high-pass filter). Therefore, deviations from the Archimedean spiral form (e.g. elliptic deformation) are no problem. The shorter tremor oscillations are obtained as the difference between the really drawn curve and the best-fit spiral curve. In this way, we transferred the original instruction from Bain and Findley to rate the "perpendicular displacement of the track from the intended trajectory"[11] into a computerized measurement.

Our procedure proved to be stable against varying tremor patterns so that even rotatory tremor needs no special treatment.

## Main Investigation and Validation

### "Spirography" from Bain and Findley[11]

The tremor patients drawings in the Bain and Findley scale[11] involve 37 printed spirals of varying tremor intensity (diagnosis not specified by the authors) and staged on a scale from 0 to 9. Stage 10 corresponds to the inability to execute the task because of the severity of the tremor. As one important step of standardization in this handbook,[11] the spirals were rated by four "blind" raters determining the median score for each spiral as standard. Although this scale was never fully standardized, it has instructions and well-matched reference material that—from the point of view of standardization—is better than any other source of literature concerning spiral drawings and tremor. In addition, Bain and Findley can refer to examinations of spirals from 100 healthy controls.

### Use of Spiralometry to Evaluate the Bain and Findley Spirals

We scanned each spiral drawing from the work of Bain and Findley from the handbook in original size and setting[11] and evaluated them individually and blindly by the fully automated procedure described earlier. All spirals were evaluated once with exactly identical settings and without any external adaptations of pictures or of program parameters. The resulting tremor amplitudes are scaled in metric units (millimetres).

### Statistics

We carried out statistical analysis of the relationship between spiralometric measures and the Bain and Findley ratings with regression analysis. The differences in measured tremor amplitudes between the Bain and Findley stages were examined with a confirmatory analysis of variance. To verify the appropriateness of the classification, we used an exploratory discriminant analysis. Considering the exponential relationship with the Bain and Findley ratings (Fig. 4), logarithms of tremor amplitudes were used in all analyses.

Appropriate to the small number of samples, we carried out cross-validation with leave-one-out-strategies (prediction of the amplitude of each single spiral with the regression-model from the other 36 samples, "residual bootstrap approach").

**TABLE 1.** *Steps of evaluation*

| Step | Description | Example in figure |
|---|---|---|
| 1 | Raw data in Cartesian coordinates | 1a, 2a, 2d, and 3 |
| 2 | Raw data in polar coordinates as base for curve fit | 1b |
| 3 | "Best-fit spiral curve" (grey line) | 1a, 2a, 2d, and 3 |
| 4 | Tremor oscillation (as difference between raw curve and "best-fit spiral curve") | 2b and 2e |
| 5 | Rectified and overlaid signal (180° long window), evaluation of (half sized) tremor amplitude as the maximum of the envelope within this window | 2c and 2f |

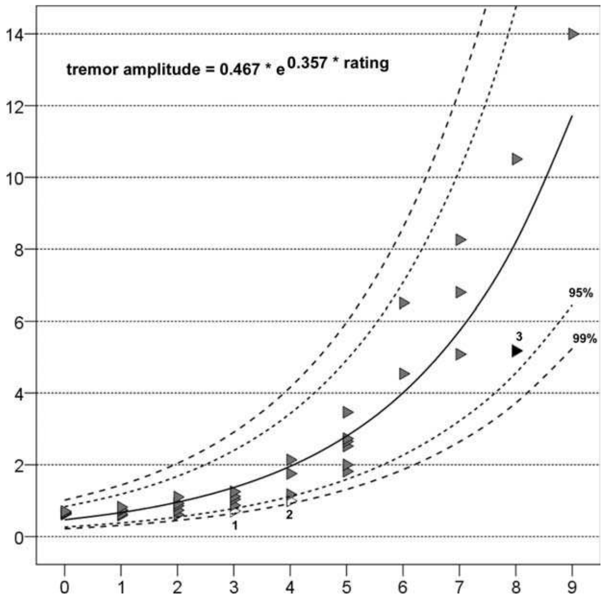


**FIG. 4.** Representation of measured tremor amplitude (y-axis) as function of Bain and Findley stages (*x*-axis), with 95% confidence intervals. The exponential model explains 88.9% of variance. (Outliers are discussed in the text).

## RESULTS

### Confirmatory Analysis

Regression analysis revealed a highly significant association between the Bain and Findley ratings and tremor amplitude as result of spiralometry, according to the formula 1:

$$\text{Spiralometry amplitude} = 0.467 \times e^{(0.357 \times \text{rating})}$$
$$(\text{method: regression analysis},$$
$$p = 1.70 \times 10^{-18}, \text{explained variance: } 88.9\%)$$

Measured tremor amplitudes were found to be highly significant different between the corresponding stages of the Bain and Findley rating (method: analysis of variance, $p = 3.29 \times 10^{-15}$).

### Cross Validation

The differences between measured and the (by regression) predicted amplitudes, with the help of the leave-one-out-model, showed one outlier (rated stage 8 and measured amplitude 5.17 mm, cross-validated: outlying 4.51 standard-deviations) that was also misclassified in the discriminant analysis as stage 6 (Fig. 4, marked as "3" and Fig. 5 as "8*"). On closer inspection, this spiral in question shows a burst of tremor with an amplitude to 10 mm on its left outer whorl. This region was not recognized very well by our algorithm because the printed line in the original drawing was interrupted several times.

### Exploratory and Descriptive Evaluation

Discriminant analysis indicated that 19 spirals were placed at the expected stage in the Bain and Findley scale (51.4%). The remaining spirals were placed one stage too high (n = 10, including all four spirals from the Bain and Findley stages 0 and 1) or one stage too low (n = 6); two spirals were placed two stages below the Bain and Findley stages (one each at stages 1 and 6). In Figure 5, the spirals are arranged in ascending order according to the spiralometry tremor amplitudes, together with the rated Bain and Findley stage. Asterisks highlight the spirals that deviated most from the Bain and Findley classification.

### Comment

Both measures are methodologically rather different approaches with distinct unavoidable errors. The present regression model with 88.9 % explained common variance ($p = 1.70 \times 10^{-18}$) provides evidence of high correspondence and withstands those few outliers without problems.

## DISCUSSION

Kinetic tremor has until now received only little attention with regard to clinical assessment, despite the fact that it often causes deficits in fine motor performance. In writing and drawing, kinetic tremor can lead to significant psychological distress (for example, when the patient experiences difficulties in providing a signature), what may even contribute to social withdrawal. There are few rating scales for kinetic tremor. Bain and Findley[11] specifically developed their scale based on spiral drawings for the objective assessment of this form of tremor. It suggested to the current authors that it could be possible to estimate tremor amplitude through computer-based analysis of drawn spirals, whereby the Bain and Findley rating was applied as the standard for cross validation of the analysis.

The two techniques were found to produce results that are significantly more congruent than had been expected by the investigators (89.9% explained variance in the regression analysis). The minor differences in classification (discriminant analysis) are partly explained by the fact that our method does not assess

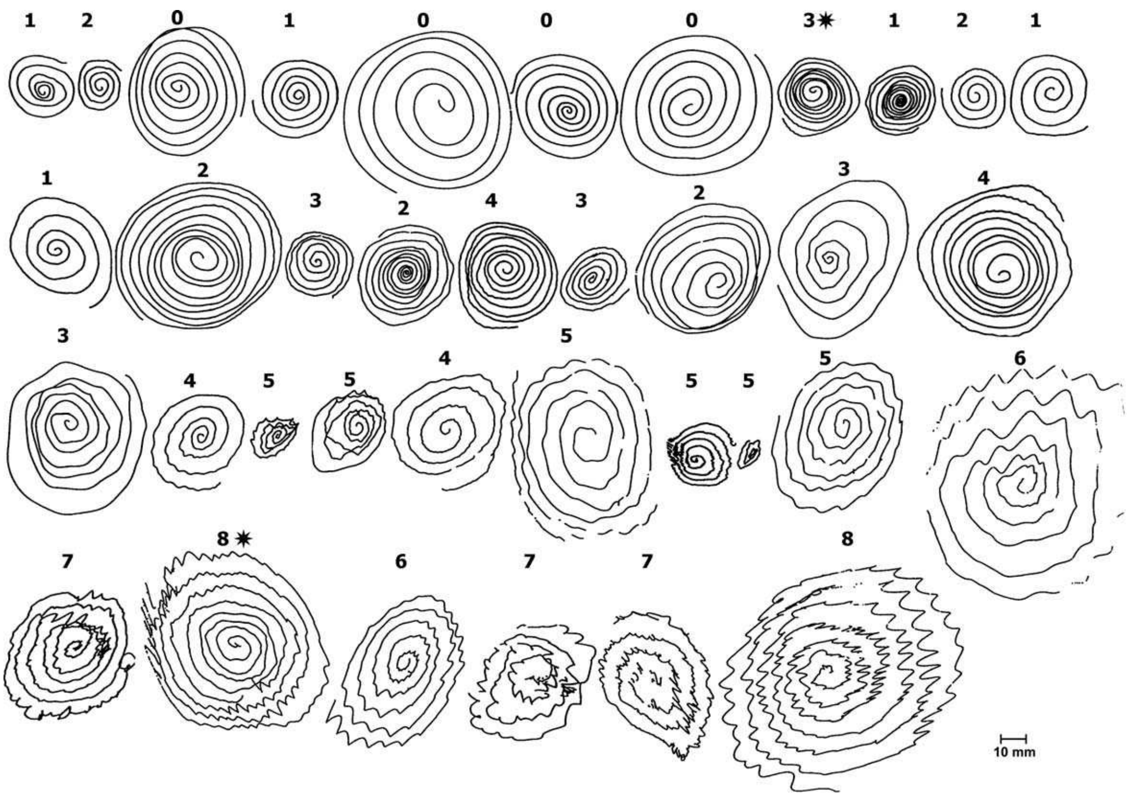


**FIG. 5.** Original spirals from Bain and Findley (11) in order of increasing tremor amplitude, as determined by spiralometry, and stages of original ratings (printed numbers). Marked (*): two spirals classified least well (spirals reproduced with kind permission of P.G. Bain and L.J. Findley).

the duration of tremor during the drawing exercise, but rather its amplitude. Continuous tremor might produce a different rating than an only intermittent tremor of the same amplitude.

In line with the noteworthy findings of Elble et al.,[24] we also found that the functional relationship between the clinical tremor ratings from Bain and Findley[11] and the tremor amplitudes of their original spirals (from our evaluation) was deviating from linearity (Fig. 4). The detected exponential relationship (formula 1) between the rating and measured tremor amplitude was clearly not as strong at the lower end of the Bain Findley scale as at the higher end. The Bain and Findley scale with 11 stages (0–10) allowed a more accurate functional analysis: our results confirm the consideration of Elble et al.,[24] that this relationship represents Weber-Fechner law.[25] The latter is a very old law describing the logarithmic relationship between a stimulus and the corresponding perception: This is the case whether the stimulus (here: spiralometric tremor amplitude) increases multiplied by a fixed factor while the corresponding perception (here: expert tremor rating) is altered in additive constant amounts. The finding of a nonlinear connection between scales and measures and especially the conformity with Weber-Fechner law is highly topical since Nieder and Miller[26,27]) discovered a cerebral correlate of the processing mode during judgment tasks.

Obviously, a disadvantage of our procedure is the loss of information concerning absolute time and thereby tremor frequency. For the further prospective application in patients, we now request that the spirals have to be drawn with a defined angular speed as close as possible to one turn per 2 seconds. Where time plays a more significant role, provision is made for use of a stopwatch. Furthermore, the patients in prospective studies will receive pre-printed forms with light yellow spirals of five turns each to minimize extraneous individual confounding factors (such as hypokinesia).

Under practical considerations the most relevant advantage of our technique refers to easy measurement of the patients' state under any circumstances where paper and pencil are available—while the expensive equipment and staff for evaluation can be provided in one single specialized centre at an optional location.

Another very important advantage of our spiralometry technique is the increased objectivity, as computerized analysis assures a blind, standardized assessment. It can also increase the value, for example, of unblinded therapeutic studies. In addition, these results are of special practical importance for planning clinical studies: data from clinical rating and those from spiralometry differ in the scales of measure and therefore need different statistical analysis—with consequences like higher resolution and lower sample size.

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**Author Roles:** P.H. Kraus is involved in research project: conception, organization, execution; statistical analysis: design, execution, review, and critique; manuscript: writing of the first draft, review, and critique. Hoffmann is involved in research project: conception, organization, execution and in manuscript: writing of the first draft, review, and critique.

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