

Contents

1	Review of Current Methodologies(Bland-Altman Methodology)	3
1.1	Bland-Altman methodology	3
1.2	Bland-Altman Approach	5
1.3	Bland-Altman plots for the Grubbs data	5
1.4	Bland-Altman plots for the Grubbs data	9
1.5	Inspecting the Data	12
1.6	The Bland Altman Plot	15
1.7	Bland Altman Plots	15
1.8	Bland Altman Plot	18
1.9	Bland Altman Plot	19
1.10	Bland-Altman Plots	19
1.11	Limits of Agreement	20
1.12	Limits Of Agreement	21
1.13	Appropriate Use of Limits of Agreement	22
1.14	Formal definition of limits of agreement	23
1.15	Inferences on Bland-Altman estimates	24
1.16	Adverse features	24
1.17	Outliers	26
1.18	Adverse features	28
1.19	Agreement	33
1.20	scatter plots	33

1.21 Effect of Outliers	34
1.22 Precision of Limits of Agreement	34
1.23 Variations of the Bland-Altman Plot	34
1.24 The Bland Altman Plot - Variations	35
1.25 Variations and Alternative Graphical Methods	35
1.26 Variants of the Bland-Altman Plot	36
1.27 Prevalence of the Bland-Altman plot	36
1.28 Bland Altman Plots In Literature	37
1.29 Bland Altman Plots In Literature	37
1.30 Bartko's Ellipse	38

Chapter 1

Review of Current Methodologies(Bland-Altman Methodology)

1.1 Bland-Altman methodology

The issue of whether two measurement methods comparable to the extent that they can be used interchangeably with sufficient accuracy is encountered frequently in scientific research. Historically comparison of two methods of measurement was carried out by use of paired sample t -test, correlation coefficients or simple linear regression. Simple linear regression is unsuitable for method comparison studies because of the required assumption that one variable is measured without error. In comparing two methods, both methods are assumed to have attendant random error.

Statisticians Martin Bland and Douglas Altman recognized the inadequacies of these analyses and articulated quite thoroughly the basis on which they are unsuitable for comparing two methods of measurement (?). Furthermore they proposed their simple methodology specifically constructed for method comparison studies. They acknowledge the opportunity to apply other valid, but complex, methodologies, but ar-

gue that a simple approach is preferable, especially when the results must be ‘explained to non-statisticians’.

Notwithstanding previous remarks about linear regression, the first step recommended, which the authors argue should be mandatory, is construction of a simple scatter plot of the data. The line of equality should also be shown, as it is necessary to give the correct interpretation of how both methods compare. In the case of good agreement, the observations would be distributed closely along the line of equality. A scatter plot of the Grubbs data is shown in Figure 1.1. Visual inspection confirms the previous conclusion that there is an inter-method bias present, i.e. Fotobalk device has a tendency to record a lower velocity.

? notes that scatter plots were very seldom presented in the Annals of Clinical Biochemistry. This apparently results from the fact that the ‘Instructions for Authors’ dissuade the use of regression analysis, which conventionally is accompanied by a scatter plot.

1.2 Bland-Altman Approach

The issue of whether two measurement methods comparable to the extent that they can be used interchangeably with sufficient accuracy is encountered frequently in scientific research. Historically, comparison of two methods of measurement was carried out by use of paired sample t -test, correlation coefficients or simple linear regression. However, simple linear regression is unsuitable for method comparison studies due to the assumption that one variable is measured without error. In comparing two methods, both methods are assumed to have attendant random error.

? highlighted the inadequacies of these approaches for comparing two methods of measurement, and proposed methodologies with this specific application in mind. Although the authors also acknowledge the opportunity to apply other, more complex, approaches, but argue that simpler approaches is preferable, especially when the results must be ‘explained to non-statisticians’.

Notwithstanding previous remarks about linear regression, the first step recommended, which the authors argue should be mandatory, is the construction of a scatter plot of the data. Scatterplots can facilitate an initial judgement and helping to identify potential outliers, with the addition of the line of equality. In the case of good agreement, the observations would be distributed closely along this line. However, they are not useful for a thorough examination of the data. ? notes that data points will tend to cluster around the line of equality, obscuring interpretation.

A scatter plot of the Grubbs data is shown in Figure 1.1. Visual inspection confirms the previous conclusion that inter-method bias is present, i.e. the Fotobalk device has a tendency to record a lower velocity.

1.3 Bland-Altman plots for the Grubbs data

In the case of the Grubbs data the inter-method bias is -0.61 metres per second, and is indicated by the dashed line on Figure 1.2. By inspection of the plot, it is also possible

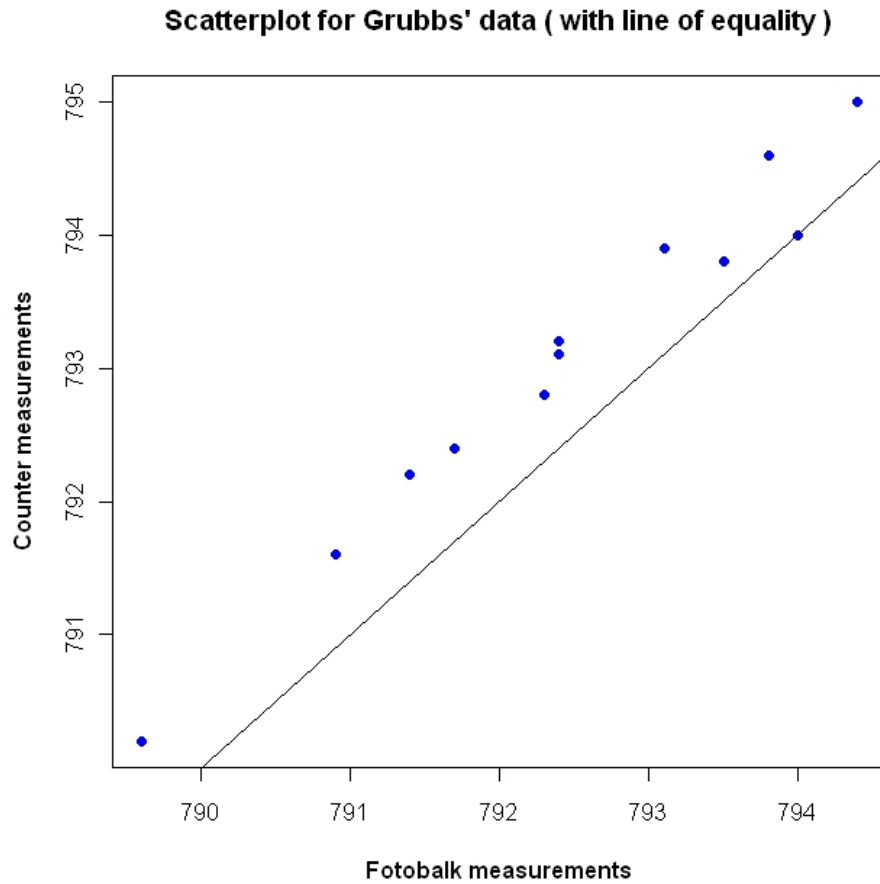


Figure 1.2.1: Scatter plot for Fotobalk and Counter methods.

to compare the precision of each method. Noticeably the differences tend to increase as the averages increase.

The Bland-Altman plot for comparing the 'Fotobalk' and 'Counter' methods, which shall henceforth be referred to as the 'F vs C' comparison, is depicted in Figure 1.2, using data from Table 1.3. The presence and magnitude of the inter-method bias is indicated by the dashed line.

Round	Fotobalk [F]	Counter [C]	Differences [F-C]	Averages [(F+C)/2]
1	793.8	794.6	-0.8	794.2
2	793.1	793.9	-0.8	793.5
3	792.4	793.2	-0.8	792.8
4	794.0	794.0	0.0	794.0
5	791.4	792.2	-0.8	791.8
6	792.4	793.1	-0.7	792.8
7	791.7	792.4	-0.7	792.0
8	792.3	792.8	-0.5	792.5
9	789.6	790.2	-0.6	789.9
10	794.4	795.0	-0.6	794.7
11	790.9	791.6	-0.7	791.2
12	793.5	793.8	-0.3	793.6

Table 1.3.1: Fotobalk and Counter methods: differences and averages.

Round	Fotobalk [F]	Terma [T]	Differences [F-T]	Averages [(F+T)/2]
1	793.8	793.2	0.6	793.5
2	793.1	793.3	-0.2	793.2
3	792.4	792.6	-0.2	792.5
4	794.0	793.8	0.2	793.9
5	791.4	791.6	-0.2	791.5
6	792.4	791.6	0.8	792.0
7	791.7	791.6	0.1	791.6
8	792.3	792.4	-0.1	792.3
9	789.6	788.5	1.1	789.0
10	794.4	794.7	-0.3	794.5
11	790.9	791.3	-0.4	791.1
12	793.5	793.5	0.0	793.5

Table 1.3.2: Fotobalk and Terma methods: differences and averages.

In Figure 1.3 Bland-Altman plots for the ‘F vs C’ and ‘F vs T’ comparisons are shown, where ‘F vs T’ refers to the comparison of the ‘Fotobalk’ and ‘Terma’ methods. Usage of the Bland-Altman plot can demonstrate the contrast between these comparisons. By inspection, there exists a larger inter-method bias in the ‘F vs C’

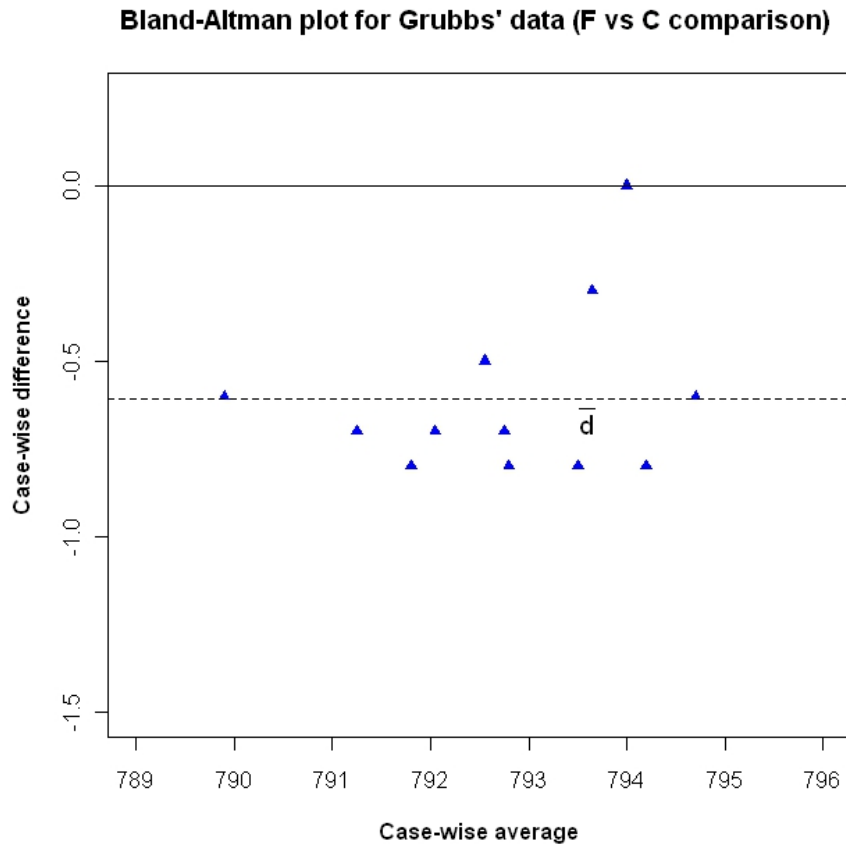


Figure 1.3.2: Bland-Altman plot For Fotobalk and Counter methods.

comparison than in the 'F vs T' comparison. Conversely there appears to be less precision in 'F vs T' comparison, as indicated by the greater dispersion of covariates.

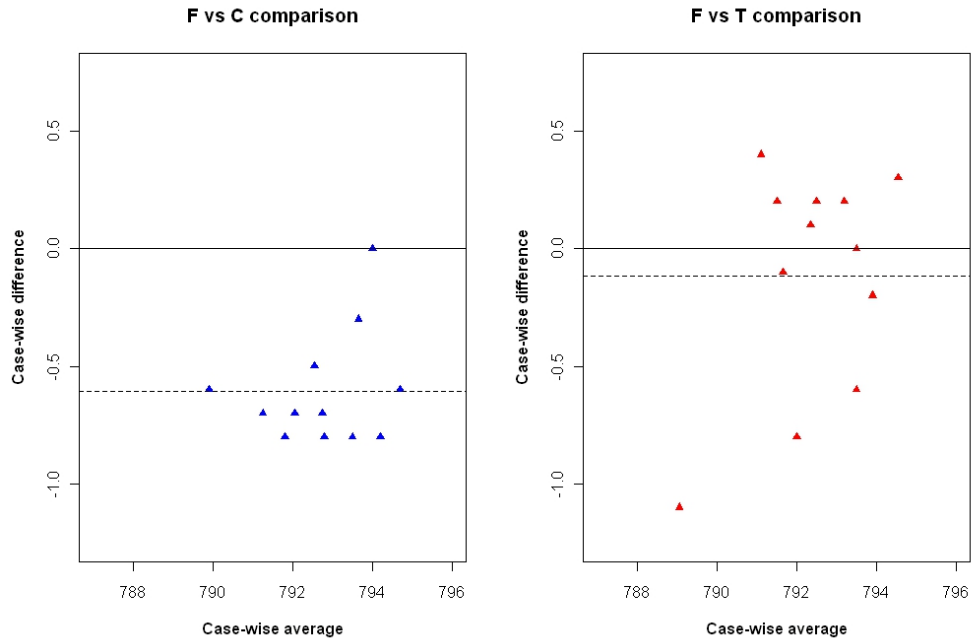


Figure 1.3.3: Bland-Altman plots for Grubbs’ F vs C and F vs T comparisons.

1.4 Bland-Altman plots for the Grubbs data

In the case of the Grubbs data the inter-method bias is -0.61 metres per second, and is indicated by the dashed line on Figure 1.2. By inspection of the plot, it is also possible to compare the precision of each method. Noticeably the differences tend to increase as the averages increase.

The Bland-Altman plot for comparing the ‘Fotobalk’ and ‘Counter’ methods, which shall henceforth be referred to as the ‘F vs C’ comparison, is depicted in Figure 1.2, using data from Table 1.3. The presence and magnitude of the inter-method bias is indicated by the dashed line.

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6	792.4	793.1	-0.7	792.8
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8	792.3	792.8	-0.5	792.5
9	789.6	790.2	-0.6	789.9
10	794.4	795.0	-0.6	794.7
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Table 1.4.3: Fotobalk and Counter methods: differences and averages.

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2	793.1	793.3	-0.2	793.2
3	792.4	792.6	-0.2	792.5
4	794.0	793.8	0.2	793.9
5	791.4	791.6	-0.2	791.5
6	792.4	791.6	0.8	792.0
7	791.7	791.6	0.1	791.6
8	792.3	792.4	-0.1	792.3
9	789.6	788.5	1.1	789.0
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Table 1.4.4: Fotobalk and Terma methods: differences and averages.

In Figure 1.3 Bland-Altman plots for the ‘F vs C’ and ‘F vs T’ comparisons are shown, where ‘F vs T’ refers to the comparison of the ‘Fotobalk’ and ‘Terma’ methods. Usage of the Bland-Altman plot can be demonstrate in the contrast between these comparisons. By inspection, there exists a larger inter-method bias in the ‘F vs C’ comparison than in the ‘F vs T’ comparison. Conversely there appears to be less precision in ‘F vs T’ comparison, as indicated by the greater dispersion of covariates.

1.5 Inspecting the Data

Bland-Altman plots are a powerful graphical methodology for making a visual assessment of the data. ? express the motivation for this plot thusly:

”From this type of plot it is much easier to assess the magnitude of disagreement (both error and bias), spot outliers, and see whether there is any trend, for example an increase in (difference) for high values. This way of plotting the data is a very powerful way of displaying the results of a method comparison study.”

Figures 1.3 1.4 and 1.5 are three Bland-Altman plots derived from simulated data, each for the purpose of demonstrating how the plot would inform an analyst of trends that would adversely affect use of the recommended methodology. Figure 1.3 demonstrates how the Bland Altman plot would indicate increasing variance of differences over the measurement range. Figure 1.4 is an example of cases where the inter-method bias changes over the measurement range. This is known as proportional bias (?).

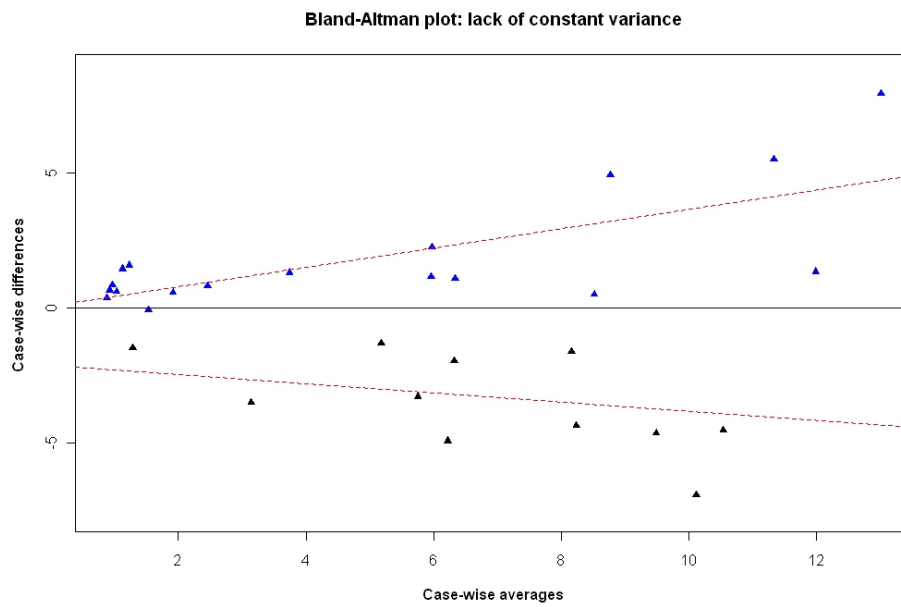


Figure 1.5.4: Bland-Altman Plot demonstrating the increase of variance over the range

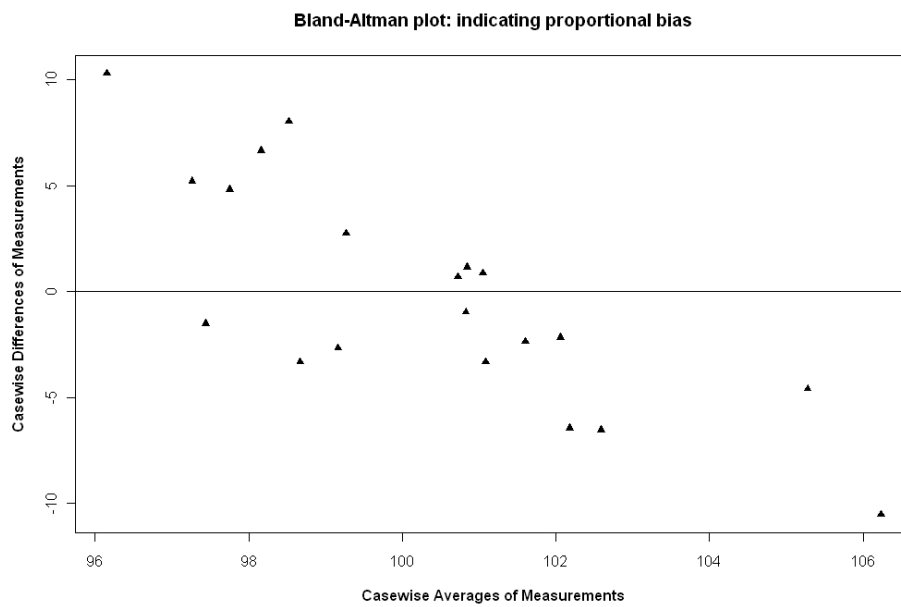


Figure 1.5.5: Bland-Altman Plot indicating the presence of proportional bias

Figure 1.4 is an example of cases where the inter-method bias changes over the measurement range. This is known as proportional bias (Ludbrook, 1997). Both of these cases violate the assumptions necessary for further analysis using limits of agreement, which shall be discussed later. The plot also can be used to identify outliers. An outlier is an observation that is numerically distant from the rest of the data. Classification thereof is a subjective decision in any analysis, but must be informed by the logic of the formulation. Figure 1.5 is a Bland Altman plot with two conspicuous observations, at the extreme left and right of the plot respectively.

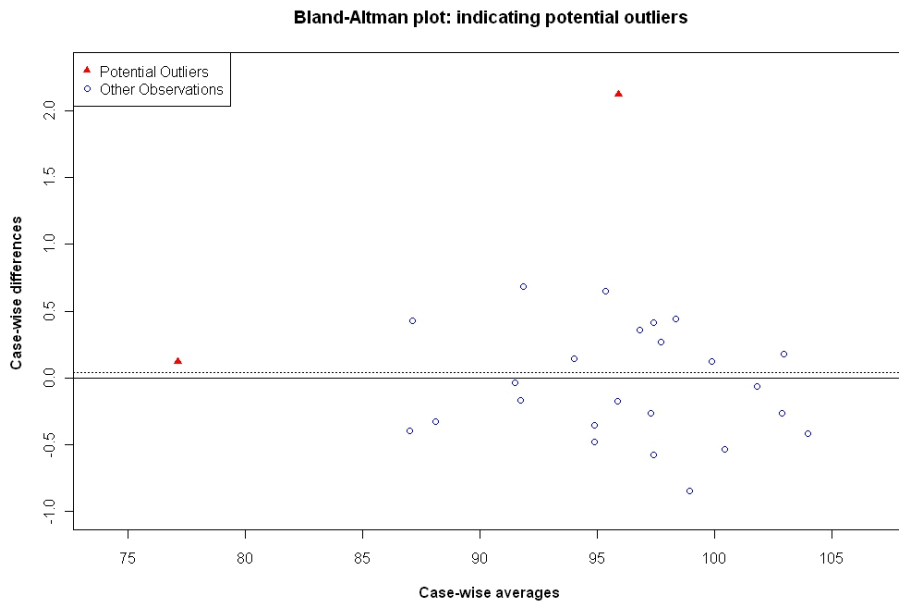


Figure 1.5.6: Bland-Altman Plot indicating the presence of Outliers

In the Bland-Altman plot, the horizontal displacement of any observation is supported by two independent measurements. Hence any observation, such as the one on the extreme right of figure 1.5, should not be considered an outlier on the basis of a noticeable horizontal displacement from the main cluster. The one on the extreme left should be considered an outlier, as it has a noticeable vertical displacement from the rest of the observations.

? do not recommend excluding outliers from analyses. However recalculation of the inter-method bias estimate , and further calculations based upon that estimate, are useful for assessing the influence of outliers.(?) states that "*We usually find that this method of analysis is not too sensitive to one or two large outlying differences.*"

1.6 The Bland Altman Plot

In 1986 Bland and Altman published a paper in the Lancet proposing the difference plot for use for method comparison purposes. It has proved highly popular ever since. This is a simple, and widely used , plot of the differences of each data pair, and the corresponding average value. An important requirement is that the two measurement methods use the same scale of measurement.

1.7 Bland Altman Plots

The issue of whether two measurement methods comparable to the extent that they can be used interchangeably with sufficient accuracy is encountered frequently in scientific research. Historically comparison of two methods of measurement was carried out by use of correlation coefficients or simple linear regression. Bland and Altman recognized the inadequacies of these analyses and articulated quite thoroughly the basis on which of which they are unsuitable for comparing two methods of measurement (?).

Furthermore they proposed their simple methodology specifically constructed for method comparison studies. They acknowledge that there are other valid, but complex, methodologies, and argue that a simple approach is preferable to this complex approaches, *especially when the results must be explained to non-statisticians* (?).

Notwithstanding previous remarks about regression, the first step recommended ,which the authors argue should be mandatory,is construction of a simple scatter plot of the data. The line of equality ($X = Y$) should also be shown, as it is necessary to give the correct interpretation of how both methods compare. A scatter plot of the Grubbs

data is shown in figure 2.1. A visual inspection thereof confirms the previous conclusion that there is an inter method bias present, i.e. Fotobalk device has a tendency to record a lower velocity.

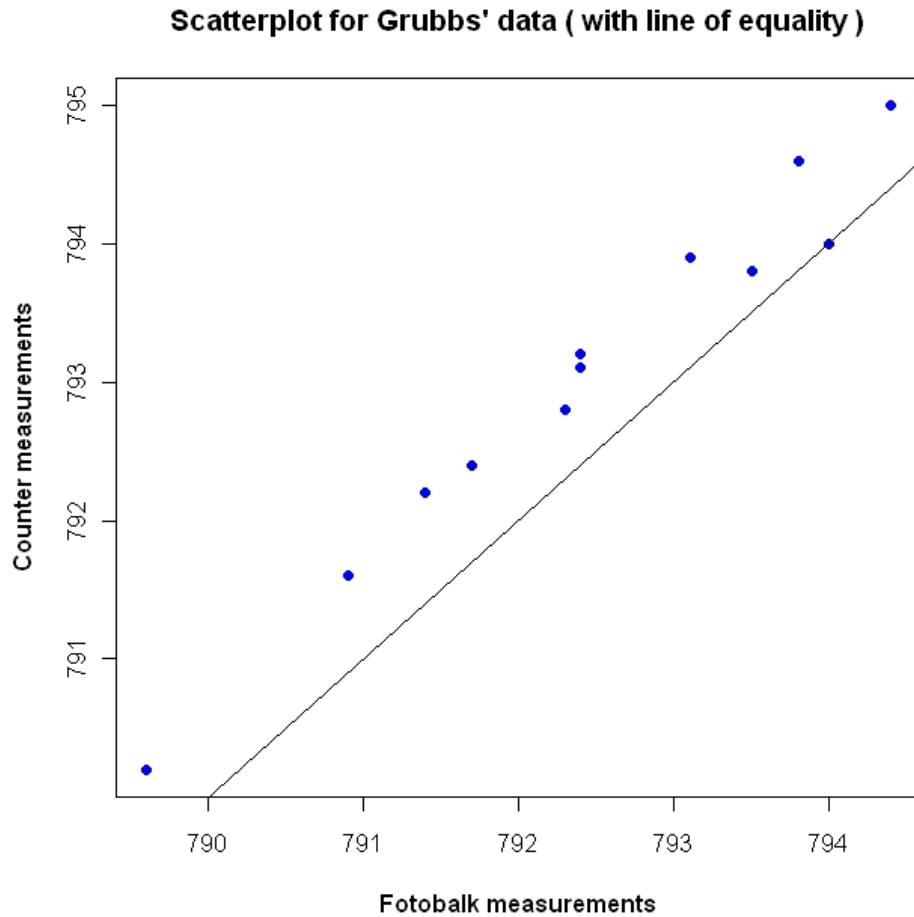


Figure 1.7.7: Scatter plot For Fotobalk and Counter Methods

In light of shortcomings associated with scatterplots, ? recommend a further analysis of the data. Firstly differences of measurements of two methods on the same subject should be calculated, and then the average of those measurements (Table 2.1). These differences and averages are then plotted (Figure 2.2).

The dashed line in Figure 2.2 alludes to the inter method bias between the two methods, as mentioned previously. Bland and Altman recommend the estimation of

inter method bias by calculating the average of the differences. In the case of Grubbs data the inter method bias is -0.6083 metres per second.

Round	Fotobalk [F]	Counter [C]	Differences [F-C]	Averages [(F+C)/2]
1	793.80	794.60	-0.80	794.20
2	793.10	793.90	-0.80	793.50
3	792.40	793.20	-0.80	792.80
4	794.00	794.00	0.00	794.00
5	791.40	792.20	-0.80	791.80
6	792.40	793.10	-0.70	792.80
7	791.70	792.40	-0.70	792.00
8	792.30	792.80	-0.50	792.50
9	789.60	790.20	-0.60	789.90
10	794.40	795.00	-0.60	794.70
11	790.90	791.60	-0.70	791.20
12	793.50	793.80	-0.30	793.60

Table 1.7.5: Fotobalk and Counter Methods: Differences and Averages

By inspection of the plot, it is also possible to compare the precision of each method. Noticeably the differences tend to increase as the averages increase.

1.8 Bland Altman Plot

Bland Altman have recommended the use of graphical techniques to assess agreement. Principally their method is calculating , for each pair of corresponding two methods of measurement of some underlying quantity, with no replicate measurements, the difference and mean. Differences are then plotted against the mean.

Hopkins argued that the bias in a subsequent Bland-Altman plot was due, in part, to using least-squares regression at the calibration phase.

measurements

1.9 Bland Altman Plot

Bland Altman have recommended the use of graphical techniques to assess agreement. Principally their method is calculating , for each pair of corresponding two methods of measurement of some underlying quantity, with no replicate measurements, the difference and mean. Differences are then plotted against the mean.

Hopkins argued that the bias in a subsequent Bland-Altman plot was due, in part, to using least-squares regression at the calibration phase.

1.10 Bland-Altman Plots

In light of shortcomings associated with scatterplots, ? recommend a further analysis of the data. Firstly case-wise differences of measurements of two methods $d_i = y_{1i} - y_{2i}$, for $i = 1, 2, \dots, n$, on the same subject should be calculated, and then the average of those measurements, $(a_i = (y_{1i} + y_{2i})/2$ for $i = 1, 2, \dots, n$.

Following a technique known as the Tukey mean-difference plot, as noted by ? ? proposed that a_i should be plotted against d_i , a plot now widely known as the Bland-Altman plot, and motivated this plot as follows:

“From this type of plot it is much easier to assess the magnitude of disagreement (both error and bias), spot outliers, and see whether there is any trend, for example an increase in (difference) for high values. This way of plotting the data is a very powerful way of displaying the results of a method comparison study.”

The case wise-averages capture several aspects of the data, such as expressing the range over which the values were taken, and assessing whether the assumptions of constant variance holds. Case-wise averages also allow the case-wise differences to be presented on a two-dimensional plot, with better data visualization qualities than a one dimensional plot. ? cautions that it would be the difference against either measurement value instead of their average, as the difference relates to both value. This approach

has proved very popular, and the Bland-Altman plots is widely regarded as powerful graphical tool for making a visual assessment of the data.

The magnitude of the inter-method bias between the two methods is simply the average of the differences \bar{d} . This inter-method bias is represented with a line on the Bland-Altman plot. As the objective of the Bland-Altman plot is to advise on the agreement of two methods, the individual case-wise differences are also particularly relevant. The variances around this bias is estimated by the standard deviation of these differences S_d .

1.11 Limits of Agreement

A third element of the Bland-Altman approach, an interval known as ‘limits of agreement’ is introduced in ? (sometimes referred to in literature as 95% limits of agreement). Limits of agreement are used to assess whether the two methods of measurement can be used interchangeably. ? refer to this as the ‘equivalence’ of two measurement methods. The specific question to which limits of agreement are intended as the answer to must be established clearly. ? comment that the limits of agreement show ‘how far apart measurements by the two methods were likely to be for most individuals’, a definition echoed in their 1999 paper:

“We can then say that nearly all pairs of measurements by the two methods will be closer together than these extreme values, which we call 95% limits of agreement. These values define the range within which most differences between measurements by the two methods will lie.”

The limits of agreement (LoA) are computed by the following formula:

$$LoA = \bar{d} \pm 1.96s_d$$

with \bar{d} as the estimate of the inter method bias, s_d as the standard deviation of the differences and 1.96 (sometimes rounded to 2) is the 95% quantile for the standard

normal distribution. The limits of agreement methodology assumes a constant level of bias throughout the range of measurements. Importantly the authors recommend prior determination of what would constitute acceptable agreement, and that sample sizes should be predetermined to give an accurate conclusion. However ? highlight inadequacies in the correct application of limits of agreement, resulting in contradictory estimates of limits of agreement in various papers.

For the Grubbs ‘F vs C’ comparison, these limits of agreement are calculated as -0.132 for the upper bound, and -1.08 for the lower bound. Figure 1.9 shows the resultant Bland-Altman plot, with the limits of agreement shown in dashed lines.

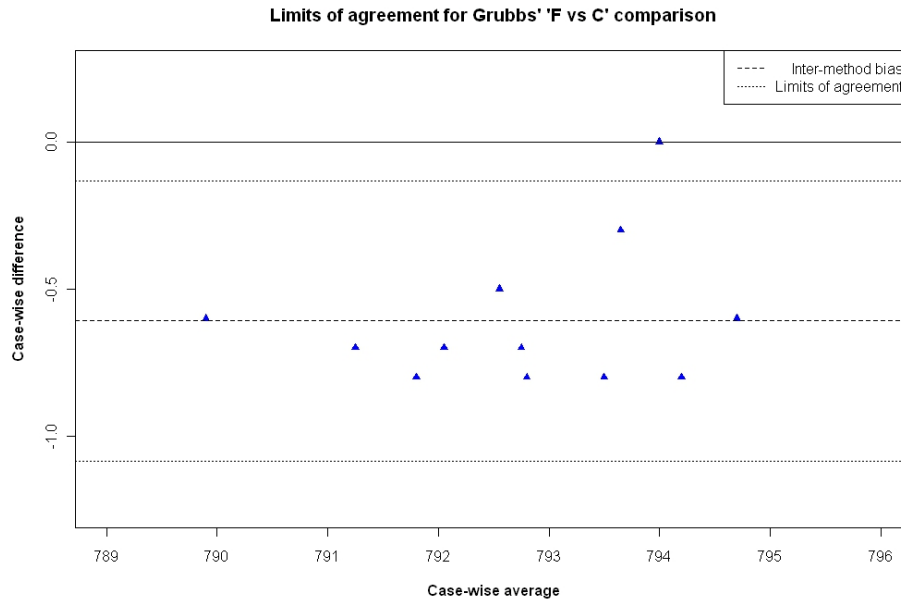


Figure 1.11.8: Bland-Altman plot with limits of agreement

1.12 Limits Of Agreement

Bland and Altman proposed a pair of Limits of agreement. These limits are intended to demonstrate the range in which 95% of the sample data should lie. The Limits

of agreement centre on the average difference line and are 1.96 times the standard deviation above and below the average difference line.

How this relates the overall population is unclear. It seems that it depends on an expert to decide whether or not the range of differences is acceptable. In a study A Bland-Altman plots compare two assay methods. It plots the difference between the two measurements on the Y axis, and the average of the two measurements on the X axis.

The bias is computed as the average of the difference of paired assays.

If one method is sometimes higher, and sometimes the other method is higher, the average of the differences will be close to zero. If it is not close to zero, this indicates that the two assay methods are producing different results systematically.

1.13 Appropriate Use of Limits of Agreement

Importantly ? makes the following point:

These estimates are meaningful only if we can assume bias and variability are uniform throughout the range of measurement, assumptions which can be checked graphically.

The import of this statement is that , should the Bland Altman plot indicate that these assumptions are not met, then their entire methodology, as posited thus far, is inappropriate for use in a method comparison study. Again, in the context of potential outlier in the Grubbs data (figure 1.2), this raises the question on how to correctly continue.

Carstensen attends to the issue of repeated data, using the expression replicate to express a repeated measurement on a subject by the same methods. Carstensen formulates the data as follows Repeated measurement - Arrangement of data into groups, based on the series of results of each subject.

1.14 Formal definition of limits of agreement

? note the similarity of limits of agreement to confidence intervals, but are clear that they are not the same thing. Interestingly, they describe the limits as ‘being like a reference interval’.

Limits of agreement have very similar construction to Shewhart control limits. The Shewhart chart is a well known graphical methodology used in statistical process control. Consequently there is potential for misinterpreting the limits of agreement as they were Shewhart control limits.

? regards the limits of agreement as a prediction interval for the difference between future measurements with the two methods on a new individual, but states that it does not fit the formal definition of a prediction interval, since the definition does not consider the errors in estimation of the parameters. Prediction intervals, which are often used in regression analysis, are estimates of an interval in which future observations will fall, with a certain probability, given what has already been observed. ? offers an alternative formulation, a 95% prediction interval for the difference

$$\bar{d} \pm t_{(0.025, n-1)} s_d \sqrt{1 + \frac{1}{n}}$$

where n is the number of subjects. Carstensen is careful to consider the effect of the sample size on the interval width, adding that only for 61 or more subjects is the quantile less than 2.

? offers an alternative description of limits of agreement, this time as tolerance limits. A tolerance interval for a measured quantity is the interval in which a specified fraction of the population’s values lie, with a specified level of confidence. ? describes them as a probability interval, and offers a clear description of how they should be used; ‘if the absolute limit is less than an acceptable difference d_0 , then the agreement between the two methods is deemed satisfactory’.

The prevalence of contradictory definitions of what limits of agreement strictly are will inevitably attenuate the poor standard of reporting using limits of agreement, as mentioned by ?.

1.15 Inferences on Bland-Altman estimates

? advises on how to calculate confidence intervals for the inter-method bias and limits of agreement. For the inter-method bias, the confidence interval is simply that of a mean: $\bar{d} \pm t_{(\alpha/2, n-1)} S_d / \sqrt{n}$. The confidence intervals and standard error for the limits of agreement follow from the variance of the limits of agreement, which is shown to be

$$\text{Var}(LoA) = \left(\frac{1}{n} + \frac{1.96^2}{2(n-1)} \right) s_d^2.$$

If n is sufficiently large this can be following approximation can be used

$$\text{Var}(LoA) \approx 1.71^2 \frac{s_d^2}{n}.$$

Consequently the standard errors of both limits can be approximated as 1.71 times the standard error of the differences.

A 95% confidence interval can be determined, by means of the t distribution with $n-1$ degrees of freedom. However, ? comment that such calculations may be ‘somewhat optimistic’ on account of the associated assumptions not being realized.

1.16 Adverse features

Estimates for inter-method bias and variance of differences are only meaningful if there is uniform inter-bias and variability throughout the range of measurements. Fulfilment of these assumptions can be checked by visual inspection of the plot. The prototype Bland-Altman plots depicted in Figures 1.4, 1.5 and 1.6 are derived from simulated data, for the purpose of demonstrating how the plot would inform an analyst of features that would adversely affect use of the recommended methodology.

Figure 1.4 demonstrates how the Bland-Altman plot would indicate increasing variance of differences over the measurement range. Fitted regression lines, for both the upper and lower half of the plot, has been added to indicate the trend. Figure 1.5 is an example of cases where the inter-method bias changes over the measurement range.

This is known as proportional bias, and is defined by ? as meaning that ‘one method gives values that are higher (or lower) than those from the other by an amount that is proportional to the level of the measured variable’. In both Figures 1.4 and 1.5, the assumptions necessary for further analysis using the limits of agreement are violated.

Application of regression techniques to the Bland-Altman plot, and subsequent formal testing for the constant variability of differences is informative. The data set may be divided into two subsets, containing the observations wherein the difference values are less than and greater than the inter-method bias respectively. For both of these fits, hypothesis tests for the respective slopes can be performed. While both tests can be considered separately, multiple comparison procedures, such as the Benjamini-Hochberg (?) test, should be also be used.

1.17 Outliers

The Bland-Altman plot also can be used to identify outliers. An outlier is an observation that is conspicuously different from the rest of the data that it arouses suspicion that it occurs due to a mechanism, or conditions, different to that of the rest of the observations. ? do not recommend excluding outliers from analyzes, but remark that recalculation of the inter-method bias estimate, and further calculations based upon that estimate, are useful for assessing the influence of outliers. The authors remark that ‘we usually find that this method of analysis is not too sensitive to one or two large outlying differences’. Figure 1.6 demonstrates how the Bland-Altman plot can be used to visually inspect the presence of potential outliers.

As a complement to the Bland-Altman plot, ? proposes the use of a bivariate confidence ellipse, constructed for a predetermined level. ? provides the relevant calculations for the ellipse. This ellipse is intended as a visual guidelines for the scatter plot, for detecting outliers and to assess the within- and between-subject variances.

The minor axis relates to the between subject variability, whereas the major axis relates to the error mean square, with the ellipse depicting the size of both relative to each other. Consequently Bartko’s ellipse provides a visual aid to determining the relationship between variances. If $\text{var}(a)$ is greater than $\text{var}(d)$, the orientation of the ellipse is horizontal. Conversely if $\text{var}(a)$ is less than $\text{var}(d)$, the orientation of the ellipse is vertical.

The Bland-Altman plot for the Grubbs data, complemented by Bartko’s ellipse, is depicted in Figure 1.7. The fourth observation is shown to be outside the bounds of the ellipse, indicating that it is a potential outlier.

The limitations of using bivariate approaches to outlier detection in the Bland-Altman plot can demonstrated using Bartko’s ellipse. A covariate is added to the ‘F vs C’ comparison that has a difference value equal to the inter-method bias, and an average value that markedly deviates from the rest of the average values in the comparison, i.e. 786. Table 1.8 depicts a 95% confidence ellipse for this manipulated

data set. By inspection of the confidence interval, a conclusion would be reached that this extra covariate is an outlier, in spite of the fact that this observation is wholly consistent with the conclusion of the Bland-Altman plot.

Importantly, outlier classification must be informed by the logic of the data's formulation. In the Bland-Altman plot, the horizontal displacement of any observation is supported by two independent measurements. Any observation should not be considered an outlier on the basis of a noticeable horizontal displacement from the main cluster, as in the case with the extra covariate. Conversely, the fourth observation, from the original data set, should be considered an outlier, as it has a noticeable vertical displacement from the rest of the observations.

In classifying whether a observation from a univariate data set is an outlier, many formal tests are available, such as the Grubbs test for outliers. In assessing whether a covariate in a Bland-Altman plot is an outlier, this test is useful when applied to the case-wise difference values treated as a univariate data set. The null hypothesis of the Grubbs test procedure is the absence of any outliers in the data set. Conversely, the alternative hypotheses is that there is at least one outlier present.

The test statistic for the Grubbs test (G) is the largest absolute deviation from the sample mean divided by the standard deviation of the differences,

$$G = \max_{i=1,\dots,n} \frac{|d_i - \bar{d}|}{S_d}.$$

For the 'F vs C' comparison it is the fourth observation gives rise to the test statistic, $G = 3.64$. The critical value is calculated using Student's t distribution and the sample size,

$$U = \frac{n-1}{\sqrt{n}} \sqrt{\frac{t_{\alpha/(2n), n-2}^2}{n-2 + t_{\alpha/(2n), n-2}^2}}.$$

For this test $U = 0.75$. The conclusion of this test is that the fourth observation in the 'F vs C' comparison is an outlier, with p -value = 0.003, according with the previous result using Bartko's ellipse.

1.18 Adverse features

Estimates for inter-method bias and variance of differences are only meaningful if there is uniform inter-bias and variability throughout the range of measurements. Fulfilment of these assumptions can be checked by visual inspection of the plot. The prototype Bland-Altman plots depicted in Figures 1.4, 1.5 and 1.6 are derived from simulated data, for the purpose of demonstrating how the plot would inform an analyst of features that would adversely affect use of the recommended approach.

Figure 1.4 demonstrates how the Bland-Altman plot would indicate increasing variance of differences over the measurement range. Fitted regression lines, for both the upper and lower half of the plot, has been added to indicate the trend. Figure 1.5 is an example of cases where the inter-method bias changes over the measurement range. This is known as proportional bias, and is defined by ? as meaning that ‘one method gives values that are higher (or lower) than those from the other by an amount that is proportional to the level of the measured variable’. In both Figures 1.4 and 1.5, the assumptions necessary for further analysis using the limits of agreement are violated.

Application of regression techniques to the Bland-Altman plot, and subsequent formal testing for the constant variability of differences is informative. The data set may be divided into two subsets, containing the observations wherein the difference values are less than and greater than the inter-method bias respectively. For both of these fits, hypothesis tests for the respective slopes can be performed. While both tests could be considered separately, multiple comparison procedures, such as the Benjamini-Hochberg (?) test, are advisable.

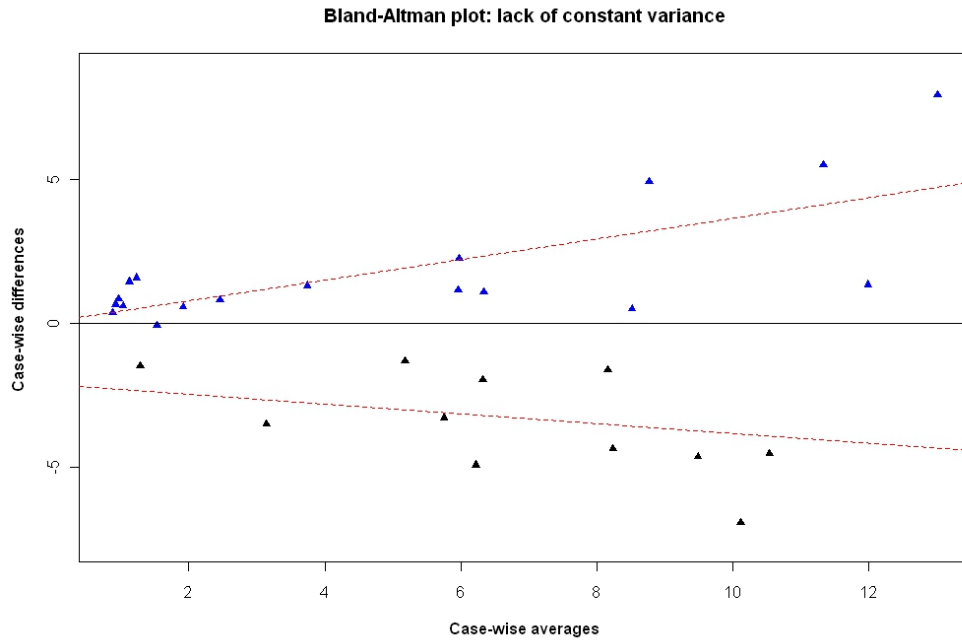


Figure 1.18.9: Bland-Altman plot demonstrating the increase of variance over the range.

The Bland-Altman plot also can be used to identify outliers. An outlier is an observation that is conspicuously different from the rest of the data that it arouses suspicion that it occurs due to a mechanism, or conditions, different to that of the rest of the observations. ? do not recommend excluding outliers from analyses, but remark that recalculation of the inter-method bias estimate, and further calculations based upon that estimate, are useful for assessing the influence of outliers. The authors remark that ‘we usually find that this method of analysis is not too sensitive to one or two large outlying differences’. Figure 1.6 demonstrates how the Bland-Altman plot can be used to visually inspect the presence of potential outliers.

As a complement to the Bland-Altman plot, ? proposes the use of a bivariate confidence ellipse, constructed for a predetermined level. ? provides the relevant calculations for the ellipse. This ellipse is intended as a visual guidelines for the scatter plot, for detecting outliers and to assess the within- and between-subject variances.

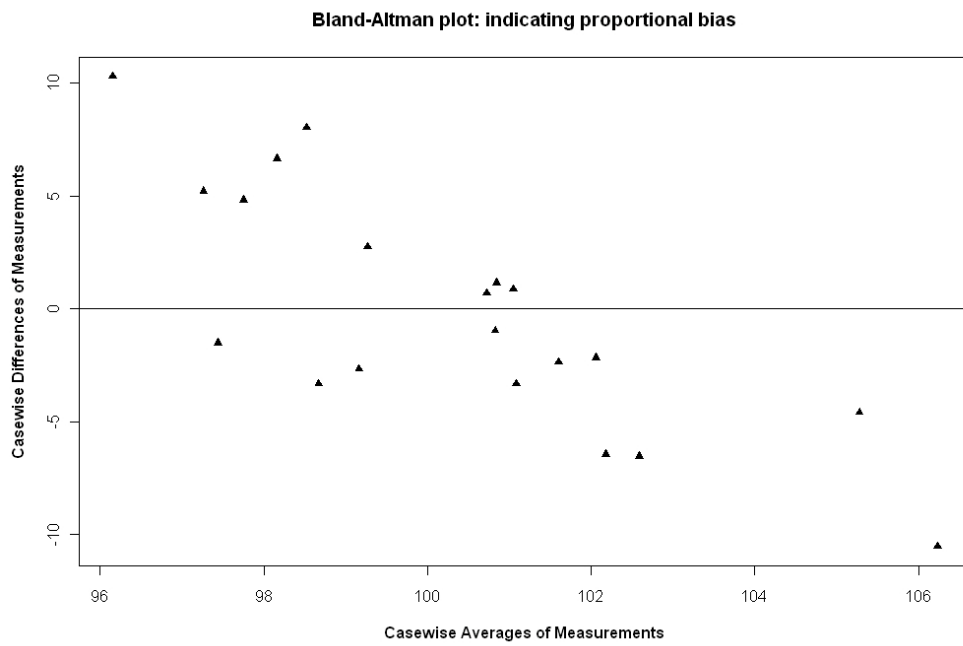


Figure 1.18.10: Bland-Altman plot indicating the presence of proportional bias.

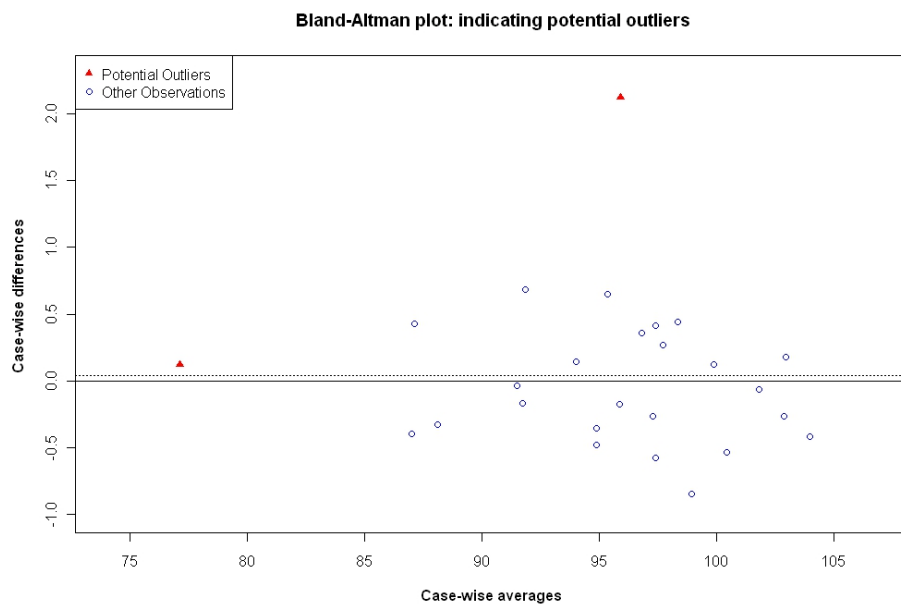


Figure 1.18.11: Bland-Altman plot indicating the presence of potential outliers.

The minor axis relates to the between subject variability, whereas the major axis relates to the error mean square, with the ellipse depicting the size of both relative to each other. Consequently Bartko's ellipse provides a visual aid to determining the relationship between variances. If $\text{var}(a)$ is greater than $\text{var}(d)$, the orientation of the ellipse is horizontal. Conversely if $\text{var}(a)$ is less than $\text{var}(d)$, the orientation of the ellipse is vertical.

The Bland-Altman plot for the Grubbs data, complemented by Bartko's ellipse, is depicted in Figure 1.7. The fourth observation is shown to be outside the bounds of the ellipse, indicating that it is a potential outlier.

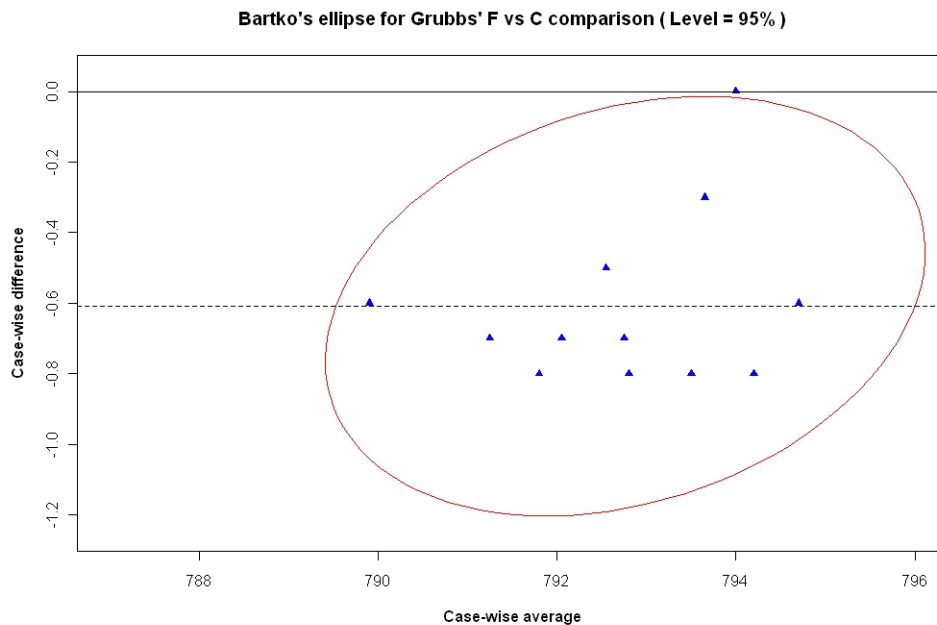


Figure 1.18.12: Bartko's Ellipse for Grubbs' data.

The limitations of using bivariate approaches to outlier detection in the Bland-Altman plot can be demonstrated using Bartko's ellipse. A covariate is added to the 'F vs C' comparison that has a difference value equal to the inter-method bias, and an average value that markedly deviates from the rest of the average values in the comparison, i.e. 786. Table 1.8 depicts a 95% confidence ellipse for this manipulated data set. By inspection of the confidence interval, we would conclude that this extra

covariate is an outlier, in spite of the fact that this observation is very close to the inter-method bias as determined by this approach.

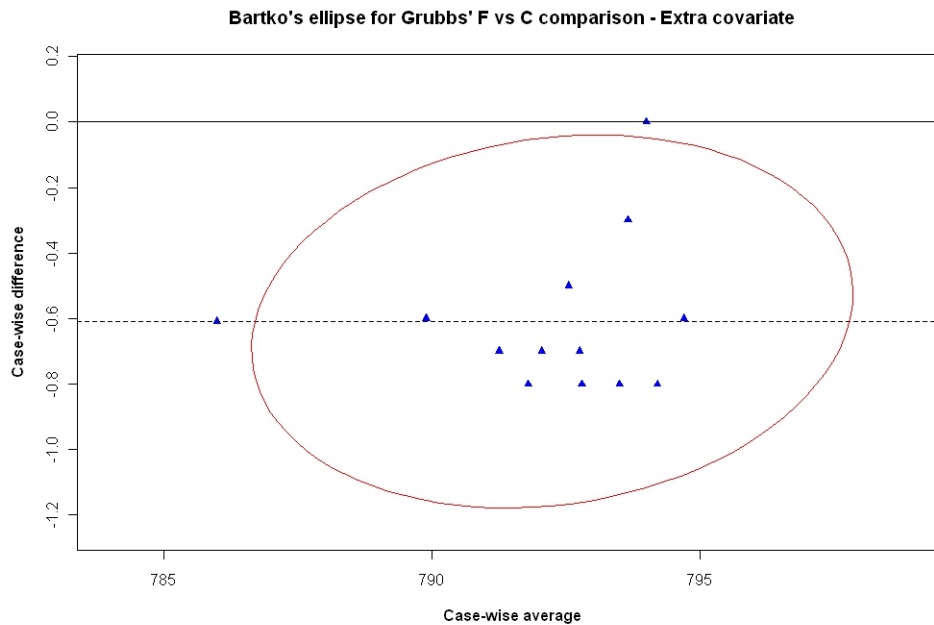


Figure 1.18.13: Bartko's Ellipse for Grubbs' data, with an extra covariate.

Importantly, outlier classification must be informed by the logic of the mechanism that produces the data. In the Bland-Altman plot, the horizontal displacement (i.e. the average) of any observation is supported by two separate measurements. Any observation should not be considered an outlier on the basis of a noticeable horizontal displacement from the main cluster, as in the case with the extra covariate. Conversely, the fourth observation, from the original data set, should be considered an outlier, as it has a noticeable vertical displacement from the rest of the observations.

In classifying whether a observation from a univariate data set is an outlier, many formal tests are available, such as the Grubbs test for outliers. In assessing whether a covariate in a Bland-Altman plot is an outlier, this test is useful when applied to the case-wise difference values treated as a univariate data set. The null hypothesis of the Grubbs test procedure is the absence of any outliers in the data set. Conversely, the alternative hypotheses is that there is at least one outlier present.

The test statistic for the Grubbs test (G) is the largest absolute deviation from the sample mean divided by the standard deviation of the differences,

$$G = \max_{i=1,\dots,n} \frac{|d_i - \bar{d}|}{S_d}. \quad (1.1)$$

For the ‘F vs C’ comparison it is the fourth observation gives rise to the test statistic, $G = 3.64$. The critical value is calculated using Student’s t distribution and the sample size,

$$U = \frac{n-1}{\sqrt{n}} \sqrt{\frac{t_{\alpha/(2n),n-2}^2}{n-2+t_{\alpha/(2n),n-2}^2}}.$$

For this test $U = 0.75$. The conclusion of this test is that the fourth observation in the ‘F vs C’ comparison is an outlier, with p -value = 0.003, in accordance with the previous result of Bartko’s ellipse.

1.19 Agreement

Bland and Altman (1986) defined perfect agreement as the case where all of the pairs of rater data lie along the line of equality, where the line of equality is defined as the 45 degree line passing through the origin(i.e. the $X = Y$ line).

Bland and Altman (1986)expressed this in the terms *we want to know by how much the new method is likely to differ from the old; if this is not enough to cause problems in clinical interpretation we can replace the old method by the new or use the two interchangeably. How far apart measurements can be without causing difficulties will be a question of judgment. Ideally, it should be defined in advance to help in the interpretation of the method comparison and to choose the sample size .*

1.20 scatter plots

The authors advise the use of scatter plots to identify outliers, and to determine if there is curvilinearity present. In the region of linearity ,simple linear regression may yield results of interest.

1.21 Effect of Outliers

Another argument against the use of model I regression is based on outliers. Outliers can adversely influence the fitting of a regression model. Cornbleet and Cochrane compare a regression model influenced by an outlier with a model for the same data set, with the outlier excluded from the data set. A demonstration of the effect of outliers was made in Bland Altman's 1986 paper. However they discourage the exclusion of outliers.

1.22 Precision of Limits of Agreement

The limits of agreement are estimates derived from the sample studied, and will differ from values relevant to the whole population. A different sample would give different limits of agreement. ? advance a formulation for confidence intervals of the inter-method bias and the limits of agreement. These calculations employ quantiles of the 't' distribution with $n - 1$ degrees of freedom.

1.23 Variations of the Bland-Altman Plot

Referring to the assumption that bias and variability are constant across the range of measurements, ? address the case where there is an increase in variability as the magnitude increases. They remark that it is possible to ignore the issue altogether, but the limits of agreement would wider apart than necessary when just lower magnitude measurements are considered. Conversely the limits would be too narrow should only higher magnitude measurements be used. To address the issue, they propose the logarithmic transformation of the data. The plot is then formulated as the difference of paired log values against their mean. Bland and Altman acknowledge that this is not easy to interpret, and may not be suitable in all cases.

? offers two variations of the Bland-Altman plot that are intended to overcome potential problems that the conventional plot would be inappropriate for. The first variation is a plot of case-wise differences as percentage of averages, and is appropriate when there is an increase in variability of the differences as the magnitude increases. The second variation is a plot of case-wise ratios as percentage of averages. This will remove the need for *log* transformation. This approach is useful when there is an increase in variability of the differences as the magnitude of the measurement increases. ? proposed such a ratio plot, independently of Bland and Altman. ? commented on the reception of this article by saying ‘Strange to say, this report has been overlooked’.

1.24 The Bland Altman Plot - Variations

Variations of the Bland Altman plot is the use of ratios, in the place of differences.

$$D_i = X_i - Y_i \quad (1.2)$$

Altman and Bland suggest plotting the within subject differences $D = X_1 - X_2$ on the ordinate versus the average of x_1 and x_2 on the abscissa.

1.25 Variations and Alternative Graphical Methods

In this section, we will look at some variations and enhancements of the Bland-Altman plot, as well as some alternative graphical techniques. Strictly speaking, the Identity Plot is advised by Bland and Altman as a prior analysis to the Bland-Altman plot, and therefore is neither a variant nor an alternative approach. However it is worth mentioning, as it is a simple, powerful and elegant technique that is often overlooked in method comparison studies. The identity plot is a simple scatter-plot approach of measurements for both methods on either axis, with the line of equality (the $X = Y$ line, i.e. the 45 degree line through the origin). This plot can give the analyst a

cursory examination of how well the measurement methods agree. In the case of good agreement, the covariates of the plot accord closely with the line of equality.

1.26 Variants of the Bland-Altman Plot

In light of some potential pitfalls associated with the conventional difference plot, a series of alternative formulations for the Bland-Altman approach have been proposed.

Referring to the assumption that bias and variability are constant across the range of measurements, ? address the case where there is an increase in variability as the magnitude increases. They remark that it is possible to ignore the issue altogether, but the limits of agreement would be wider apart than necessary when just lower magnitude measurements are considered. Conversely the limits would be too narrow should only higher magnitude measurements be used. To address the issue, they propose the logarithmic transformation of the data. The plot is then formulated as the difference of paired log values against their mean. Bland and Altman acknowledge that this is not easy to interpret, and may not be suitable in all cases.

1.27 Prevalence of the Bland-Altman plot

?, which further develops the Bland-Altman methodology, was found to be the sixth most cited paper of all time by the ?. ? describes the rate at which prevalence of the Bland-Altman plot has developed in scientific literature. ? reviewed the use of Bland-Altman plots by examining all articles in the journal ‘Clinical Chemistry’ between 1995 and 2001. This study concluded that use of the Bland-Altman plot increased over the years, from 8% in 1995 to 14% in 1996, and 31-36% in 2002.

The Bland-Altman Plot has since become expected, and often obligatory, approach for presenting method comparison studies in many scientific journals (?). Furthermore ? recommend its use in papers pertaining to method comparison studies for the journal of the British Hypertension Society.

1.28 Bland Altman Plots In Literature

? contains a study the use of Bland Altman plots of 44 articles in several named journals over a two year period. 42 articles used Bland Altman's limits of agreement, wit the other two used correlation and regression analyses. ? remarks that 3 papers, from 42 mention predefined maximum width for limits of agreement which would not impair medical care.

The conclusion of ? is that there are several inadequacies and inconsistencies in the reporting of results ,and that more standardization in the use of Bland Altman plots is required. The authors recommend the prior determination of limits of agreement before the study is carried out. This contention is endorsed by ?, which makes a similar recommendation for the sample size, noting that *sample sizes required either was not mentioned or no rationale for its choice was given.*

In order to avoid the appearance of "data dredging", both the sample size and the (limits of agreement) should be specified and justified before the actual conduct of the trial. (?)

? remarks that the limits of agreement should be compared to a clinically acceptable difference in measurements.

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? remarks that the limits of agreement should be compared to a clinically acceptable difference in measurements.

1.30 Bartko's Ellipse

As an enhancement on the Bland Altman Plot, ? has expounded a confidence ellipse for the covariates. ? proposes a bivariate confidence ellipse as a boundary for dispersion. The stated purpose is to 'amplify dispersion', which presumably is for the purposes of outlier detection. The orientation of the the ellipse is key to interpreting the results. The minor axis is related to the between-item variability whereas the major axis is related to the mean squared error (referred to here as Error Mean Square). The ellipse illustrates the size of both relative to each other.

Consequently Bartko's ellipse provides a visual aid to determining the relationship between variances. Furthermore, the ellipse provides a visual aid to determining the relationship between the variance of the means $Var(a_i)$ and the variance of the differences $Var(d_i)$. If $var(a)$ is greater than $var(d)$, the orientation of the ellipse is horizontal. Conversely if $var(a)$ is less than $var(d)$, the orientation of the ellipse is vertical. The more horizontal the ellipse, the greater the degree of agreement between the two methods being tested.

Bartko states that the ellipse can, inter alia, be used to detect the presence of outliers (furthermore ? proposes formal testing procedures, that shall be discussed in

due course). The Bland-Altman plot for the Grubbs data, complemented by Bartko's ellipse, is depicted in Figure 1.30.14. The fourth observation is shown to be outside the bounds of the ellipse, indicating that it is a potential outlier.

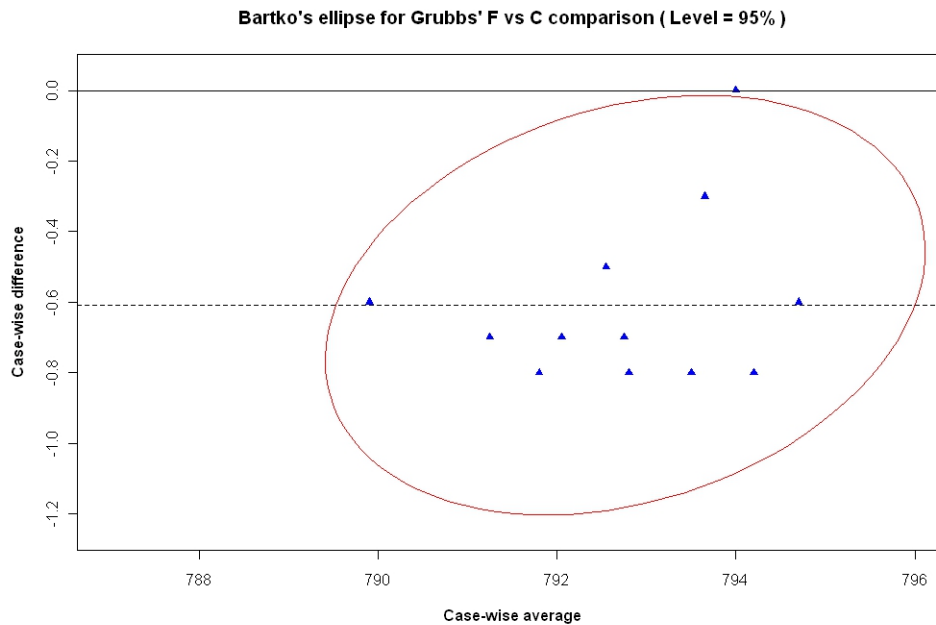


Figure 1.30.14: Bartko's Ellipse For Grubbs' Data.

The limitations of using bivariate approaches to outlier detection in the Bland-Altman plot can be demonstrated using Bartko's ellipse. A covariate is added to the 'F vs C' comparison that has a difference value equal to the inter-method bias, and an average value that markedly deviates from the rest of the average values in the comparison, i.e. 786. Table 1.8 depicts a 95% confidence ellipse for this manipulated data set. By inspection of the confidence interval, a conclusion would be reached that this extra covariate is an outlier, in spite of the fact that this observation is wholly consistent with the conclusion of the Bland-Altman plot.

Importantly, outlier classification must be informed by the logic of the data's formulation. In the Bland-Altman plot, the horizontal displacement of any observation is supported by two independent measurements. Any observation should not be considered an outlier on the basis of a noticeable horizontal displacement from the main

cluster, as in the case with the extra covariate. Conversely, the fourth observation, from the original data set, should be considered an outlier, as it has a noticeable vertical displacement from the rest of the observations.

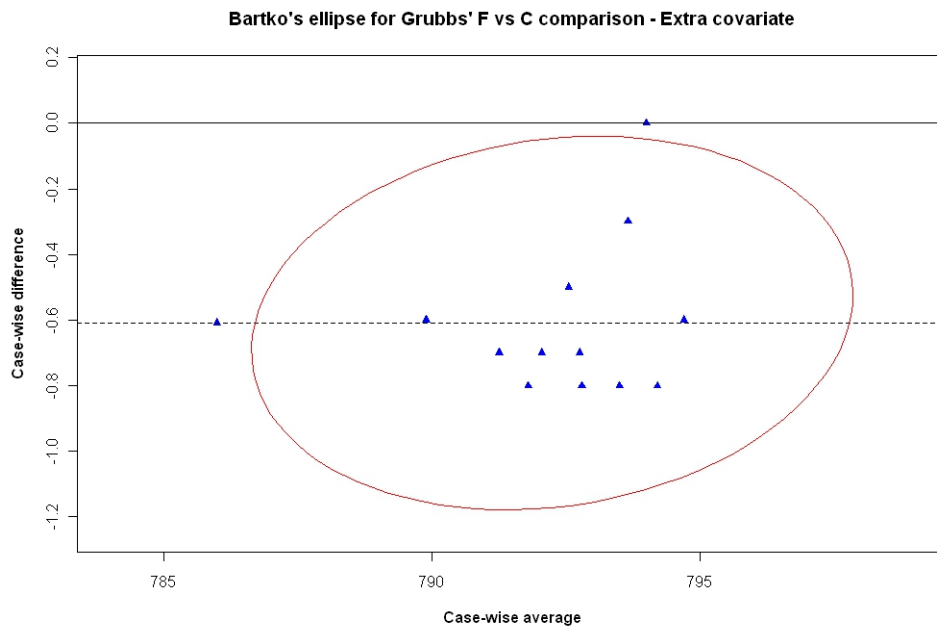


Figure 1.30.15: Bartko's Ellipse For Grubbs' Data, with an extra covariate.

In the Bland-Altman plot, the horizontal displacement of any point on the plot is supported by two independent measurements. Any point should not be considered an outlier on the basis of a noticeable horizontal displacement from the main cluster, as in the case with the extra co-variate. Conversely, the fourth point, from the original data set, should be considered an outlier, as it has a noticeable vertical displacement from the rest of the observations.