Calculation of the electromyographic jitter¹

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SYNOPSIS The electromyographic jitter is the variability at consecutive discharges in the time interval between two action potentials from two muscle fibres from the same motor unit. This paper deals with different methods of expressing the jitter. The method of choice seems to be Mean Consecutive Difference (MCD)

$$\text{MCD} = \frac{|D_1 - D_2| + |D_2 - D_3| + \dots + |D_{n-1} - D_n|}{n-1}$$

where D_1 , D_2 etc. are the individual time interval measurement data and n the number of discharges, preferably 50 or, if the jitter is not changing, 200. MCD can also be estimated from other measures of the jitter like Mean Range of Two (MR_2) (giving the same estimated value as MCD), Mean Range of Five (MR_5), Mean Range of Ten (MR_{10}) and also from the Standard Deviation (SD). In a distribution without trends the following relations hold:

$$\text{MCD} = 1.13 \times \text{SD}$$

$$\text{MCD} = 0.49 \times \text{MR}_5$$

$$\text{MCD} = 0.37 \times \text{MR}_{10}.$$

The presence of slow variations and trends in most recordings makes SD not well suited for calculation because of the risk of getting too high estimates of the jitter.

Ekstedt (1964) showed that when recording the action potentials from two muscle fibres from the same motor unit there is always a variability in the time intervals between the two muscle fibre potentials at consecutive discharges. The variability is called the *jitter*. The variability, expressed as standard deviation, is in the normal human muscle of the order of magnitude of 20 μs (Stålberg *et al.*, 1971).

The jitter is increased in, for example, myasthenia gravis (Ekstedt and Stålberg, 1965, 1967), in various neurological disorders (Ekstedt and Stålberg, 1965, Stålberg and Ekstedt, 1969, 1973), under the influence of D-tubocurarine (Ekstedt and Stålberg, 1969), and in ischaemia (Dahlbäck *et al.*, 1968, 1970), and it therefore seems to offer a sensitive method for functional

studies of the transmission in individual endplates in man.

For calculating the jitter, Ekstedt (1964) used the standard deviation (SD) of the interpotential intervals. He also used a simplified method where the range of variability in interpotential intervals within groups of five consecutive discharges was determined. The mean value for several consecutive measurements of this sort was found to correspond roughly to double the standard deviation.

Lately, other methods for expressing the jitter numerically have been used which may have some advantages because they tend to eliminate influences of slow changes or trends of the mean interpotential interval, which may cause a wrong numerical value of the jitter. This paper is intended to elucidate and compare different methods for calculating the jitter.

METHODS

The methods are described by Ekstedt (1964), Stålberg (1966), Ekstedt and Stålberg (1969), and

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FIG. 1. Computer output for a jitter recording of 200 consecutive interpotential intervals. This graph is to exemplify a Gaussian distribution of interpotential intervals in an experimental recording. The histogram at the bottom shows the individual time intervals sorted in ascending order in classes of $5 \mu\text{s}$. The extreme values and the mean value for the interpotential intervals are indicated below the histogram. The number of items in each class is indicated above each staple. The curve crossing the diagram from the left lower corner to the right upper corner is the cumulative probability curve. The ordinate is transformed to probits and probit 5 is indicated. For a Gaussian distribution the curve approximates a straight line. The right vertical trace (to be read from the top to the bottom) is the individual time intervals for the 200 items of data. The vertical line is the mean interpotential interval and the horizontal line at the bottom indicates $10 \mu\text{s}$. The zero is suppressed. The middle trace indicates the individual differences between consecutive items of data; positive ones to the right, negative ones to the left of the line. The scale is the same as for the trace to the right. The oblique line originating at the top of the middle trace is a continuous summing of the absolute values of the differences between consecutive items of data. The scale is here one-fifth that used in the middle diagram. The left vertical trace is a continuous summing of each interpotential interval, where from each value the mean interpotential interval for the 200 items of data has been subtracted. This is to visualize the presence of low variations and trends in the recording. In the present recording the following values of the jitter were obtained. SD (calculated for 200 items): $15.4 \mu\text{s}$, SD (calculated for four groups of 50 items): $16.2 \mu\text{s}$, MCD: $19.1 \mu\text{s}$, $\text{MR}_2 = 18.6 \mu\text{s}$, $\text{MR}_5 = 38.8 \mu\text{s}$, $\text{MR}_{10} = 51.2 \mu\text{s}$, $\text{SD}_{\text{CD}} = 17.17 \mu\text{s}$. The relations between the measurement values are very close to the theoretical one. Skewness was 0.16 and kurtosis 0.09.

Ekstedt and Stålberg (1973). Briefly, action potentials from two muscle fibres (a 'potential pair') from the same motor unit are recorded and the time intervals between the first and second action potential in the potential pair are measured with an accuracy of $\pm 0.3 \mu\text{s}$ (SD). The measurement values are recorded in digital form on a tape recorder and the tape serves as input medium to a computer (CDC 3600), on which all calculations are performed (Ekstedt and Stålberg, 1970).

All recordings from normal muscles used in this investigation were taken from experiments reported by Stålberg *et al.* (1971). Recordings from potential pairs with increased jitter were mainly taken from patients with myasthenia gravis (Ekstedt and Stålberg, 1965, 1967).

In order to test some of the theoretical calculations and to show the influence of trends on the jitter measurement values, a computer Monte Carlo method has been used. Gaussian distributed random data were generated by a computer programme (G5 WISC RANSS from University of Wisconsin Computing Center) and optional linear or sinusoidal trends were superimposed.

RESULTS AND DISCUSSION

DISTRIBUTION OF INTERPOTENTIAL INTERVALS In many of the recordings in normal muscles the interpotential intervals seem to be grouped about a stable mean value. There are several examples of recordings lasting more than 30 minutes, where the mean interval at the end of the recording is within $\pm 20 \mu\text{s}$ from the initial mean value and where no obvious changes of the mean value are seen during the recording.

Thirty series of recordings of 200 consecutive action potential discharges from normal muscles, where no slow changes of the mean time interval were detected by observation, have been analysed with the aim of testing whether or not the distribution of time intervals could be considered as Gaussian. The time intervals were plotted as histograms and as a cumulative distribution where the ordinate was transformed so that a cumulative normal distribution takes the form of a straight line (plotting on normal probability paper). Standard deviation, skewness, and kurtosis measures⁴ (see, for example, Snedecor and Cochran, 1967) were calculated. An example

⁴ When sampling 200 data from a normal distribution, 95% of the skewness measures will fall within 0.0 ± 0.280 . For kurtosis the corresponding 95% limits are -0.67 (a too flat distribution, 'excessive breadth of the shoulders'), and 0.57 (a too peaky distribution, 'excessive pointedness of the peak').

of the computer output is shown in Fig. 1. In most cases the normal probability plot approximated a straight line. Eighteen of the 30 samples of 200 data had skewness and kurtosis measures within the 95% confidence limits. Note, however, that this does not represent a true frequency because the recordings were selected for being without trends.

Thus, recordings are encountered where the distributions of interpotential intervals can be considered as approximately Gaussian. It is, however, not uncommon, especially in pathological cases, that distributions are found which obviously are not Gaussian. There has been a skewness, positive kurtosis or, which is more common, a negative kurtosis (Fig. 2). Also bimodal distributions of the type reported by Ekstedt (1964, p. 55) and Thiele and Stålberg (1974), were sometimes found. The too flat distributions seem to be most common when there have been slow linear or periodic variations in the mean time interval.

The present investigation will mainly deal with the deviations from the Gaussian distribution caused by these slow variations of the mean time interval, while the other abnormalities in the distribution, which are often met in pathological cases, will be dealt with in a separate investigation.

If the interpotential intervals be assumed to have a Gaussian distribution, which is the best way of measuring the jitter? And, further, if there are deviations from the Gaussian distribution caused by slow variations—which are considered to be irrelevant in the present context—how are these variations to be eliminated and the best expression for the jitter obtained?

Some different methods for expressing the variability will be discussed first.

STANDARD DEVIATION (SD) The standard deviation is the most commonly used measure of dispersion

$$SD = \sqrt{\frac{\sum_{i=1}^{i=n} (D_i - \bar{D})^2}{n-1}} \quad (1)$$

(D_i , $i=1, 2, \dots, n$ =experimental data; $\bar{D}$ =their mean value; n =number of items.)

If no slow variations or trends in the mean interpotential interval are present during the period

FIG. 2. Positive skewness in an experimental jitter recording of 200 consecutive interpotential intervals. Jitter as $MCD=16.8 \mu s$. The other jitter measurement values have almost exactly the value expected when using the conversion factors.

of measurement the jitter may be estimated by the standard deviation for the whole sample. The standard error (SE) of the estimate of SD decreases with the sample size according to the function

$$SE = \frac{\sigma}{\sqrt{2(n-1)}} \quad (2)$$

(where SE is standard error of the estimate of SD, σ = the true SD and n = the sample size (Fig. 3)). For $n=50$, 95% of the estimates will fall within $\sigma \pm 0.2\sigma$, and for $n=200$, 95% of the estimates will fall within $\sigma \pm 0.1\sigma$. In order to double the accuracy the sample size has to be increased four times. A sample size of 200 seems therefore suitable from a practical point of view.

However, if there are slow variations or trends in the mean interpotential interval during the period of measurement, the standard deviation

will be overestimated in relation to the σ about the trend line. To lessen the effect of trends the total sample of data may be divided into smaller samples. A sample size of 2 will be the most efficient in eliminating the trend effect at the cost, however, of increased standard error of the estimated SD. For a total sample size of n , the standard deviation (SD_D), estimated from $n/2$ samples of two (D_i = the individual items of data), becomes

$$SD_D = \sqrt{\frac{\sum_{i=1}^{n/2} (D_{2i} - D_{2i-1})^2}{n}} \quad (3)$$

The standard error (SE) for the estimate of σ according to this formula is

$$SE = \frac{\sigma}{\sqrt{n}} \quad (4)$$

FIG. 3. Relation between sample size and standard error of estimate of SD. Calculated from formula 3. The value asymptotically approaches zero with increasing sample size.

This method of calculating SD_D gives a SE that is about 1.4 times greater than when calculating SD for the whole sample.

A somewhat more efficient estimate of σ is the following based on consecutive differences (SD_{CD})

$$SD_{CD} = \sqrt{\frac{\sum_{i=1}^{n-1} (D_i - D_{i+1})^2}{2(n-1)}} \quad (5)$$

SD_{CD} has a SE that is about 1.2 times the SD calculated for the whole sample. The method is extensively treated by, for example, Hald (1952, mean square successive difference, p. 357).

In the methods mentioned above the dispersion of measurement values—that is, the jitter—has been expressed as the standard deviation, which has been calculated from the estimates of variance (s^2). It is also possible to get an expression of the dispersion—related to the standard deviation—by calculating from ranges of groups of data. Some methods for this will now be discussed.

MEAN CONSECUTIVE DIFFERENCE (MCD) MCD is calculated as follows:

$$MCD = \frac{|D_1 - D_2| + |D_2 - D_3| + \dots + |D_{n-1} - D_n|}{n-1} \quad (6)$$

$D_1, \dots, D_n$ = experimental data

$|D_1 - D_2|$ denotes the absolute value of the difference $D_1 - D_2$

For a Gaussian distribution without trends the following theoretical relation holds (see, for example, Dixon and Massey, 1957, p. 404).

$$SD = 0.886 \times MCD \quad (7)$$

The standard error when calculating MCD is 1.2 times the SE for the standard deviation calculation (Table 1).

Mean range of two (MR_2) MR_2 is defined as

$$MR_2 = \frac{|D_1 - D_2| + |D_3 - D_4| + \dots + |D_{n-1} - D_n|}{n/2} \quad (8)$$

TABLE 1

DIFFERENT ESTIMATES OF σ CALCULATED FROM 151 SERIES OF 40 COMPUTER GENERATED GAUSSIAN DISTRIBUTED DATA ($\sigma=20$)*

Based on calculated values	SD	SD _{CD}	MCD	R ₂	R ₅	R ₁₀
Mean	20.07	20.16	22.84	22.91	47.02	62.10
Standard deviation	2.15	2.55	2.89	3.27	5.70	7.28
Conversion factor†	1.00	1.00	0.89	0.89	0.43	0.33
Estimates of σ :						
Mean	20.07	20.16	20.33	20.39	20.22	20.49
Standard error	2.15	2.55	2.57	2.91	2.45	2.40
Coefficient of variation calculated from the above values (%)	10.7	12.6	12.6	14.3	12.1	11.7
Coefficient of variation calculated theoretically (%)	10.1	—	—	15.1	11.7	11.6

* It has thus been possible to estimate the standard error of these estimates. To obtain standard errors for sample sizes of 200 the values should be divided by 2.

† Factor by which the standard deviation should be multiplied to give an unbiased estimate of σ .

MR₂ should give the same value as MCD but about 1.1 times higher standard error (1.3 times higher than for SD) because the basic information is not so well utilized when calculating MR₂ as when calculating MCD (Table 1).

MEAN RANGE OF GROUPS OF SEVERAL ITEMS OF DATA It is possible to estimate σ from ranges of more than two items of data. Ekstedt (1964) used Mean Range of Five (MR₅).

$$\text{MR}_5 = [(D_{\max} - D_{\min} \text{ for } D_1 \rightarrow D_5) + (D_{\max} - D_{\min} \text{ for } D_6 \rightarrow D_{10}) + \dots + (D_{\max} - D_{\min} \text{ for } D_{n-4} \rightarrow D_n)] / (n/5) \quad (9)$$

In analogy with this, any number of items can be the basis for the range measurement.

To get an estimate of σ the mean value of ranges must be multiplied by a factor, which for MR₅ is 0.43 and for MR₁₀ is 0.33. The SE of the estimate of σ from MR₅ and MR₁₀ is 1.13 and 1.09 times the SE for the estimate from SD, respectively. Thus the SE in relation to the estimate from MCD becomes 0.96 and 0.93 for MR₅ and MR₁₀, respectively. This may seem astonishing, because one might have guessed that the information is not so efficiently utilized when calculating R₅ and R₁₀ as when calculating MCD. That is, however, not the case, and this is clearly visible

from the experiments with the computer-generated random data, shown in Table 1.

Another type of estimation for σ based on ranges should also be mentioned because it can be of a certain practical value for estimation of the jitter when only a histogram of the interpotential intervals is available—for example, produced by a CAT-type computer. In a Gaussian distribution half the observations lie within the range of ± 0.67 SD—that is, within the interquartile range. Two-thirds of the observations lie within ± 1 SD and 95% within ± 2 SD. So, the range within which half the observations lie, multiplied by 0.74, will give an estimate of SD, as will the range, within which two-thirds of the observations lie, multiplied by 0.5, and the range within which 95% of the observations lie, multiplied by 0.25. This should, however, be used only to get a gross estimate of the jitter when there are no slow variations or trends in the mean interpotential interval.

SAMPLE SIZE PREFERRED FOR EACH JITTER CALCULATION As already discussed, the standard error will decrease approximately with the square root of the sample size (formula 2). If the jitter is constant during the experiment it seems reasonable to choose sample size 200, because the increase in accuracy that can be gained by further increasing the sample size seems to be negligible (page 529). However, changes of the jitter often occur during experiments. From the experience with D-tubocurarine (Ekstedt and Stålberg, 1969b) and with ischaemia (Dahlbäck *et al.*, 1971), it has been found that a sample size of 200 tends to swamp the changes in the jitter and in those cases a sample size of 50 has been chosen, at the cost, however, of the accuracy, which is halved. This holds for any of the jitter measurement values chosen.

BEST EXPRESSION FOR JITTER IN ABSENCE OF SLOW VARIATIONS OR TRENDS IN MEAN INTERPOTENTIAL INTERVAL Of course the method giving the least standard error (=the highest accuracy) should be chosen. The accuracy of the different methods described above is given in Table 1.

The ranking list with regard to standard error for the different expressions for the jitter (calculated for groups of 50 items of data) in record-

FIG. 4. Corresponding values of SD and MCD (groups of 50) for the human experimental material in recordings, where there were obvious trends or other slow variations in the mean interpotential interval. The theoretical regression line ($MCD = 1.13 \times SD$) is indicated. A considerable amount of measurement values will fall below this line. See Table 2 and text.

ings, where there are no slow variations or trends of the mean interpotential interval, would then be

	Coefficient of variation (SE)
SD	10.7
MR ₁₀	11.7
MR ₅	12.1
SD _{CD} , MCD	12.6
MR ₂	14.3

However, in the authors' experience, the presence of slow variations and trends, easily recognized on inspection of the records, is very common. In Fig. 4 the recordings that obviously contained slow variations or trends, are correlated. The deviations from the theoretical relation are very pronounced. The mean SD/MCD for the whole material (all calculations for groups of 50 items) was found to be $1.578 (\pm 0.798, n=309)$. Subdividing the material according to jitter size gives $2.130 (\pm 0.912, n=82)$ for $MCD=0-19.9$; $1.566 (\pm 0.632, n=147)$ for $MCD=20-99.9$ and $0.957 (\pm 0.180, n=80)$

FIG. 5. Corresponding values of SD and MCD (groups of 50) in an experimental material where no slow variations or trends in the mean interpotential interval on inspection were considered to be present. However, such variations must nevertheless have been present, especially in the measurement points with low jitter, which are mainly lying below the theoretical regression line, indicated in the diagram ($MCD = 1.15 \times SD$). See text and Table 2.

for MCD exceeding 100. In Fig. 5 the measurement values of the jitter, expressed as SD and MCD, are correlated for recordings which, on inspection, were considered to be without slow variations in the mean interpotential intervals. The highest measurement values seem to be well grouped about the theoretical regression line indicated ($SD = 0.886 \times MCD$). The lower measurement values, however, are mainly lying below this line. When calculating the mean ratio SD/MCD for the whole material one gets 1.051 (SD of the ratio $= 0.319, n=279$). When subdividing the material according to the size of the jitter, the mean SD/MCD ratio was $1.386 (\pm 0.403, n=82)$ for $MCD=0-19.9$, $0.942 (\pm 0.124, n=86)$ for $MCD=20-99.9$ and $0.886 (\pm 0.077, n=109)$ for MCD greater than 100.

(For the Gaussian distributed random data the mean SD/MCD ratio was $0.883 (\pm 0.057, n=$

TABLE 2
RATIOS BETWEEN DIFFERENT EXPRESSIONS FOR JITTER IN EXPERIMENTAL MATERIAL

<i>Recordings without trends</i>	<i>SD/MCD</i>	<i>SD/R₂</i>	<i>SD/R₅</i>	<i>MCD/R₂</i>	<i>MCD/R₅</i>
MCD 0-19.9					
M =	1.386	1.406	0.598	1.016	0.439
SD about mean = n = 82	0.403	0.422	0.150	0.091	0.048
MCD 20-99.9					
M =	0.942	0.948	0.458	1.007	0.490
SD about mean = n = 86	0.124	0.151	0.093	0.090	0.101
MCD 100-					
M =	0.886	0.876	0.430	0.988	0.488
SD about mean = n = 109	0.077	0.113	0.027	0.090	0.037
The whole material					
M =	1.051	1.055	0.488	1.002	0.474
SD about mean = n = 279	0.319	0.342	0.1214	0.091	0.070
<i>Recordings with trends</i>					
MCD 0-19.9					
M =	2.130	2.169	0.824	1.015	0.396
SD about mean = n = 82	0.912	1.008	0.321	0.121	0.055
MCD = 20-99.9					
M =	1.566	1.572	0.688	1.004	0.462
SD about mean = n = 147	0.632	0.660	0.374	0.110	0.330
MCD = 100					
M =	0.957	0.961	0.479	1.00	0.512
SD about mean = n = 80	0.180	0.208	0.078	0.077	0.104
M =	1.558	1.572	0.670	1.006	0.457
SD about mean = n = 309	0.7728	0.822	0.3329	0.1054	0.238
Theoretical values					
M =	0.886	0.886	0.430	1.000	0.485

151), which is close to the theoretically calculated value.)

It seems as if the explanation of the high SD/MCD ratio for the lower jitter measurements must be the presence of slow variations in the mean interpotential interval, not easily detected with the naked eye. Of course, a certain slow variation in the mean interpotential interval will influence the jitter measurement value less with increasing jitter. A non-Gaussian distribution will not influence the SD/MCD ratio (see below) from what has been said it is obvious that the relation between σ estimated from SD and σ estimated from MCD could be used as an index for the presence of slow variations or trends. Let us call this index 'Trend Index' (TI).

TI = SD / (MCD x 0.886) (10)

In a Gaussian distribution TI = 1.0. The presence

of trends increases the value of TI. The value of course depends on the sample size.

From a theoretical point of view it should be more satisfactory to use

TI = SD / SD_{CD} (11)

because both factors are based on σ^2 . (Even better would be to use the ratio between the variances obtained in the two ways.)

In the experimental material without trends, the corresponding values for MCD and MR₂ are plotted in Fig. 6 and for MCD and MR₅ in Fig. 7. In Table 2 the ratios between the jitter calculated with the different methods are shown. In conclusion, it can be said that in an experimental material slow variations or trends in the mean interpotential interval are so common that it seems wise not to use the SD as a numerical expression for the jitter.

FIG. 6. Corresponding values for MCD and MR_2 in the human experimental material 'without trends'. Theoretically $MCD = MR_2$ and this also holds for this material. See Table 3.

BEST EXPRESSION FOR JITTER IN PRESENCE OF SLOW VARIATIONS OR TRENDS IN MEAN INTERPOTENTIAL INTERVAL In Fig. 8 the effect of trends is shown for the different expressions for the jitter. It can be concluded that if allowing the trend to increase the jitter measurement value by 20%, the maximally permissible trends become

	Calculated for groups of 200 items of data
SD	1-2%
	Calculated for groups of 50 items of data
SD	4-5%
MR_{10}	20%
MR_5	45%
SD_{CD} , MCD, and MR_2	85%

(Percentage trend is defined as the systematic increase in the value of each consecutive item of data by the given percentage of σ .)

An example of the computer output of a simulated recording with a linear trend is shown

FIG. 7. Corresponding values for MCD and MR_5 in the human experimental material 'without trends'. The line is the theoretical regression line ($MR_5 = 2.04 \times MCD$). For recording with $MCD \geq 20 \mu s$ this relation holds for the experimental material, but for $MCD < 20 \mu s$ the factor is 2.28, probably due to the presence of undetected slow variations in the mean interpotential interval. See Table 3.

in Fig. 9 and with a sinusoidal variation of the mean interpotential interval in Fig. 10.

In the experimental material with trends (Fig. 5) the mean trend index ($TI = SD / (MCD \times 0.886)$), calculated for groups of 50 items in the whole material, was 1.87 and for the part of the material where MCD was less than 20 it was 2.42. In this group an extreme value of 5.5 was found (jitter as $SD = 35.8$ and as $MCD = 7.57$). In this case a linear trend of 45% should have

FIG. 8. Influence of linear trends on the bias in the measurement value for different methods of calculating the jitter. The graph is based on experiments with computer-generated Gaussian distributed data (7,050 items of data). For a trend of 100% the bias in estimation of SD for 200 items would be about 5,700, for SD calculated for 50 items, 1,400 and for MR_{10} 210.

caused the same TI. It is interesting to note that in this particular case the ratio MCD/R_2 was 0.957 (theoretically for a Gaussian distribution 1.0) and MCD/R_5 was 0.3249 (theoretically 0.49).

INFLUENCE OF NON-GAUSSIAN DISTRIBUTIONS ON

CONVERSION FACTORS In order to test the influence on the conversion factors by a non-Gaussian distribution, the following was done by means of the computer-generated random data.

One distribution was made that contained only the items exceeding the mean value of the original Gaussian distribution (Fig. 10, 'the half Gaussian distribution'). Another distribution was obtained by adding $3 \times \sigma$ to all items below the mean value of the original gaussian distribution, giving it a bizarre appearance like a Turkish saddle. Finally, a purely rectangular distribution was generated.

The mean ratios between the different jitter measurement values are given in Table 3. There is a very good agreement between these ratios and those theoretically calculated for a Gaussian distribution.

The results are really astonishing. The investigation was made in order to illustrate how cautious one must be when using the conversion factors on non-Gaussian distributed data, and the outcome was that this does not seem to be an important source of error. In the experience of the authors no such gross deviations from the gaussian distribution as here simulated have been encountered in human jitter recordings from normal or pathological muscles.

The non-Gaussian distributions will be further elaborated in a coming paper.

LESSENING THE INFLUENCE OF ERRONEOUS DATA Under practical recording conditions erroneous data occur now and then. The usual cause is that other motor units than that under study are active at the same time, so that from time to time an irrelevant action potential adds to one of the action potentials under study. From the protocol notations of the experiment these measurement

TABLE 3

MEAN RATIOS BETWEEN DIFFERENT MEASURES OF JITTER IN COMPUTER GENERATED NON-GAUSSIAN DATA*

	SD/SD_{CD}	SD/MCD	SD/R_5	SD/R_{10}	MCD/R_5	MCD/R_{α_0}
Theoretical ratio	1.00	0.89	0.43	0.33	0.49	0.37
'Half Gaussian'	0.98	0.89	0.43	0.34	0.50	0.37
'Turkish saddle'	1.00	0.86	0.44	0.38	0.52	0.44
'Rectangular'	1.00	0.86	0.43	0.35	0.51	0.41

* Nineteen measurements of 50 items of data were the basis for the calculations. Cf. the text.

FIG. 9. Computer output for the calculation of 200 computer-generated items of data with $\sigma = 20 \mu\text{s}$ and a trend of 10%. SD calculated for the 200 items = $119.2 \mu\text{s}$; SD calculated for four groups of 50 items = $35.0 \mu\text{s}$; $\text{SD}_{\text{CD}} = 19.3 \mu\text{s}$; $\text{MCD} = 22.2 \mu\text{s}$; $\text{MR}_2 = 22.2 \mu\text{s}$; $\text{MR}_5 = 35.6 \mu\text{s}$; $\text{MR}_{10} = 62.3 \mu\text{s}$. Thus only the SD calculations were affected by the presence of the trend.

values may often be detected and excluded, but some will pass undetected.

When calculating SD, SD_{D} , or SD_{CD} , the measurement values will be given a weight that is proportional to the square of the difference, either to the mean value or to the preceding or succeeding item of data. Using MCD or MR_2 , MR_5 , or MR_{10} the weight is only directly proportional to this difference. However, assuming that one erroneous datum occurs in every sample of 50 consecutive items, the mean value for measurements made for these 50 items will be based on the erroneous item in one-fifth of the MR_{10} measurements, 1/10 in the MR_5 , and 1/25 in MR_2 and MCD measurements. Thus, the influence of erroneous data on the measurement

value of the jitter is least when using MCD or MR_2 .

When using computer treatment of data the possibility always exists of skipping automatically certain data which fall outside certain specifications. This is a dangerous solution which may give misleading results. It is preferable to exclude an item manually when it has been proved that that particular item was erroneous for technical reasons.

PRACTICAL CONSIDERATIONS If an automatic system is available, either in the form of recording on digital magnetic tape with subsequent computer treatment (Ekstedt and Stålberg, 1970) or as a Jittermeter (Ekstedt *et al.*, 1970) it seems

FIG. 10. Computer output from an experiment with random data with $\sigma = 20 \mu\text{s}$ on which a sinus wave was superimposed. The period length corresponded to 87 items and the peak-to-peak excursion of the sinus wave was $200 \mu\text{s}$. SD calculated for the 200 items was $74.5 \mu\text{s}$; SD calculated for groups of 50 items was $49.48 \mu\text{s}$; $SD_{CD} = 19.29 \mu\text{s}$; $MCD = 21.41 \mu\text{s}$; $MR_2 = 21.5 \mu\text{s}$; $MR_5 = 49.2 \mu\text{s}$; $MR_{10} = 72.86 \mu\text{s}$. The SD values were greatly affected by the 10% higher sinusoidal disturbance, but the other values were close to the expected ones (MR_{10} than expected).

TABLE 4

CONVERSION FACTOR FOR OBTAINING CORRESPONDING MCD VALUE
FROM OTHER EXPRESSIONS FOR JITTER

	Jitter measure											
	MCD	SD	SD_{CD}	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
Factor	1.00	1.13	1.13	1.00	0.67	0.55	0.49	0.45	0.42	0.40	0.38	0.37

FIG. 11. Computer output from an experiment with random data, where the lower half of the distribution (σ of the original distribution = $20 \mu\text{s}$) was suppressed. The mean ratio between the different expressions for the jitter was very close to those theoretically expected in a Gaussian distribution (the values given in text).

obvious that MCD should be chosen as an expression of the jitter. If, however, the measurement has to be performed manually from oscilloscope photographs, which method will then cause least work? If a value of the jitter for each 50 discharges is desired, should one then make 49 measurements for calculating MCD, 25 measurements for calculating MR_2 , 10 measurements for calculating MR_5 , or five measurements for calculating MR_{10} ?

Then it seems reasonable to use the MR_2 which gives the same expected value as MCD. The somewhat lower accuracy for R_2 in comparison with MCD seems to be of minor practical importance.

Usually, even at a non-Gaussian distribution, there is a good correlation between the jitter expressed in the different ways and therefore also

MR_5 or MR_{10} (or any range below 10) seem to be usable for calculating the jitter. If there are small trends, MR_{10} can be used, if there are more pronounced trends, MR_5 .

When superimposing several oscilloscope sweeps on photographs it might easily happen that different numbers of sweeps occur on the different photographs. To permit calculation of data, conversion factors to MCD for different ranges have been calculated (Table 4).

DISCUSSION

Taking all factors into account, it seems reasonable to use MCD as the measure for the jitter. Even when calculating the jitter with other methods, the measurement value ought to be converted to MCD in order to make comparison

possible (Table 3). MR_2 will give the same expected numerical value as MCD. MR_5 or MR_{10} seem to be simple and reliable methods when having to perform the measurements manually from the oscilloscope photographs, but one must bear in mind that excessive trends may increase the measurement values.

It might be argued that one should keep to the SD as a *reference* and recalculate the MCD or other expressions to SD by the conversion factor. (From what has been said above, SD should not be used for *calculation* but preferably then SD_{CD} according to formula 5.)

SD is an accepted way of expressing a variability, and the mathematics for treating SD values are well known. However, if recommending *calculation* of the jitter as MCD, it does not seem to make sense to express it as something else. Recalculating the MCD value to SD_{CD} would give the reader the impression that the value was an estimation of σ based on calculation of variance, but this is not the case. (However, no great error will probably be introduced at conversion of MCD to SD_{CD} , if needed for mathematical reasons.) Therefore, we recommend calculation and expression of the jitter as MCD. If calculated from other ranges—for example, MR_5 , MR_{10} —it must, however, be practical to convert the values to MCD (also based on ranges) in order to make comparisons and understanding possible between different laboratories.

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