MASTER-THESIS

Correcting for Measurement Error of Tracking Cardiovascular Risk Factors in Meta-analysis

by

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Abstract

Hypertension and obesity are the acknowledged risk factors of coronary heart disease and cardiovascular diseases. To prevent hypertension or obesity, it is beneficial to identify “prehypertensives” earlier in life and to control the body mass in long term. Therefore, tracking of blood pressure (BP) and body mass index (BMI) appears to be paramount. However, the measurement errors are often not taken into account when the effects of tracking are estimated and conclusions are drawn. In our study, the classical additive measurement error model is used to analyze the measurement error in measuring blood pressure, height and weight. Moreover, reliability is a useful measure to quantify the amount of error in measurement and to correct the attenuation effect of correlation coefficients. The purpose of this study is to correct measurement errors in tracking the two cardiovascular risk factors - blood pressure and BMI in meta-analysis. Due to the absence of the necessary reliability information in each primary study, the issue of corrections for measurement error in meta-analysis becomes more complicated. To reach the purpose, the reliability is estimated by gathering of data from other studies: the reliability coefficient of BP measurement is estimated by assessing two components, between-visit and within-visit variation; and the reliability of BMI is derived from its components, height and weight. The reliability of BMI is much higher than that of BP. Comparing the tracking effects before and after correction of measurement errors, the corrected tracking correlations of blood pressure from childhood to manhood rise substantially, whereas, there are no obvious improvements for tracking effect of BMI.

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Chapter 1

Introduction

As growing evidence indicates, high blood pressure (BP) is the major known contributor to cardiovascular morbidity and mortality[1]. Furthermore, effective medical treatment of hypertension can reduce risk of stroke and coronary heart disease. Thus, it may be desirable to increase emphasis on detecting and treating hypertensives. A couple of studies also show that strategies for prevention of pre-hypertension or hypertension and its sequelae have included attempts to identify children at future high risk[2, 3]. Thus, it might be even more beneficial to identify "prehypertensives" earlier in life and more attention has focused on the feasibility of identifying such children and adolescents[4]. The capacity to evaluate the predictive value of blood pressures for future levels may be estimated by the tracking correlation, which is defined as the correlation between an initial and subsequent blood pressure readings on the same person and is used to quantify the association between blood pressure levels at two different times[5]. The term "Tracking" has been widely used to reflect the degree to which the readings of individuals maintain their ranking relative to their peers over time. Most previous studies have demonstrated positive tracing correlation of low magnitude for BP measurements. These published values, however, were possible underestimates of true tracking correlations because the variability of blood pressure readings had not been considered. The variability of BP measurements that included the extrinsic variability and inherent variability provided the information to determine a person's true BP status. Therefore, it is important to analyze the source and nature of errors in measurement of blood pressure and to evaluate the reliability of casual measurements. The magnitude of the reliability depends on the variance components of blood pressure, which consist of between-person and within-person variability. One clinically relevant way is to divide this within-person variability into between-visit component and within-visit component. Between-visit variability appears to be larger than within-visit variability. Any attempt to correct tracking correlations for within-person variability, therefore, must consider the effect of between-visit variance component.

In addition, numerous studies indicate that body mass index (BMI) is one of the most important anthropometric measurements in the assessment linking physical activity and fitness with reduction in the incidence of cardiovascular disease, obesity, and mortality[6]. The body mass index is defined as weight (kg) divided by the square of height (m), where body weight is in kilograms and height is in meters, thus both components body mass and stature should be taken into account in assessment of error in measurement of BMI. The BMIs have the potential to help physicians in their assessment of their patients' obesity-related cardiovascular risk and are also believed to be easy to perform. One of the attractive features of BMI is that it is derived from measurements of height and weight. These two anthropometric dimensions are the ones most commonly and simply collected worldwide. Moreover, they are noninvasive, relatively inexpensive to obtain, and easily understood by health practitioners and individuals being measured. As with any use of quantitative biological measure, it is important to minimize error, and to know and understand the various ways in which is estimated and assessed. One potentially important source of variability in BMI that could affect tracking is within-individual variation. It consists of two sources of error: imprecision and short-term physiological fluctuations. Reliability is commonly defined operationally as the extent to which a measurement is reproducible over time. If the reliability of health status indicator is poor, no matter how valid the indicator is thought to be, its usefulness for epidemiologic purposed is limited.

However, corrections for measurement error in meta-analysis become more complicated owing to the limitation of the data. Often the reliability information which is necessary to correct each tracking correlation is not presented in most of the primary studies. Researchers have to select appropriated reliability from other previously published studies or estimate them based on additional data under similar circumstance.

The purpose of this study is to correct measurement errors in tracking cardiovascular risk factors - blood pressure and BMI in meta-analysis. To reach the purpose, the appropriate reliability coefficients of BP measurement are estimated by assessing two components, between-visit and within-visit variation, and the reliability of BMI can be derived from its components, height and weight. The optimal time interval between examinations should reflect both measuring errors and short-term physiological fluctuations upon measurement errors. The present thesis is mainly organized as follows: Chapter 2 gives some basic insights in measurement error and its impact on the tracking correlations. Chapter 3 presents methods for correcting measurement error of tracking correlation in meta-analysis. Chapter 4 and Chapter 5 describes detailedly the models of estimating reliability and the procedures of correcting measurement error in tracking BP and BMI measurements, respectively. Moreover, the meta-data extracted from Toschke *et al.* would be utilized as practical study to compare the results before and after correction of measurement errors, because the measurement errors of casual BP measurements and BMI were not taken into account when they analyzed data and came to a conclusion. All calculations were performed with the program R. In addition, the back cover is accompanied by a CD containing the R-Code.

Chapter 2

Basic Theories of Measurement Error

2.1 Types of Measurement Error

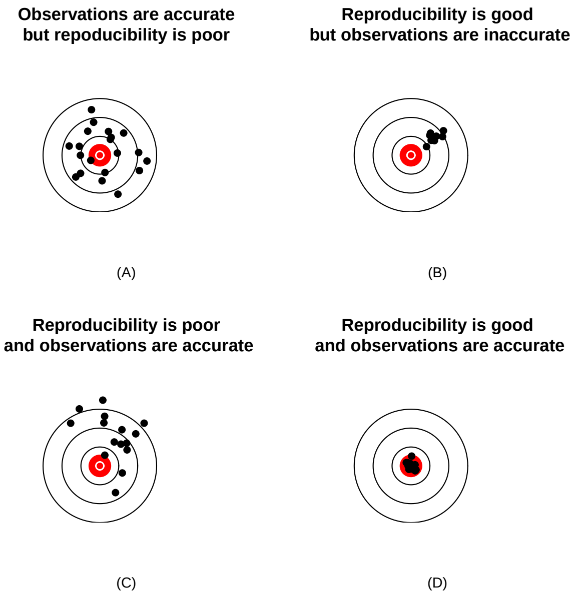
Various terms are used to describe measurement error, such as unreliability, imprecision, undependability and inaccuracy, as well as reproducibility and bias. Despite the varied terminology, measurement error has two predominant types of effect on the quality of the data collected. They are accuracy and reproducibility (Figure 2.1), which are quite different, yet the terms are sometimes confused.

(1) Accuracy

Accuracy is the extent to which the ‘true’ value of a measurement is attained. This is a measure of the closeness of observations to the target measurement. D’ Agostini[7] made the definition of “true value” as “*the value obtained after an infinite series of measurements performed under the same conditions with an instrument not affected by systematic errors*”. But he also indicated that the International Organization for Standardization (ISO)[8] definition “*true value is a value compatible with the definition of a given particular quantity*” was more practical and pragmatic, because it holds causes in which it makes no sense to speak about repeated measurements under the same conditions. Inaccuracy is systematic bias, and may be due to instrument error, or to errors of measurement technique. Hence, a well-calibrated equipment used by an experienced and well-trained anthropometrist can to great extent avoid inaccuracy. However, in most cases the ’true’ values of measurements are impossible to determine. With an accurate instrument, the mean of a large number of observations would hit the target, irrespective of the size of their spread, provided the error is random (Figure 2.1 (A)).

(2) Reproducibility (precision)

Reproducibility is that repeated measures give the same value. In the real world, repeat measurements on the same individual often differ. Such difference is due to those two main factors: imprecision and physiological variation. Imprecision is the variability of repeated measurements, and is due to intra- and inter- observer measurement differences. The greater the variability between repeated measurements of the same subject by one (intra-observer difference) or two or more (inter-observer difference) observers, the greater the imprecision and the lower the precision[9]. Physiological variation reflects the short-term biological fluctuation, which are generally beyond the control of any observers, such as differences in height of an individual across the day as a consequence of compression of the spinal column. The smaller the physiological variance is, the greater the reproducibility is. Measurements would be reproducible without being accurate, if the variation about their mean was small, but that mean did not coincide with the target value (Figure 2.1 (B)).



Observations are accurate
but repoducibility is poor

(A)

Reproducibility is good
but observations are inaccurate

(B)

Reproducibility is poor
and observations are accurate

(C)

Reproducibility is good
and observations are accurate

(D)

Figure 2.1: Dartboard analogy to illustrate the accuracy and reproducibility (The concept come from Voss *et al.*[10])

2.2 Models for Measurement Error

A fundamental prerequisite for analyzing a measurement error problem is specification of a model for the measurement error process. There are two general types:

- *The classical error model* : $X^* = X + e_x, \qquad (2.1)$

where e_X, the error, is assumed independent of true value X and must have mean zero, in symbols, $\mathrm{E}(e_X|X) = 0$. The classical measurement error model is that the observed value equals the true value plus measurement error. This means that the variability of the observed values will be greater than the variability of true values, namely, $Var(X^*) > Var(X)$.

- *The Berkson error model* : $X = X^* + e_x, \qquad (2.2)$

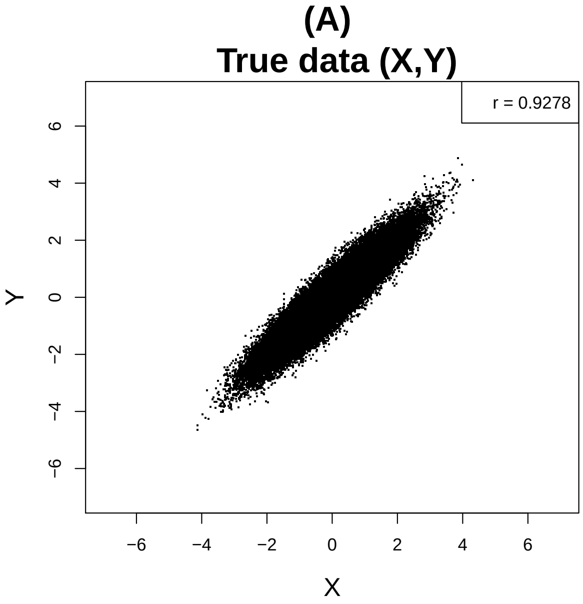
where e_X, the error, is assumed independent of measured X^* and $\mathrm{E}(e_X|X^*) = 0$. In contrast to the classical error model, the Berkson model is assumed that the true value is equal to the measured value plus measurement error, so the true values have more variability than measured values, namely, $Var(X) > Var(X^*)$.

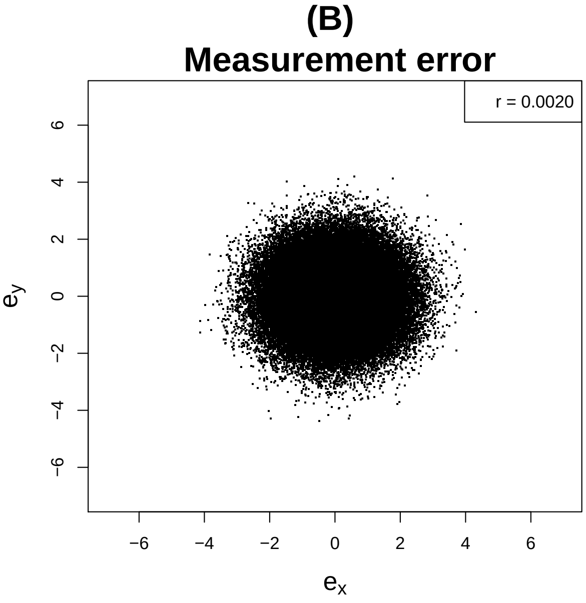
Determining an appropriate error model to use in the data analysis depends upon the circumstances and the available data. If the measured X^* is fixed by design and true value X varies due to error, so then the Berkson model is appropriate. On the other hand, in the study of measurement of blood pressure, it is the true blood pressure that is fixed for an individual, and the measured value that is perturbed by error, so the classical error model should be used. Another difference between Berkson and classical measurement error is attempting power calculations. Carroll *et al.*[11] indicated that for a given measurement error variance, if you want to convince yourself that you have lots of statistical power despite measurement error, just pretend that the measurement error is Berkson and not classical. That is because the smaller variability of true values under the classical model implies that the power for detecting effects will be smaller than if the errors are Berkson. In practice, it should be more careful decide whether data follow the classical error model or the Berkson error model, in respect that an incorrect measurement error model often causes erroneous inferences.

2.3 The Impact of Measurement Error in Tracking Correlation

In Spearman's classic paper of the year 1904 [12], the attenuation of correlations due to measurement errors have been revealed. And many textbooks contain a brief description of measurement error in correlation coefficients, arriving at the conclusion that the effect of measurement error is to bias the correlation estimate in the direction of zero. Bias of this nature is commonly referred to as attenuation. Here, we will through a simulation to illustrate the process of such attenuation effect on tracking correlation.

First of all, we review the theory of error of measurement and the classic classical measurement error model. There is evidence from the foregoing description that the observed value captures true value with added variability. Such situation is often called classical measurement error. For example, let X be the extra measurement of blood pressure from a clinic visit, and let X^* be the observed value, which is equal to the true value X plus some amount of measurement error e_X. Assuming there are no correlations between error and true values in the population, and no correlation between observed values across measures in the population. Now, we carry through a simulation to show the effect of measurement errors on the correlation. First, two highly correlated variables without measurement error X and Y are sampled randomly from normal distribution. And their corresponding measurement error e_X and e_Y are generated randomly also from standard normal distribution, but e_X and e_Y are uncorrelated with each other. The correlation coefficient between variables X and Y is 0.9278, however the correlation coefficient between the variables with measurement error X^* and Y^* is only 0.4821. Figure 2.2 illustrates the above process of attenuation by showing the results of adding random effects of measurement error to correlation of observed measurements.


(A)
True data (X,Y)
r = 0.9278
Y
X
−6
−4
−2
0
2
4
6


(B)
Measurement error
r = 0.0020
e_y
e_x
−6
−4
−2
0
2
4
6

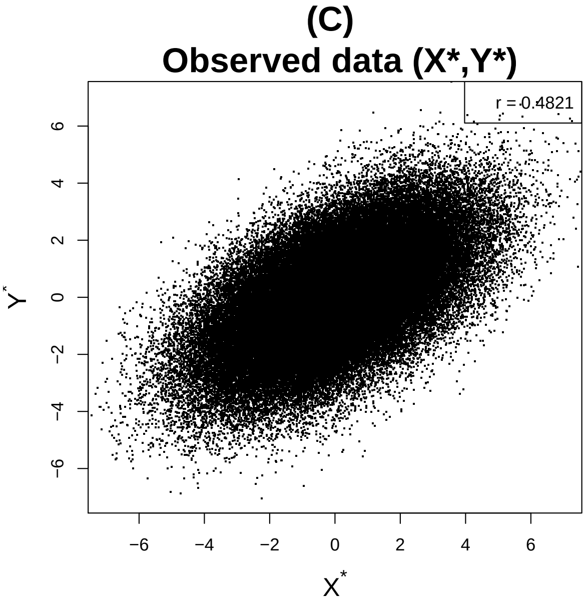


Figure 2.2: Illustration of the process of attenuation.

(A) The correlation from true data (X, Y) is 0.9278
(B) Error in measurement
(C) The correlation from observed data (X^{*}, Y^{*}) is only 0.4821

Here attenuation is obvious visually. That is, error of measurement systematically lowers the correlation between measures in comparison to the correlation between the variables themselves. If no correction is made for attenuation, then the estimated true effect size correlation are not corrected for the effect of measurement errors. These estimates will be inaccurate to the extent that uncorrected errors have a substantial impact on that research domain. Thus, we can obtain true picture of tracking correlation only if we eliminate the effects of measurement error.

Chapter 3

Methods for Correcting Measurement Error of Tracking Correlation in Meta-analysis

When tracking cardiovascular risk factors (i.e. blood pressure and body mass index) results in epidemiological studies, it is necessary to quantify variations and any effect of error on the results of the study. In addition, follow-up studies demand standardization of all measurement circumstances. To correct for the measurement error in meta-analysis, we must have information about the size and nature of the error. Ideally, this information would be given for each study (i.e., each correlation). In that case, each correlation can be corrected individually, and the meta-analysis can be conducted on the corrected correlations. This type of meta-analysis is the subject of this paper. The questions what are some of the sources of measurement error will be answered detailed in Section 4.1. At present we must be foremost confronted with the following questions: How to assess the variability of measurement errors? How to correct them in tracking correlation?

3.1 Basic Concept and Algebraic Expression of Reliability

The amount of error of measurement in a variable is typically quantified in terms of the reliability of the variable. Reliability is commonly defined operationally as the extent to which a measurement is reproducible over time. The statistics of reliability were expounded for behavioral scientists in 1958 by Haggard[13] and have since been the focus of a large literature in the social sciences and related statistics. Fleiss[14] has done a similar service for epidemiologists.

The reliability of measurements can be divided into parts: the precision referring to its freedom from measuring errors (i.e. variability in measuring technique and in instrument) and the short-term random fluctuations that are generally beyond the control of observers. Reliability defined as the ratio of true to observed variance can be expressed as

$$R = \frac{\sigma_X^2}{\sigma_{X^*}^2},$$

where $\sigma_{X^*}^2$ is observed inter-individual variance (with measurement errors) and σ_X^2 is the true inter-individual variance (without measurement errors). The observed inter-individual variance $\sigma_{X^*}^2$ includes the true inter-individual variation σ_X^2 and the intra-individual (or measurement error) variance $\sigma_{e_x}^2$. Then we can also obtain the reliability as following:

$$R = \frac{\sigma_X^2}{\sigma_{X^*}^2} = \frac{\sigma_{X^*}^2 - \sigma_{e_x}^2}{\sigma_{X^*}^2} = 1 - \frac{\sigma_{e_x}^2}{\sigma_{X^*}^2}.$$

In the context of tracking blood pressure, it can be defined as the ratio of variance of individuals' true blood pressures (σ_X^2) to the variance of their pressures with measurement errors ($\sigma_{X^*}^2$). Moreover, the contributions to intra-individual variance occur as a result of measuring errors (imprecision variance) and intra-individual short term fluctuations in a measurement due to physiological factors (biological or physiological variance).

The reliability is a value between 0 and 1 that measures the percentage of the observed variance that is true score variance. Thus, higher reliability indicates that a lesser portion of observed variance is due to errors in measurement. That is, if the reliability of the variable is 0.90, then 90% of the variance in the scores is due to the true score variation, and by subtraction, 10% of the variance is due to variation in errors of measurement.

The most commonly used estimation of measurement error variance $\sigma^2_{e_x}$ in anthropometric measurements (i.e. height and weight) is the technical error of measurement (TEM)[15], which is obtained by carrying out several repeat measurement on the same subject, either by the same observer, or by two or more observer, taking the differences and entering them into an appropriate equation. For intra-observer TEM, and for inter-observer TEM involving two measures, the equation is:

$$TEM = \sqrt{\frac{\sum_{i=1}^{N} d_i^2}{2N}},$$

where d_i^2 is the squared difference between observations taken at two different time on the ith individual, and the sum is make over N subjects. The measurement error variance $\sigma^2_{e_x}$ can be estimated as

$$\widehat{\sigma^2_{e_x}} = \frac{\sum_{i=1}^{N} d_i^2}{2N} = TEM^2.$$

Thus, the coefficient of reliability can be calculated using the equation:

$$R = 1 - \frac{TEM^2}{\sigma^2_{X^*}}.$$

Here, it is necessary to emphasize that we expect to obtain the coefficient of reliability that should reflect both measuring errors (imprecision) as well as physiological fluctuations, therefore, the intra-individual or measurement error variance $\sigma^2_{e_x}$ is supposed to be estimated from repeated measures separated by enough time, because subjects remeasured within minutes or hours usually could only represent the imprecision variation.

3.2 Use Reliability to Correct Measurement Error

The random effects of error of measurement produce a systematic effect on the correlation coefficient. We will present a formula for attenuation that expresses the exact extent to which the tracking correlation is lowered by any given amount of error of measurement. The process has been showed as following:

$$
\begin{aligned}
r_{X^*Y^*} &= \frac{Cov(X^*,Y^*)}{\sqrt{Var(X^*)}\sqrt{Var(Y^*)}} && (3.1)\\
&= \frac{Cov(X+e_X,Y+e_Y)}{\sqrt{Var(X+e_X)}\sqrt{Var(Y+e_Y)}}\\
&= \frac{Cov(X,Y)+Cov(X,e_Y)+Cov(Y,e_X)+Cov(e_X,e_Y)}{\sqrt{Var(X+e_X)}\sqrt{Var(Y+e_Y)}}\\
&= \frac{Cov(X,Y)}{\sqrt{Var(X)}\sqrt{Var(Y)}\sqrt{\frac{Var(X)+Var(e_X)}{Var(X)}}\sqrt{\frac{Var(Y)+Var(e_Y)}{Var(Y)}}}\\
&= cor(X,Y)\sqrt{\frac{Var(X)}{Var(X^*)}}\sqrt{\frac{Var(Y)}{Var(X^*)}}\\
&= r_{XY}\sqrt{\frac{Var(X)}{Var(X^*)}}\sqrt{\frac{Var(Y)}{Var(X^*)}}. && (3.1.1)
\end{aligned}
$$

By substituting $X+e_X$ and $Y+e_Y$ from classical measurement error model (2.1) into the computation of a correlation coefficient, the effect of measurement error can be determined. Let $r_(X^*Y^*)$ be the correlation between observed values and r_XY be the correlation between true-score. The terms $\frac{Var(X)}{Var(X^*)}$ and $\frac{Var(Y)}{Var(Y^*)}$ are just the Reliability of variable X^* and Y^*, respectively.

$$
r_{XX} = \frac{Var(X)}{Var(X^*)} = \frac{\sigma_X^2}{\sigma_{X^*}^2}; r_{YY} = \frac{Var(Y)}{Var(Y^*)} = \frac{\sigma_Y^2}{\sigma_{Y^*}^2}
$$

Then, the formula (3.1.1) can be algebraically reversed to provide a formula for correction for attenuation. That is, if we know the amount of error of measurement in each variable, then we can correct the observed correlation to estimate what the correlation would have been had the variables been perfectly measured.

$$r_{X^*Y^*} = r_{XY}\sqrt{r_{XX}}\sqrt{r_{YY}} \tag{3.2}$$

$$r_{XY} = \frac{r_{X^*Y^*}}{\sqrt{r_{XX}}\sqrt{r_{YY}}} \tag{3.3}$$

To correct for the effect of measurement errors on the tracking correlation, we need to know the amount of error of measurement in both variables. That is, to correct the correlation for attenuation, we need to know the reliability of both variables. If the reliability of each variable is known in each study, then the tracking correlation for each study can be separately corrected for attenuation. We can then do a meta-analysis on the corrected correlation. However, many studies do not report the reliability of their instruments. Thus, reliability information is often only sporadically available. Under such conditions, we can still estimate the reliability by gathering of data from other studies that allows source of measurement error to be reflected in the reliability coefficient.

Chapter 4

Correct Measurement Errors in Tracking of Blood Pressure

A casual blood pressure clearly cannot be perfectly measured. In estimating tracking correlation we must be aware of these problems, and be careful to remove any obvious sources of bias by standardizing procedures as far as we can.

4.1 Sources of Error in Measurement of Blood Pressure

An individual's blood pressure, like other physiological phenomena, is known to vary from one measurement to the next, even within the same visit. It is well known that one recording of blood pressure level is subject to a number of possible errors and so, along with the possibility of misclassification of persons by disease status, this could lead to the true relationship being obscured or attenuated. The outcome of blood pressure measurements depends on some factors, including numerous inherent and extrinsic sources of variability. Inherent variabilities are relative to changes in the individual, and are induced by, for instance, emotions, day- and night-rhythm, seasons, dietetic habit and posture. Extrinsic variabilities derive from the difference of the instruments used, from the stethoscope and the size of the inflatable bladder to observer bias, and from the hearing, eye, hand and ear coordination.

4.1.1 Extrinsic Variability of Blood Pressure

(1) The effect of different field observers

Blood pressure is commonly measured in population studies of cardiovascular disease and is especially liable to measurement error, dependent as it is upon observer skill in objective and observers' experience. Two observers will produce distribution of BP measurements, perhaps of differing shape, with different means and variation. It has been demonstrated in numbers that people's blood pressures respond differently to the same situation in the presence of different observers, as shown in Figure 4.1. Matthys *et al.*[16] were in a series of investigators to demonstrate and quantify some of the many factors affecting blood pressure measurement in the clinic. They have found that the presence of a final-year medical student (doctor-in-training) raises measured blood by 4.8 mmHg systolic and 1.7 mmHg diastolic.

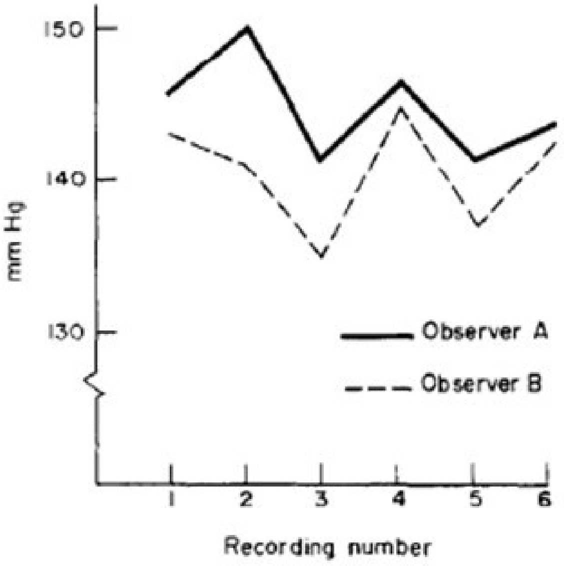


Figure 4.1: Mean systolic blood pressure levels at points during a one hour medical examination.
(Figure taken from Gardner, M.J and Heady, J.A[17])

1. Casual sitting pressure at start, 2. Supine pressure after introductory questions, 3. After electrocardiogram recording, 4.After Standard exercise, 5. After resting from exercise, 6. After telling about, but before taking of, small blood sample.

Gregory L. Burke *et al.*[18] have concluded that observer differences were the largest preventable contributor to blood pressure variation. More than 86% of systolic blood pressure readings and 90% of diastolic blood pressure readings by two different observers on the same child were within 15mmHg. These data emphasize the importance of both adequate training of field observers and the use of highly standardized methods of blood pressure measurement to determine blood pressure levels accurately in an epidemiologic survey.

(2) The effect of cuff size and bladder length

A cuff of inappropriate size in relation to the people's arm circumference can cause considerable bias in BP measurements. Variation in BP measurements can be also caused by the use of different bladder length. Maxwell *et al.*[19] concluded that a regular 12 × 23 cm cuff, used in obese subjects, gave higher BP measurements than a 15 × 33 cm cuff. This difference in measurement rose linearly with an increase in arm circumference and was 5.1 mmHg systolic and 4.1 mmHg diastolic with an arm circumference of 36 cm. Simpson *et al.*[20] compared bladders with a length of 23 and 35 cm and reported a lower BP measured with the long bladder, the difference being 4.2 mmHg systolic and 3.8 mmHg diastolic, independent of both bladder width and arm circumference. Bakx *et al.*[21] proved that the size of the inflatable bladder of the cuff influenced BP measurements for all arm circumferences, not just for obese arms and in longitudinal studies a systematic error in BP could occur when measurements were made with different bladders during the study. These hereinbefore studies determine the effect of the use of cuffs with different bladder sizes on the outcome of blood pressure measurements. Clearly, either too narrow or too wide a cuff size will cause overestimation of blood pressure. For the fat arm a wide cuff should be used to obtain actual values, as large pressures have to be used to block the artery. Thus, an appropriate blood pressure cuff size should be assigned according to upper arm length and circumference to avoid unnecessary antihypertensive treatment of individuals who might be over-diagnosed by used a too small cuff, as well as not to miss a best opportunity for therapy from truly hypertensive subjects.

(3) The effect of terminal digit preference

Although the standard mercury sphygmomanometers are widely used, the systematic and random errors caused by terminal digit preference in measurement of BP still occur in some studies. The common manifestation of these measurement errors in epidemiological studies are last digit preference of zero and prejudice for or against diagnostic thresholds in blood pressure recording, if an observer believes a value presents a division and then reads too few with this critical threshold this is one kind of source of terminal digit bias. Patterson[22] reported that when a critical threshold in approached there is a tendency to read low (readings ending in 2) rather than high (readings ending in 8) in the ration of 3:1. “Terminal digit preference” is used to describe the habit of recording BPs that end in some specific unit digits more often than in other. Auscultatory readings on account of preference for zero are not exact as there is a tendency to round off the number to the nearest 10 mmHg. Wen *et al.*[23] examined the presence, magnitude, and consequences of systematic and random errors caused by terminal digit preference in the measurement of highest systolic BP during prenatal visits in 28,841 non-referred pregnant. In the overall distribution of terminal digit readings, 78% were read to 0, 15% to even digits other than 0, 5% to 5, and only 2% to odd digits other than 5. Broad *et al.*[24] draw the similar conclusion that zero end-digits were recorded in 64% of systolic and 62% of diastolic blood pressures. This form of rounded-off data reporting error, know as heaping, can bias the estimation of parameters of interest such as mean BP level and distort the distribution of the observed counts. Keary *et al.*[25] found that heaping resulted in overestimation of BP. The mean automatic BP measurements were 155/95 mmHg, while nurse values were higher at 164/96 mmHg. To illustrate the extent of the problem, Figure 4.2 shows histograms of BP measurement from the study of Broad *et al.*[24]. In addition to the high proportion of BPs recorded with zero end-digit across the entire BP ranges, the distribution of those recorded without a zero end-digit is symmetrical, but those recorded with zero are right skewed. The effect of last digit preference for zero results in the shape of the distribution curve and reduces the power of statistical tests thereby making it more difficult to assess associations between blood pressure and other potential risk factors[26]. Moreover, zero-digit bias may inflate estimate of proportions having high blood pressure[27]. Thereby, having taken peoples’ blood pressure accurately it is important to ensure that it is recorded correctly. The use of automatic monitors may eliminate the terminal digit bias and results in more reproducible, accurate readings.

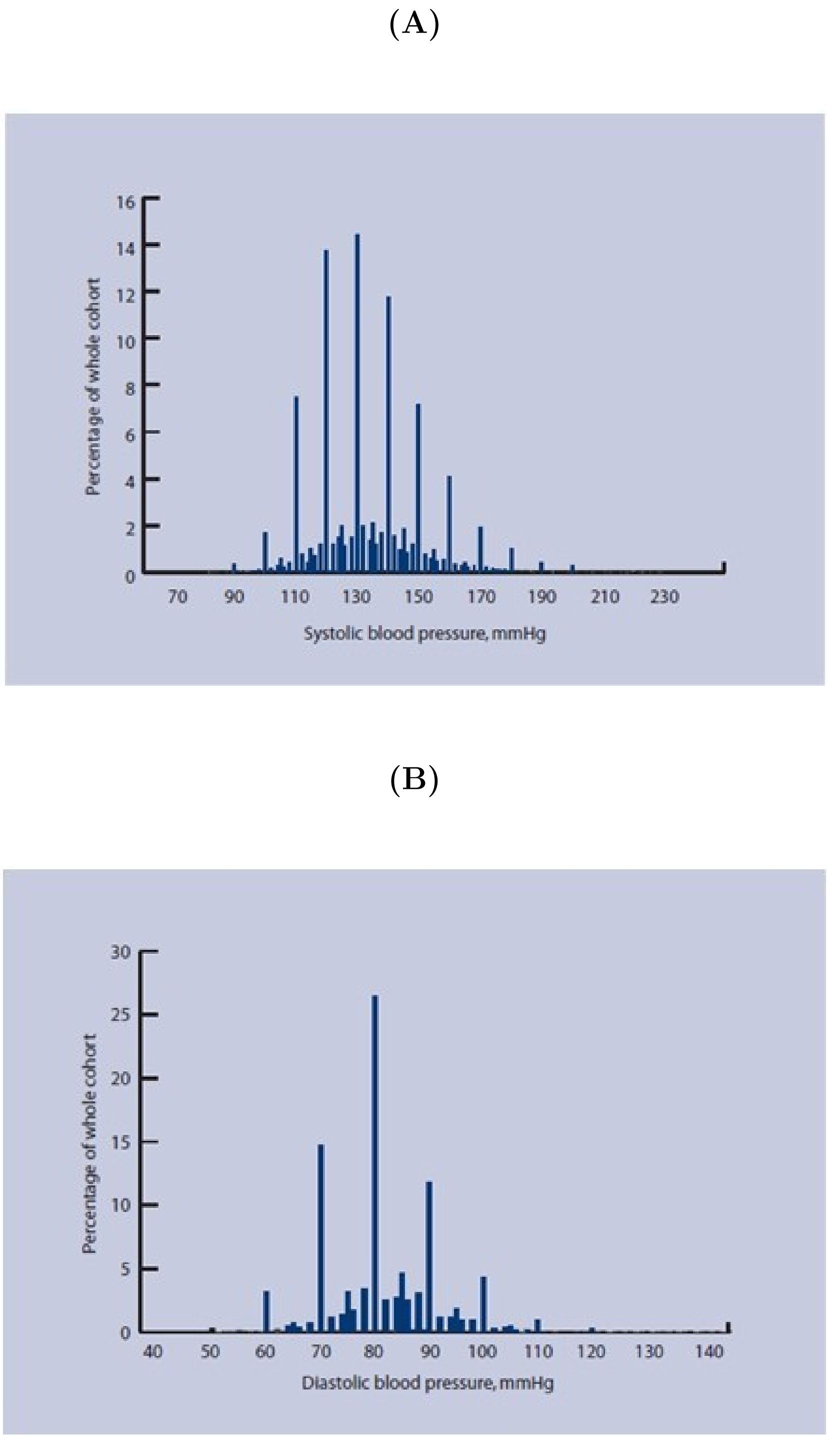


Figure 4.2: Distribution of (A) systolic and (B) diastolic blood pressure in 23676 patients. (Figure taken from Broad *et al.*[24])

(4) The effect of uncalibrated sphygmomanometers used

Accurate measure of blood pressure requires trained technicians to use accurate sphygmomanometers, which have been serviced and calibrated. The accuracy of a sphygmomanometer depends on correct maintenance and calibration regularly. However, arrangements for maintenance and calibration of sphygmomanometers are liable to be neglected in practices. Hussain and Cox[28] found that in Britain 23% of practitioners had never (>6 years) their sphygmomanometers calibrated. An another survey of 125 sphygmomanometers used in a prehospital setting in the USA, found over one-third were more than 4 mmHg inaccurate and one in 10 more than 8 mmHg inaccurate[29]. Rouse and Marshall[30] in UK reported that of 1462 sphygmomanometers, 9.2% gave readings were more than 5mmHg inaccurate and true hypertension is very uncommon in woman under 35, a BP that is measured as high is much more likely to be caused by calibration error than by hypertension. British Hypertension Society guidelines recommend clinicians estimate blood pressure based on repeated measures of separate occasions, at least three separate occasions before a diagnosis of hypertension is made[31], which can reduce the probability of making an erroneous diagnosis of hypertension due to biological variation in blood pressure and may also reduce errors due to patient factors. However, if one people's blood pressure is measured with a sphygmomanometer that has a systematic error, the BP readings will be inaccurate whatever it is repeated how many times. As it is, maintaining and calibrating instruments is not troublesome or expensive. To obtain accurate blood pressure measurement, it is therefore important to ensure that an adequately calibrated within the capacity of any practice. As a minimum first step, observers or clinicians should have a system in place to ensure that their sphygmomanometers are recalibrated regularly to the standard endorsed by relevant department.

(5) Other factors

A range of other factors, such as acoustic noise, the influence of the rest period and smoking habits, may also affect measured blood pressure. Sebald *et al.*[32] have shown that a similar blood pressure pulse appears in the two microphones with a relative time delay. Andersen *et al.*[33] described that smokers from the age of 50 years had a 2-4 mmHg lower systolic BP and 1-3 mmHg lower diastolic BP than had non-smokers. In other noise situations, such as ambulatory environments of if the patient moves slightly the current auscultatory blood pressure method may be unreliable[34]. These findings may be of both clinical and scientific importance, which led us to study patterns of variation in resting BP, since any pattern suggesting systematic differences among groups of subjects may introduce bias both concerning risk estimates and indication for BP-lowering treatment.

The recent researches and new techniques of blood pressure measurement all indicate the importance of standardizing blood pressure measurement devices and settings. It is therefore suggested that extrinsic variabilities in BP should be allowed for routinely, at least in local epidemiological surveys, in addition it should be recognize as important in daily clinical work.

4.1.2 Inherent Variability of Blood Pressure

Extrinsic variability is not the only limitation or confounding factor of the accuracy for measuring blood pressure. Apart from extrinsic variability the most important perhaps are inherent variability (within-person variability or biological variation) that has long been recognized and repeatedly examined. A single casual blood pressure is not reliable in identifying any given individual's disease status. The inherent variability reflects fluctuations in biological, mechanical and environmental circumstances, such as daytime and seasonally variation, individuals' emotions, and other non-preventable variations.

(1) The effect of psychological factor and behavior

Numerous publications already addressed the “white-coat” effect, which is defined as the occurrence of blood pressure values higher than normal when measured in the medical environment[35]. As the causes of white-coat effect, emotional responses such as anxiety in the clinic as a special situation are widely considered to play a role, but the details have not been systematically evaluated. Such psychological effect of clinic-related anxiety on measured blood pressure was concluded by Marschall *et al.*[36] that anticipation of a blood test affected measured systolic blood pressure in the group, of which the individuals were told that a blood test would be carried out after the BP measurement. Another new source of potential blood pressure measurement bias was found by Bodegard *et al.*[37] in an observational study in 2014 healthy Norwegian males aged 40-59 years. The authors described that men who were examined as number one in the row of two to four subjects each morning had higher systolic BP compared to others. In all other conditions were virtually identical, and then the increased BP represented a stress reaction to being number one in a row of subjects to be examined.

(2) Diurnal variation

BP is affect by day-by-day circadian rhythm. Such diurnal variation in BP is usually expressed as the relative difference between mean day and night-time BP. The fundamental pattern of diurnal blood pressure variations is governed by sleep-wakefulness cycle, on which the effects of different activities are superimposed[38], as illustrated by Figure 4.3. The phenomena that BP is higher in the daytime and lower in the nigh-time, is well documented by recent researchers. O'Brien *et al.*[39] have showed that ambulatory blood pressure in the 815 healthy bank employees aged 17-79 years averaged 118/72 mmHg over 24h, 124/78 mmHg during the day (10:00-22:59) and 106/61 mmHg at night (01:00-06:59). Analysis of such ambulatory blood pressure recordings would be greatly facilitated by a better understanding of the quantitative contribution of day-night difference to observed variations of blood pressure.

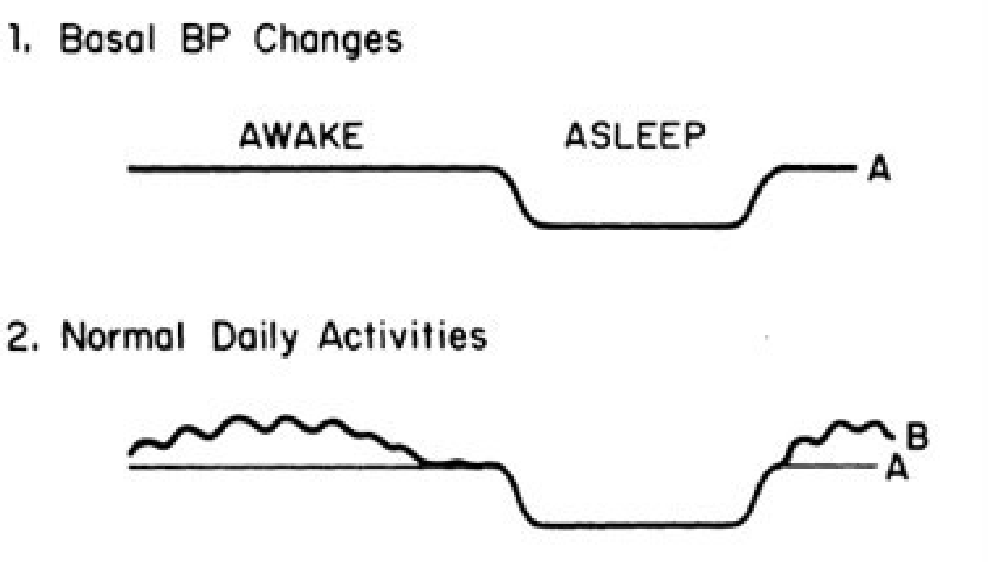


Figure 4.3: Hypothetical patterns of blood pressure variability.
(Figure taken partly from Pickering T.G. *et al.*[38])

1, Basal blood pressure changes (A) as observed in subjects immobilized throughout the 24 hr period.
2, Superimposition of normal activities (B) produces the typical diurnal pattern of blood pressure seen in free-living subjects.

(3) Seasonal variation

It has been known for a long time that human blood pressure varies with the season and other environmental factors. A seasonal influence on blood pressure was first described in year 1961 in Britain by Rose[40], who anlysed measurements in 56 men observed for 1-3 years at a clinic for ischaemic heart disease and reported lowest pressures in September and highest pressures in spring (February to May), with an average 2.5 mmHg difference. However, other Studies showed that systolic and diastolic pressures were higher in winter than in summer. Thulin *et al.*[41] in southern Sweden reported that the systolic blood pressure during the winter months was 4.1 and 5.0 mmHg higher in the male and female subjects respectively, while the diastolic blood pressure during the winter months was 1.7 and 1.9 mmHg higher in the male and female subjects, respectively. These discrepancies might result from climatic differences between the years covered by these studies. A further research was made by Brenman *et al.*[42]. They found that the seasonal variation in blood pressure was greater in older than in younger subjects and was highly significantly related to maximum and minimum daily air temperature measurements but not to rainfall. This suggests that variations in BP from month to month are also influenced by other factors as well as air temperature, e.g. season variation in working or living habits. Mundal *et al.*[43] concluded that the seasonal variation in BP can be explained by a parallel seasonal variation in physical fitness, which is considerably lower in the period September through December. Hata *et al.*[44] attributed the increase in winter blood pressure to increased sympathetic nervous activity in cold weather. Early an experimental word has shown that capillary vascular spasms occur in the cold season and are likely to lead to elevated blood pressure[45]. This phenomenon is now viewed as part human thermoregulation, consisting of constriction of the peripheral vessels of the body under the cold conditions and a consequent increase in vascular resistance and rise in blood pressure[46].

The seasonal variation in blood pressure is often recognized in epidemiological studies, furthermore, we should attempt to formulate this phenomenon more quantitatively to produce some method for correcting the seasonal bias in data. Such work is sorely needed, since the ignoring of seasonal trends in blood pressure may lead to errors when statistical analysis is carried out. Because of the inherent variability in blood pressure measurements, over- or underestimation of blood pressure and misdiagnosis of hypertension will occur. Efforts should be directed at minimizing these errors by recognizing and controlling all sources of variability.

As a summary review, influential factors in an evaluation of BP measurement variations are the observers, the equipment and the subjects. Errors such as preference for terminal digit values, observer bias, variation in technique and problems with equipment are well described above and can be minimized or prevented. Such extrinsic variabilities in Blood Pressure are potentially serious, as the bias the cause may lead to invalid diagnostic or treatment conclusions. Inherent variabilities give rise to reduced precision, and therefore the biological and environmental conditions must be monitored carefully to evaluate the effects and to standardize repeated studies. In designing epidemiological studies, it is more likely to eliminated extrinsic variabilities of BP measurement by careful planning for the surveys, in which methods were standardized, the time settings planned and equipment checked regularly. However, the inherent variability of blood pressure readings is hardly possible to be avoided, that is liable to result in the tracking correlation being underestimated or attenuated by single reading. Thus, investigation of the sources of error in measurement of blood pressure in epidemiologic studies is considered to enable an understanding of problems encountered in obtaining consistent and reliable measurements.

4.2 Modeling with Within-person Variability on Estimation of Reliability

Extrinsic Variability in BP measurement can be reduced by standardizing methods and circumstances of blood pressure measurement, and by rigorous training of observers. Even when this has been done, there will almost certainly be other sources of error that will affect BP measurement. Inherent variability of an individual's BP may occur for measures obtained minutes, hours, days or weeks apart. One clinically relevant way is to divide this within-person variability into two components: first, between visits days or weeks apart, and second, between measurements minutes apart at the same visit. Of most previously reported data, substantial between-visit variability was demonstrated in studies. Glock *et al.*[47] obtained blood pressure measurements on health department employees at several visits over a three-week period. Between-visit variability appeared to be larger than within-visit variability, and individual subjects demonstrated widely differing degrees of variability. Rosner and Polk[48] have estimated the components of variability in blood pressure for 326 workers in a suburban Boston company. They observed that additional visits gave more information than replicated measurements on a single visit. Gillman *et al.*[4] noted that the number of visits was more important than the number of measurements per visit, reflecting the fact that the between-visit component of variance is large than the within-visit component. Thus, any attempt to correct tracking correlations for within-person variability must have information about the between-visit component. From the results of the above section, we can eliminate the attenuation of tracking correlation by utilizing reliability coefficient. In estimating the reliability coefficient, we should make every effort to use the appropriate reliability coefficient, in the meantime, between-visit variability and within-visit should be certainly taken into account. Above all, suppose we collect K blood pressure measurements on each of J visits. Let X^*_{ijk} denote the measured BP of individual i (in one population group) at jth visit and at repetition (within visit) k. We will assume that the following model:

$$X^*_{ijk} = \mu + \alpha_i + \beta_{ij} + e_{ijk}, i = 1, ..., N, j = 1, ..., J, k = 1, ..., K, \tag{4.1}$$

where:
μ =overall mean blood pressure;
$\alpha_i \sim \mathrm{N}(0, \sigma^2_\alpha)$ and represents between-person variability;
$\beta_{ij} \sim \mathrm{N}(0, \sigma^2_\beta)$ and represents between-visit variability for a specific person;
$e_{ijk} \sim \mathrm{N}(0, \sigma^2_e)$ and represents within-visit variability for a specific person and visit.

From equation (4.1), it follows that the distribution of true underlying level of blood pressure over the persons in a particular group (based on age, sex or other characteristics) is normal with mean μ and variance σ_α^2. It could be possible to estimate the parameters of the true BP measurements distributions (μ, σ_α^2) of certain specific groups from a larger sample which are more likely to be representative of the general population. In particular, for an age and sex-specific group, unbiased estimates of μ and σ_α^2 can be obtained from

$$\widehat{\mu} = \overline{x}_{BP};$$

$$\widehat{\sigma_\alpha^2} = s_{BP}^2 - (\frac{\sigma_\beta^2}{J} + \frac{\sigma_e^2}{JK}), \tag{4.2}$$

where $\overline{x}_{BP}$, s_{BP}^2 are the observed age and sex-specific mean and variance of blood pressure from a large population, each of whom provided a summary measurement consisting of an average of K measurements at each of J visits. Furthermore, under this model (4.1), the underlying variance components are assumed to be the same for each person within a population.

Thus, the variance across individuals of a given measurement is:

$$\sigma^2 = Var(X_{ijk}^*) = \sigma_\alpha^2 + \sigma_\beta^2 + \sigma_e^2,$$

which is constant. This assumption has been verified by Rosner and Polk[48]. They obtained blood pressure measurements for 123 persons in an industrial setting and concluded that the variance components for any given individual remained reasonably constant.

Then the coefficient of reliability of a single measurement is:

$$r_{XX}^{11} = \frac{\sigma_\alpha^2}{\sigma^2} = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \sigma_\beta^2 + \sigma_e^2}, \tag{4.3}$$

which represents the coefficient of reliability of BP measurement that has only one visit and single reading per visit. From the results of the previous studies[49], the between-visit component is larger than the within-visit component. Therefore, we assume that:

$$\sigma_\beta^2 = \mathrm{M}\sigma_e^2. \tag{4.4}$$

And then we can obtain the coefficient of reliability of k blood pressure measurements on each of J visits as following:

$$r_{XX}^{JK} = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \frac{\sigma_\beta^2}{J} + \frac{\sigma_e^2}{JK}} = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \frac{(MK+1)}{JK}\sigma_e^2}. \tag{4.5}$$

The relationship between r_{XX}^{11} and r_{XX}^{JK} can be algebraically deduced to estimate an appropriate reliability coefficient according to character of data in studies, which is given by:

$$r_{XX}^{JK} = \frac{1}{1 + L(\frac{1}{r_{XX}^{11}} - 1)}, \quad L = \frac{MK + 1}{JK(M + 1)}. \tag{4.6}$$

For any value of M, r_{XX}^{JK} approaches unity as J approaches infinity. Rather, the average of a fixed number of measurements (even one) each taken at different visits tends towards perfect reliability. On the other hand, increasing the number of readings at a single visit cannot eliminate the between-visit variability and does not towards perfect reliability. This relation is paramount in our study. If we know the reliability coefficient under a certain circumstance, for example, three measurements at two separate visits, then we can estimate the reliability for a single recording using formula (4.6), vice versa.

4.3 Estimations and Comparisons of Reliability Coefficients in Previously Published Data

Before comparing reliability coefficients we must be first faced with the main problem is: what is the extent of coefficient M in assumption (4.4)? namely, how many times is the between-visit variance bigger than the within-visit variance in BP measurements.

Rosner and Polk[48] have estimated the components of variability in blood pressure for 326 adults in a suburban Boston company. They concluded that the median between-visit component of variability for systolic (diastolic) blood pressure 18.5 (12.3) was about 1.68 (1.41) times as large as the corresponding within-visit component of variability 11.0 (8.7). Therefore, we come to a conclusion that although both the number of visits and the number of measurements per visit have importance in characterizing a person's BP, the number of visits is the more important of two.

4.3.1 The Reliability Coefficients of BP Measurements for Adults

Shepard[50] calculated the reliability is 0.94 for systolic and 0.92 for diastolic BP on three visits with two replication at each visit from Rosner and Polk's data[48]. Then, we set $M = 1.68$ and $r_{XX}^{32} = 0.94$ for systolic BP ($M = 1.41$, $r_{XX}^{32} = 0.92$ for diastolic) into formula (4.6) to estimate the single BP measurement reliability r_{XX}^{11}. In addition, the BP reliability coefficients of different number of visits and different repeating times within the same visit can also be deduced. The outcomes are presented in Table 4.1.

Table 4.1: Coefficientsof reliability of measured blood pressure according to number of visits and replications averaged in adults

Number of	Systolic BP				Diastolic BP			
	Replications per visit (K)				Replications per visit (K)			
visits(J)	1	2	3	limit	1	2	3	limit
1	0.8094	0.8393	0.8497	0.8714	0.7524	0.7931	0.8077	0.8385
2	0.8947	0.9126	0.9188	0.9313	0.8587	0.8846	0.8936	0.9122
3	0.9272	**0.9400**	0.9443	0.9531	0.9011	**0.9200**	0.9265	0.9397
4	0.9444	0.9543	0.9577	0.9644	0.9240	0.9388	0.9438	0.9541
limit	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 4.1 shows that the coefficients of reliability of a single reading in adults are 0.8094 for systolic BP and 0.7524 for diastolic BP. Comparisons across a row show that the coefficient of reliability increases with the number of visits. This finding is consistent with the conclusion of Souchek *et al.*[51] that two measurements are better than one, and the average of three measurements is better than two measurements for classifying individuals as to future hypertension status. The right column, labeled “limit”, shows the limiting value of coefficient of reliability with a very large number of repetitions all confined to the limited number of visits. This limit is less than unity because one cannot eliminate the between-visit component of variance in blood pressures by increasing the number of readings within each visit. Comparisons down a column show that the limit of the correlation with a very large number of visits, regardless of the number of repetitions per visit, is 1.0000. Increasing the number of visits reduces all components of variance. The more reliably BP is measured, the greater is the coefficient of reliability r_{XX}^{11} and the less is the attenuation.

4.3.2 Age-and Sex-specific Reliability Coefficients of BP measurements

Rosner *et al.*[52] estimated quantitatively the age- and sex-specific variance component of BP measurement in children and adults. All children had their blood pressure measured with a standard mercury sphygmomanometer in a school setting on four visits one week apart with three measurements per visit. The adults aged 30-69 years not on antihypertensive medication, were screened over two to five visits at weekly intervals with three reading. It is interesting to compare the reliability coefficients in Table 4.1 with those obtained directly from Rosner *et al.*’s data[52]. Since the variance components for standard BP measurements are given in Table 5 in their paper, we can estimate the age- and sex-specific reliability coefficients through equation (4.3.6). The results have been summarized in Table 4.2.

Table 4.2: Age- and sex-specific reliability coefficients of a single reading for systolic and diastolic blood pressures

	Children by age (years)		Adults by age (years)	
	8-12	13-18	30-49	50-59
	Systolic BP			
Male	0.6068	0.6896	0.7702	0.8337
Female	0.6744	0.6465	0.7851	0.8251
	Diastolic BP			
Male	0.1946	0.6295	0.7101	0.7734
Female	0.2392	0.6275	0.7496	0.7724

Data for white adults from Rosner and Polk[53]
For diastolic BP, K4 was used for 8-12-years-olds;
K5 was used for 13-18-years-olds and for adults

As a whole, the reliabilities for children are slight lower than those for adults except the reliability for diastolic BP from the children aged 8-12. It seems to be no obvious difference between male and female, which is consistent with the conclusion of Rosner *et al.*[52]. They reported that no meaningful effect of sex on variability of BP were found. However, age had a large and independent inverse association with variability of diastolic pressure. Since no obvious gender differences in the reliability coefficients were observed, the reliability can be calculated by combining sex categories. The coefficients of reliability of a single reading in children 13-18 yr old is are 0.6823 for systolic BP and 0.6308 for diastolic BP, whereas the reliability in children 8-12 yr old are only 0.6430 for systolic BP and 0.2169 for diastolic BP. These data highlight the extreme unreliability of diastolic pressure for young children (ages 8-12 years). Comparing with other studies, the similar reliability levels of diastolic BP for young children are detected. Insel *et al.*[54] have estimated signal and noise variance of blood pressure in children. Their results suggest that the coefficients of reliability of a single reading in children 11-12 yr old are only 0.45 for systolic pressure and 0.25 for diastolic pressure–only about half the corresponding values for adults. This low reliability for children might be caused by the following main reasons. One could be the lower observed total variance s^2_{BP} for children's BP measurements comparing with those for adults. Another might be that the within-person variance components (between-visit and within-visit variance) for BP measurements tend to decrease with age, particularly for the diastolic BP measurements. According to the equation (4.2), the low observed variance s^2_{BP} and high within-person variance components σ^2_β and σ^2_e could result in the lower between-person variance $\widehat{\sigma}^2_\alpha$. After algebraic rearranging terms in the equation (4.3), we obtain

$$r_{XX}11 = \frac{1}{1 + \frac{\sigma_\beta^2 + \sigma_e^2}{\sigma_\alpha^2}} \tag{4.7}$$

From the above equation, we can find that increasing within-person variance components σ_β^2 and σ_e^2 or diminishing between-person variance could finally lead to the small reliability coefficient for BP measurement.

To verify the above supposition about the low observed variance s_{BP}^2 for children's BP measurements, data from National Health and Nutrition Examination Survey (1971-1974) in United States are used to compare the observed variance for BP measurements in different age group. Figure 4.5 indicates that the variability in both systolic and diastolic BP among people shows a general pattern of increase with age. From 25 years on, the increment is substantially much larger among systolic BP measurements than diastolic BP measurement. One of possible causations is that the absolute value of systolic BP is much higher than those of diastolic BP, which can be proved in Figure 4.4. The black line for mean systolic BP runs always above the red line for mean diastolic BP. Similarly, the mean BP shows an increasing trend with age. It is not surprising that aged people are more likely to be hypertensive than youths, resulting in the great mean absolute BP values among adults. That higher blood pressure levels are associated with greater variability has also been proved by Gordon *et al.*[55]. They reported that on average a difference of 10 mmHg in pressure was associated with a difference of about 1 mmHg in the standard deviation of a person's blood pressure and at higher blood pressure levels the increment was somewhat greater than at lower. These findings are probably one reflection of the small variability of BP measurement among children, finally leading to the low reliability coefficient for younger children's blood pressure. Furthermore, that could also explain why the reliability coefficient of systolic pressure is higher than that of diastolic pressure.

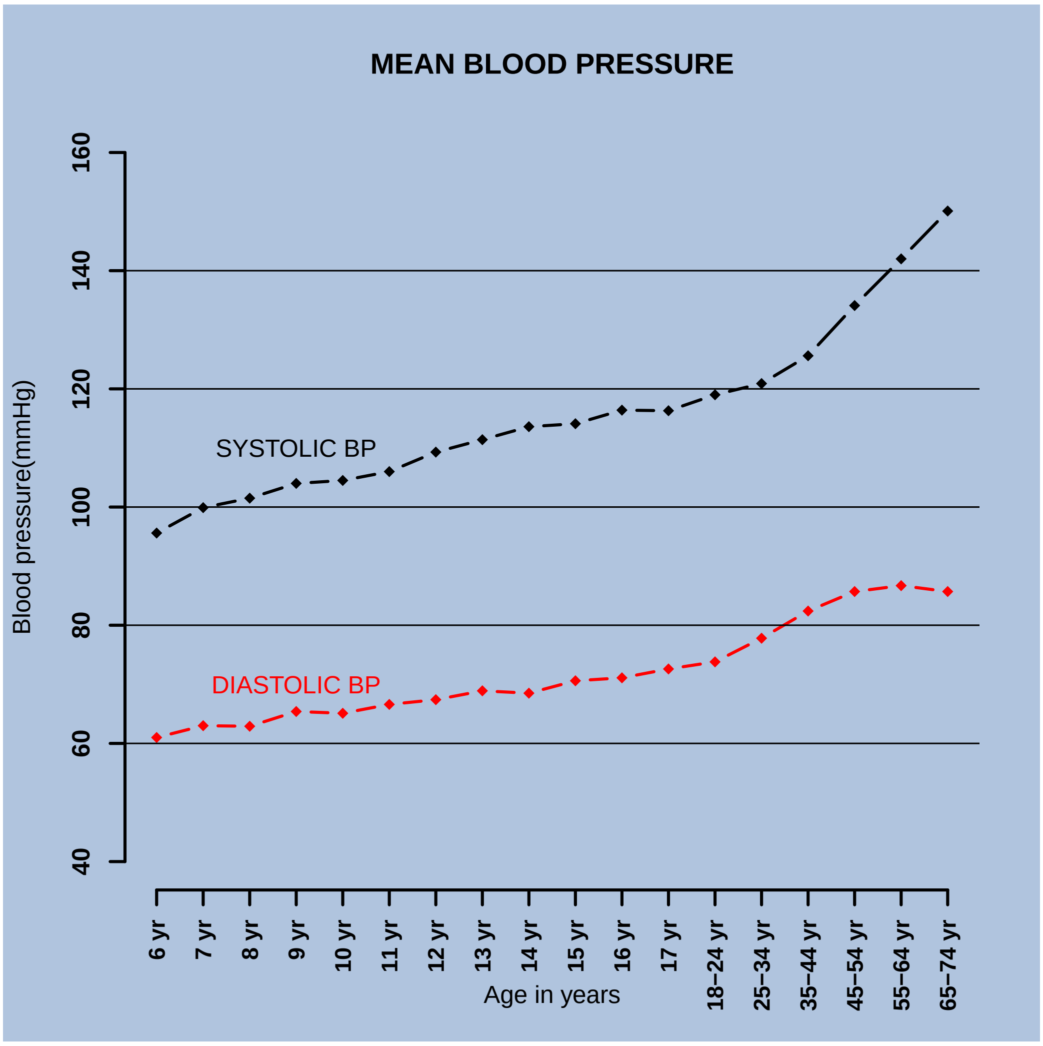


Figure 4.4: Mean systolic and diastolic blood pressure of children and adults 6-74 years: United States
Data from adopted National Health and Nutrition Examination Survey (1971-1974)

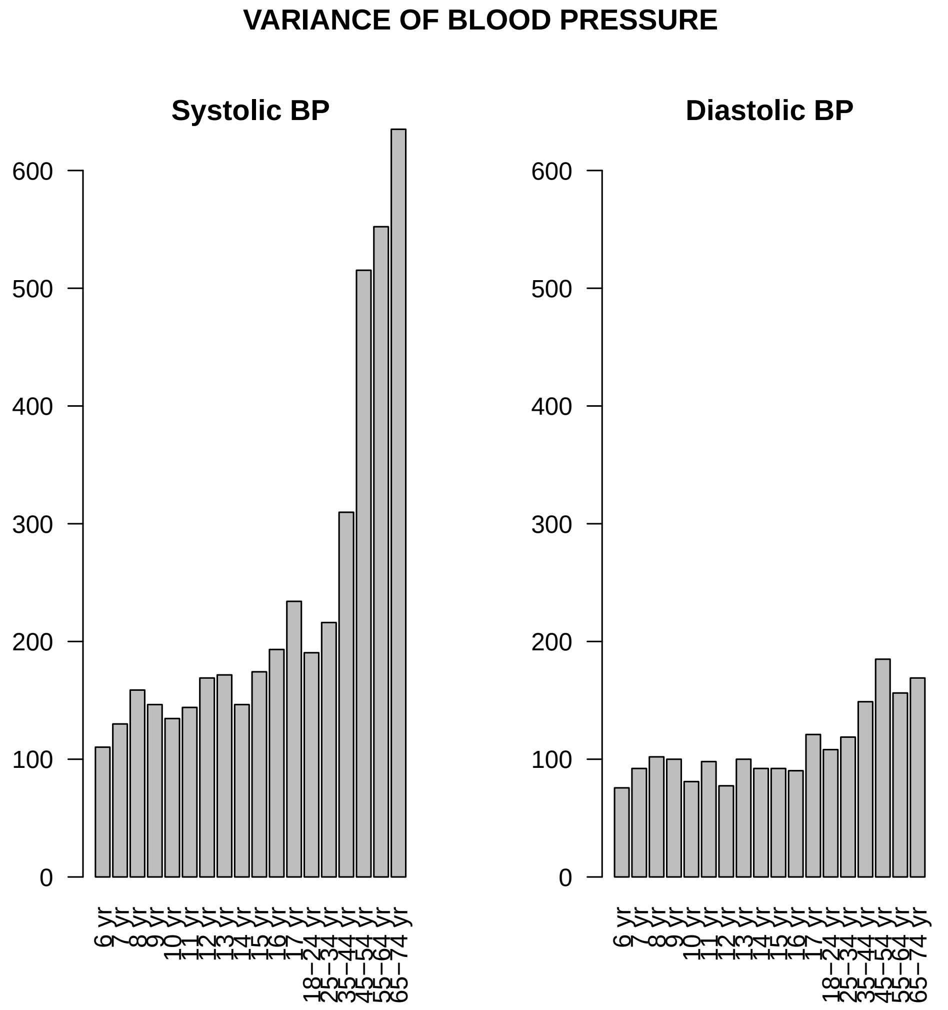


Figure 4.5: Variance for systolic and diastolic blood pressure measurements in adults and children 6-74 years: United States
Data adopted from National Health and Nutrition Examination Survey (1971-1974)

As regards the high within-person variance components of BP measurements for children, particularly for diastolic pressure, the study from Rosner *et al.*[52] had been reached the conclusion. The results in point are illustrated with Figure 4.6. It is unexpectedly that the within-person variance components for systolic pressure tend to increase moderately with age. In contrast, within-person variation for diastolic pressure is much larger for children than adults and there is a two- to threefold decline with maturity in both variance components, which is consistent with our supposition.

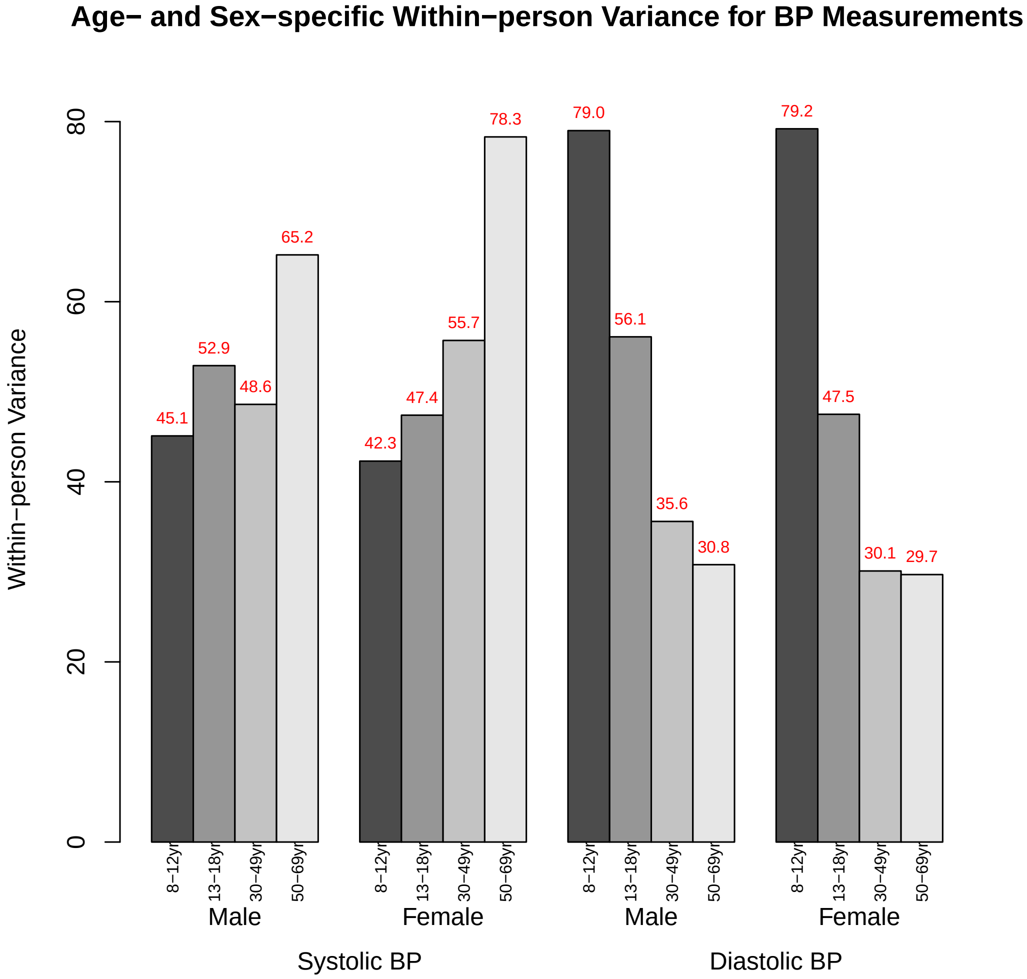


Figure 4.6: Comparison the within-person variance for standard blood pressure measurements
Data adopted from Table 5 of Rosner *et al.*[52]

For diastolic BP, K4 was used for 8-12-years-olds;
K5 was used for 13-18-years-olds and for adults

From those above findings about the between-person and within-person variance components, we can currently further compare and analyze the difference of reliability at different age groups and between the systolic and diastolic pressure. As shown in Table 4.2, the improvements of the coefficients of reliability for systolic BP measurements with age are slight, which results from that while the within-person variance for systolic pressure is increasing, the corresponding between-person variance is as well as rising dramatically. The effect on the improved reliability caused by the accretion of the between-person variance is partially counteracted by the increase of within-person variance for systolic BP measurements. However, for the diastolic pressure that is a strikingly imprecise measurement for young children (ages 8-12 years). These data in Table 4.2 highlight the extreme unreliability of diastolic pressure for these young children. One obvious reason is that the within-person variance of diastolic BP measurements for pre-adolescent children (age 12 years or younger) is almost 1.5 times as great as adolescent children (ages 13-18 years) and nearly 2.5 times as great as adults (Figure 4.6).

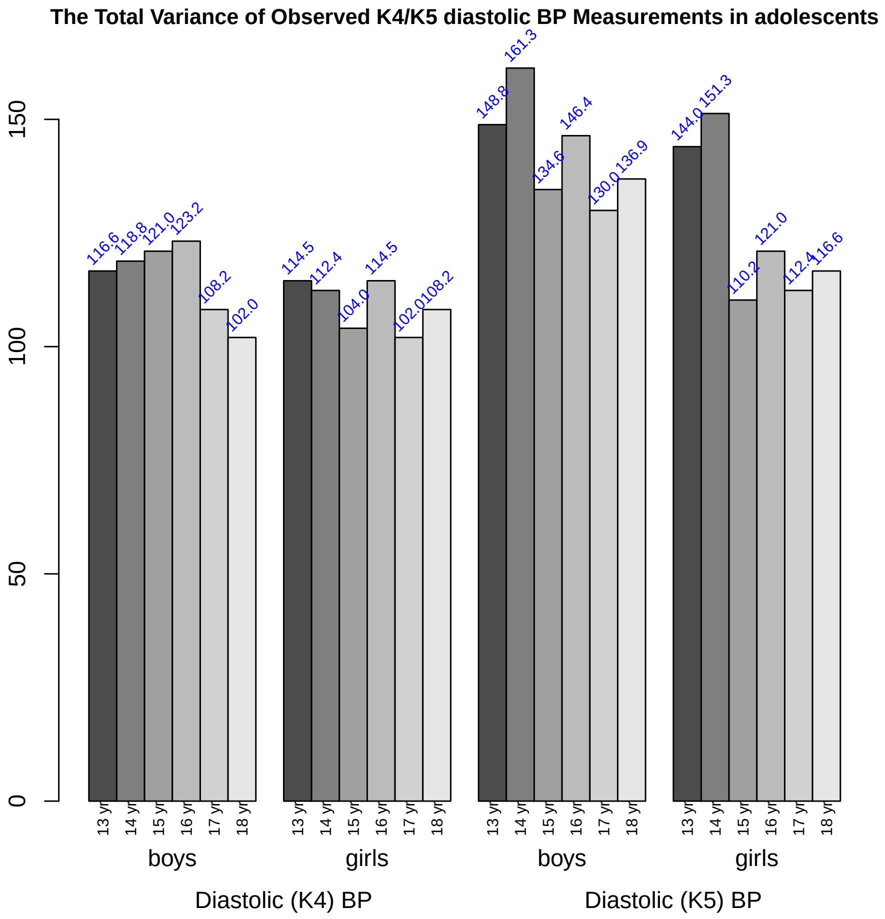


Figure 4.7: Comparison of the total observed variance of diastolic BP presented in K4 and K5 phases among adolescents (ages 13-18 years)
Data adopted from Appendix Table 3, 4 and 5 of the Task Force[3]

Another reason is that the different Korotkoff phases are used to record accurate BPs among children. The K5 diastolic pressures are often difficult to obtain in infants and pre-adolescent children, however that are more easily obtainable on adolescents and adults. Therefore, K4 diastolic BPs are used in the standards for infants and children 3 to 12 years of age, and K5 diastolic BPs were used in the standards for adolescents 13 to 18 years of age and adults[3]. It can be found in Figure 4.7 that the total observed variances of K5 diastolic pressures are generally larger than those of K4 diastolic pressures among the adolescents. According to equation (4.2), the above double effect of the small total observed variance s^2_{BP} and the larger within-person variance σ^2_β, σ^2_e could induce the lower between-person variance σ^2_α of diastolic pressure for children, particularly for younger children under 13 years old. Such effect can be illustrated by Figure 4.8.

To summarize, the individual variability of the systolic pressure continues to become much larger into maturity owing to the remarkable increase of absolute mean systolic BP values. Whereas such growing trend of the inherent variability for systolic BP measurements is not so dramatically. Consequently, the reliability coefficients for systolic pressure rise somewhat with the aging process. In contrast, as people grow older the inherent variability for diastolic pressure tends to decline greatly. However, there is no obvious increment of variance among individuals with increasing age except pre-adolescents versus adolescents. That is why the diastolic BP measurements for adolescents (ages 13-18 years) are much more reliable than those for pre-adolescents (age 12 years or younger). This low reliability is one of the reasons that screening for hypertension in children is more difficult than in adults and may not be worthwhile. Many more visits will be required to correctly identify children under age 13 years as having high diastolic pressure than high systolic pressure using these results. If children are to be screened, however, then multiple replications are even more important than in adults. These findings have also implications for tracking diastolic blood pressure for pre-adolescent children (age under 13 years).

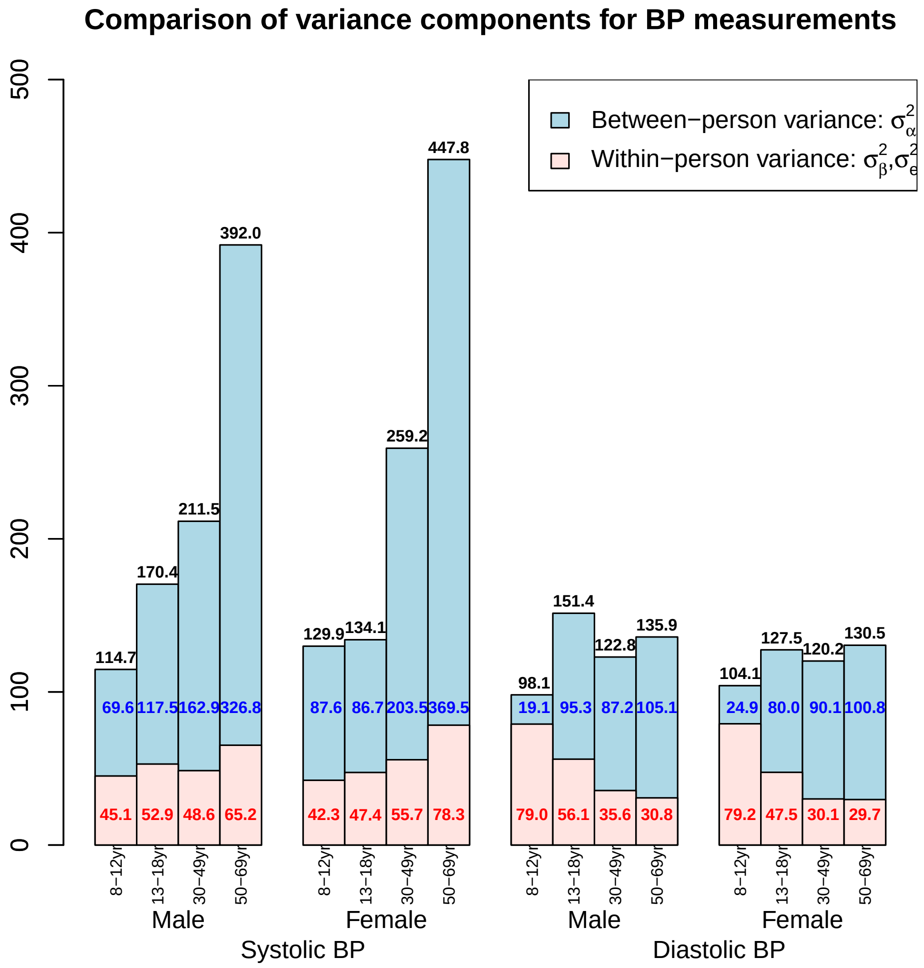


Figure 4.8: Comparison of variance components for standard blood pressure measurements at different age and sex groups
Data adopted from Table 5 of Rosner *et al.*[52]

For diastolic BP, K4 was used for 8-12-years-olds;
K5 was used for 13-18-years-olds and for adults

Since important age trends were found in the levels of the reliability among children and adults, and that no obvious difference by sex group is observed, the age-specific reliability coefficients of different number of visits and replications within visit are summarized in Table 4.3. Comparing with Table 4.1 and Table 4.2 we found that the single reading reliabilities for adults are quite similar. The little differences may be due to sampling variation, differences in technique, or the interval for estimating between-visit variability. Nevertheless, the comparability indicates that the values obtained by Shepard[50] are generally similar to those from other ostensible healthy populations. Accordingly, the reliability coefficients of 0.81 for systolic BP and 0.75 for diastolic BP measured with 3 visits and 3 replications per visit are selected to be combined in Table 4.3 as the reference of BP reliability coefficients in adults group. The age trends are observed in Table 4.3, both systolic and diastolic reliabilities increase with age, which is consistent with the characteristic of the variability of BP measurements. These findings are remarkably importance to help us to obtain more steady estimators of BP tracking correlation in meta-analysis.

Table 4.3: Age-specific reliability coefficients for systolic and diastolic blood pressures according to number of visits and replications averaged

Age Group: 8-12 (pre-adolescent children)								
	Systolic BP				Diastolic BP			
Number of visits	Replications per visit (K)				Replications per visit (K)			
(J)	1	2	3	limit	1	2	3	limit
1	0.6430	0.6748	0.6861	0.7099	0.2169	0.2434	0.2537	0.2773
2	0.7827	0.8058	0.8138	0.8303	0.3565	0.3915	0.4048	0.4342
3	0.8438	0.8616	0.8677	0.8801	0.4538	0.4911	0.5050	0.5351
4	0.8781	0.8925	0.8974	0.9073	0.5256	0.5627	0.5763	0.6055
limit	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Age Group: 13-18 (adolescent children)								
	Systolic BP				Diastolic BP			
Number of visits	Replications per visit (K)				Replications per visit (K)			
(J)	1	2	3	limit	1	2	3	limit
1	0.6823	0.7093	0.7188	0.7386	0.6309	0.6624	0.6737	0.6974
2	0.8112	0.8300	0.8407	0.8497	0.7737	0.7970	0.8050	0.8217
3	0.8656	0.8798	0.8847	0.8945	0.8368	0.8548	0.8610	0.8736
4	0.8957	0.9071	0.9071	0.9187	0.8724	0.8870	0.8920	0.9021
limit	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Age Group: >18 (Adults)								
	Systolic BP				Diastolic BP			
Number of visits	Replications per visit (K)				Replications per visit (K)			
(J)	1	2	3	limit	1	2	3	limit
1	0.8094	0.8393	0.8497	0.8714	0.7524	0.7931	0.8077	0.8385
2	0.8947	0.9126	0.9188	0.9313	0.8587	0.8846	0.8936	0.9122
3	0.9272	**0.9400**	0.9443	0.9531	0.9011	**0.9200**	0.9265	0.9397
4	0.9444	0.9543	0.9577	0.9644	0.9240	0.9388	0.9438	0.9541
limit	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

4.4 Methods and Design of the Practical Study

4.4.1 Data and background

Toschke *et al.*[56] have selected the date about BP correlation coefficients from previously published articles from a period of January 1, 1976 to December 31, 2007, among them there are 30 studies fulfilled the following criteria:

(i) at least two diastolic or systolic blood pressure measurements at different time point,

(ii) at least a time lag of one or more years between one pair of consecutive blood pressure measurements,

(iii) publication language English, German, French or Spanish,

(iv) at least one subgroup of study subjects included with first blood pressure measurements between 11 and 40 years,

(v) apparently healthy human subjects not under medication,

(vi) Information on correlation between time points.

Duplicate publication of the same study were excluded and only the respective paper reporting the largest sample size and longest follow-up interval was considered for further analysis. In the 30 studies, systolic information was available in 29 of them, while 28 studies reported diastolic tracking estimates. Toschke *et al.*[56] chose to include sex, baseline age, length of follow-up years, continents of study origin, the number of measurements and method of BP measurement as the potential predictors of BP tracking in their meta-analysis. Their researches have shown BP tracking correlations from childhood to adulthood to be positive but were low-to-moderate, because they do not take account of the short-term biological variability of an individual's blood pressure over days to week. In present study we will estimate the tracking correlation based on corrected errors in blood pressure measurement.

4.4.2 Statistical Analysis and Results

In Toschke *et al.*'s data, the information about the particular situation of BP measurement, for example, whether extended period of quiet and rest exists before measurement, are not available. In order to carry out analyses we assume that the measurement situation and method had been standardized, which is rational, because the extrinsic variability of BP measurement is likely to be controlled. Thus, the short-term biological variability is still remained. We must make corrections for inherent errors in BP before estimating and evaluating their tracking correlation, that is, we should make every effort to use the appropriate reliability coefficient. Estimation of the appropriate reliability coefficient requires the specification of the kinds of measurement error in the specific study and requires the information about individuals' BP between-visit and within-visit variabilities. Certainly, the best way to correct error at the level of meta-analysis is to make the procedure of correction for each study individually, which would not cause the over- or under-estimation of measurement errors. That is to say, any attempt to correct tracking correlations for measurement errors in meta-analysis must be have information about estimating the reliability coefficient for each published study and then corrected the measurement error with the corresponding reliability coefficient. While there are numerous known factors associated with variation of intra-individual blood pressure, only a limited number of them are available for investigation from Toschke *et al.*'s collected data. Therefore, we cannot obtain the reliability coefficient immediately from that. Although such information is absent in present data, we could obtain the reliability from other published data as reference.

4.4.2.1 Overall Correction for Tracking of BP Measurements

First of all, without regard to the factor of age we make overall correction for tracking correlation of BP measurements. To avoid overestimating the inherent variability of BP measurements, we utilize the reliability coefficients of adults (Table 4.1) obtained from Rosner and Polk's data[48] and then compare the results with uncorrected BP correlation coefficient. Review of present data we find that there is some important information for further consideration, that is the number of measurements helping us to select the appropriate reliability coefficient. Although Toschke *et al.*[56] have drawn the conclusion that the number of multiple readings was not associated with the correlation possibly because of sample power as only seven studies with single measurements were included. There are 5 studies are absence of the number of measurements, which would be temporarily regard as single reading BP measurement. For lack of the detailed information of the number of measurement at present, such as these blood pressures were measured at the same time or at separate time interval, that would be first assumed that the number of BP measurements less than 3 were taken at the same times. As regards the number 6, it is treated that BPs were measured 3 times on each of 2 successive separately visits.

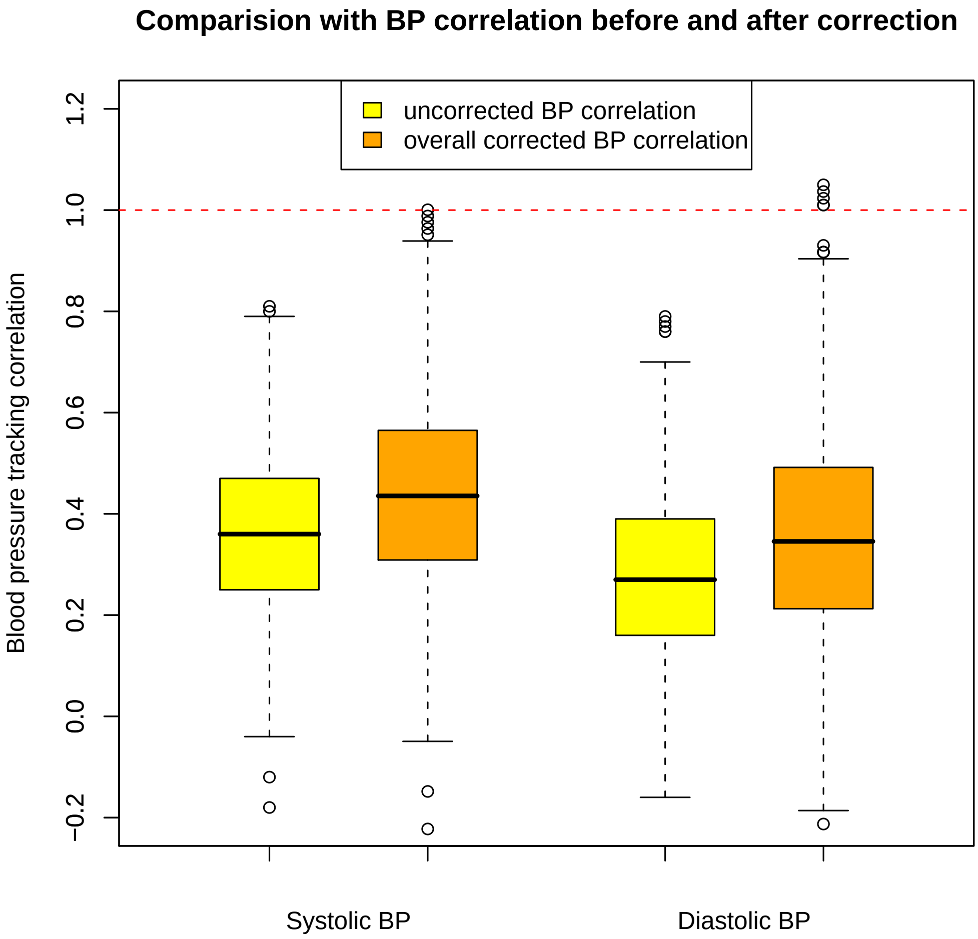


Figure 4.9: Comparision wtih BP tracking correlation before and after overall correction

The results have been also shown in Figure 4.9. The median/mean correlation coefficient is 0.3600/0.3686 (0.2700/0.2861) for systolic (diastolic) measurements in uncorrected data. The median/mean tracking correlation corrected by reliability coefficient increase to 0.4354/0.4439 for systolic BP and 0.3456/0.3670 for diastolic BP, respectively. There is only one correlation for systolic BP greater than one (1.0007) after correction, but it is very close to 1, while there are five correlations for diastolic BP larger than one, which are within the range of 1.01 to 1.05. This phenomena lead to debate whether a procedure that resulted in a correlation greater than one is valid. Many explanations for correction for attenuation due to measurement error supposed flaw have been suggested. Spearman[57] has explained corrected correlation greater than 1.0 as the normal result of sampling error. Worded more explicitly, this asserts that corrected correlations of these values range from 1.01 to 1.05 should fall within the sampling distribution of corrected correlations produced by a population with a true-score correlation less than or equal to one. Others, including Johnson [58], demonstrated that random errors would occasionally raise the level of observed correlations above the true-score correlation. In conclusion, both fluctuations in observed coefficients due to errors of measurement and fluctuations caused by errors of sampling could lead to the phenomena that corrected coefficients are greater than unity.

4.4.2.2 Age-specific Correction for Tracking of BP Measurements

Since important age trends were found in the levels of the reliability among children and adults, in Figure 4.10 illustrates the age-specific corrected tracking corrections for both systolic and diastolic by used the reliability coefficients in Table 4.3. These estimates were compared with estimates from previously computed overall corrected correlations where similar methods of correction and assumption were utilized. Here, it should to be remarked that the tracking reliability coefficients at two time points of the follow-up for a subject are not always the same. For example, for longer follow-up, in which the children would be grown to manhood, and that there are some difference of the variance components for BP measurements among children and adults, particularly for diastolic pressure for younger children. Data that span the period from childhood to early adulthood would be useful in further evaluating tracking correlations crossover age group. Therefore, such variety of reliability coefficients at the beginning and end of the follow-up is taken into account when we correct the BP tracking correlation.

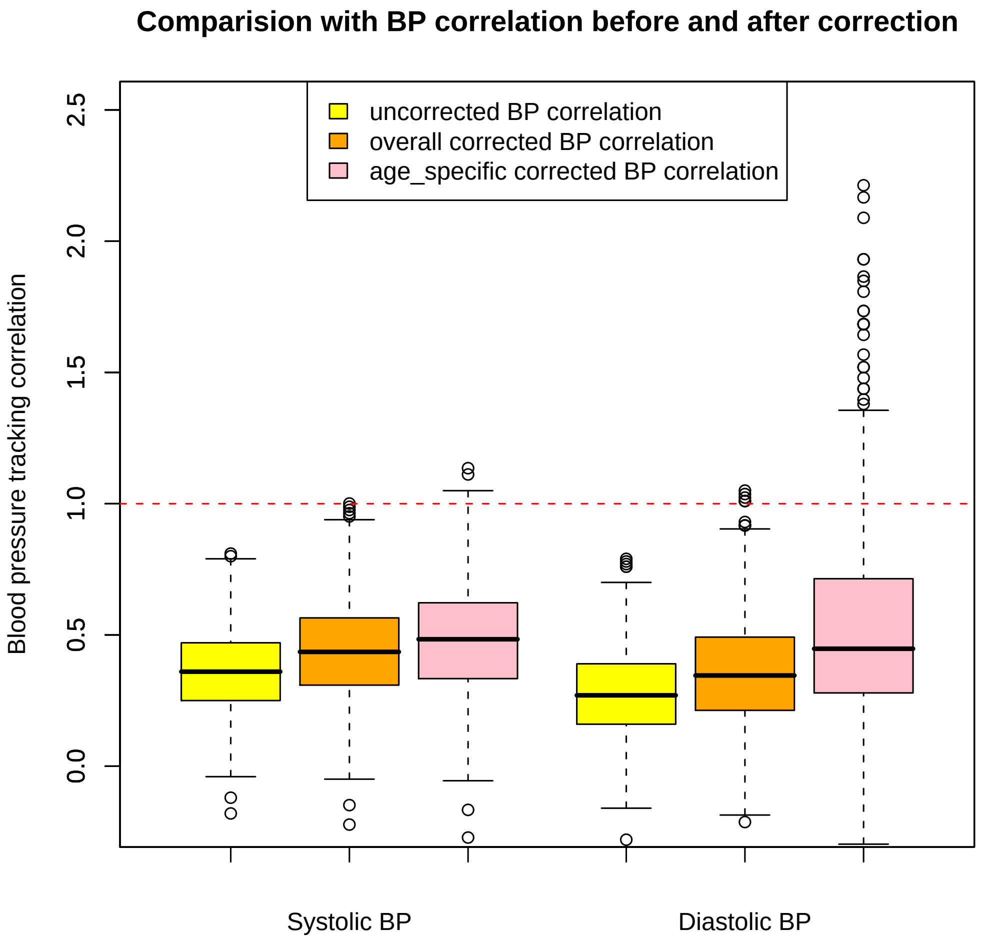


Figure 4.10: Comparision wtih BP tracking correlation before and after overall/age-specific correction

As shown in Figure 4.10, although the effect of correcting tracking correlation is improved, there are 6 (1.6%) correlations for systolic pressure greater than one and 46 (12.0%) correlations for diastolic pressure exceeding one. These results of correction are quite implausible. After check-up these invalid data, we find that the correlations greater than one are mostly with the number of measurements of 2 or 3, which might be the assumption of the number of BP measurements is improper. It may well be that these BPs were obtained in separately examinations. Therefore, the correction process is carried out once more after changing the assumption of the number of BP measurements. However, the results are still unsatisfactorily. There are 3 (<1%) correlations for systolic pressure greater than one and 28 (7.3%) tracking correlations for diastolic pressure greater than one. In these 28 correlations, 23 correlations of them with age at baseline are younger than 13 years old. It can be concluded that the reliability coefficient of diastolic pressure for pre-adolescent children in Table 4.3 are too small. Based on the above findings (Chapter 4.3), the so low reliability coefficient is due to the double effect of the larger within-person variance (21.91) and small between-person variance (79.1) of diastolic pressures for children under 13 years old. The data from Osborne *et al.*[59] are used to validate the magnitude of the variance components of diastolic pressure for pre-adolescent children and estimate the corresponding coefficients of reliability. They examined the sources and amount of variation present in the blood pressure of 99 third grade children, using data collected from three repeated measurements made on three separate visits and reported that the between-subject variance for diastolic pressure is 41.99 and within-subject variance is 71.57. Comparison with those from Rosner *et al.*[49], there is no remarkable difference between the within-person variance, but the between-person variance from Osborne *et al.* (41.99) is much higher than that from Rosner *et al.* (21.91). One of possibilities is the between-person variance of diastolic pressures for younger children were underestimated in the Rosner *et al.*'s data. The relevant reliability coefficients used the variance information from Osborne *et al.* are presented in Table 4.4.

Table 4.4: Coefficients of reliability of measured blood pressure according to number of visit and replications averaged in age group 6-9 years

Age Group: 6-9 (pre-adolescent children)								
Number of visits	Systolic BP Replications per visit (K)				Diastolic BP Replications per visit (K)			
(J)	1	2	3	limit	1	2	3	limit
1	0.5024	0.5376	0.5505	0.5781	0.3698	0.4063	0.4202	0.4510
2	0.6688	0.6993	0.7101	0.7327	0.5399	0.5779	0.5917	0.4510
3	0.7518	0.7772	0.7860	0.8043	0.6377	0.6725	0.6850	0.7113
4	0.8015	0.8230	0.8305	0.8457	0.7012	0.7325	0.7435	0.7667

Since they did not compute the inherent BP variability of between-visit and within-visit, we assume that the coefficient M equal to 2.5 for diastolic BP measurements among the pre-adolescents, namely, the between-visit variance is 2.5 times bigger than the within-visit variance in BP measurements, which have estimated by Rosner *et al.*. Comparing Table 4.4 with Table 4.3, the reliabilities for systolic pressures from Rosner *et al.*'s data are slightly higher than those in Osborne *et al.*'s data. The difference is understandable that the children who were measured BPs by Osborne *et al.* are in the age group 6-9 years, however, targeted children in Rosner *et al.*'s data are under 8-12 years age. The different age groups lead to the difference of the reliability of measured BP. As expect, the reliabilities for diastolic pressures from Rosner *et al.*'s data are lower than those in Osborne *et al.*'s data. With these reliabilities to correct the tracking correlations of diastolic pressure among pre-adolescent children may be eliminate the implausible corrected correlations exceeding unity.

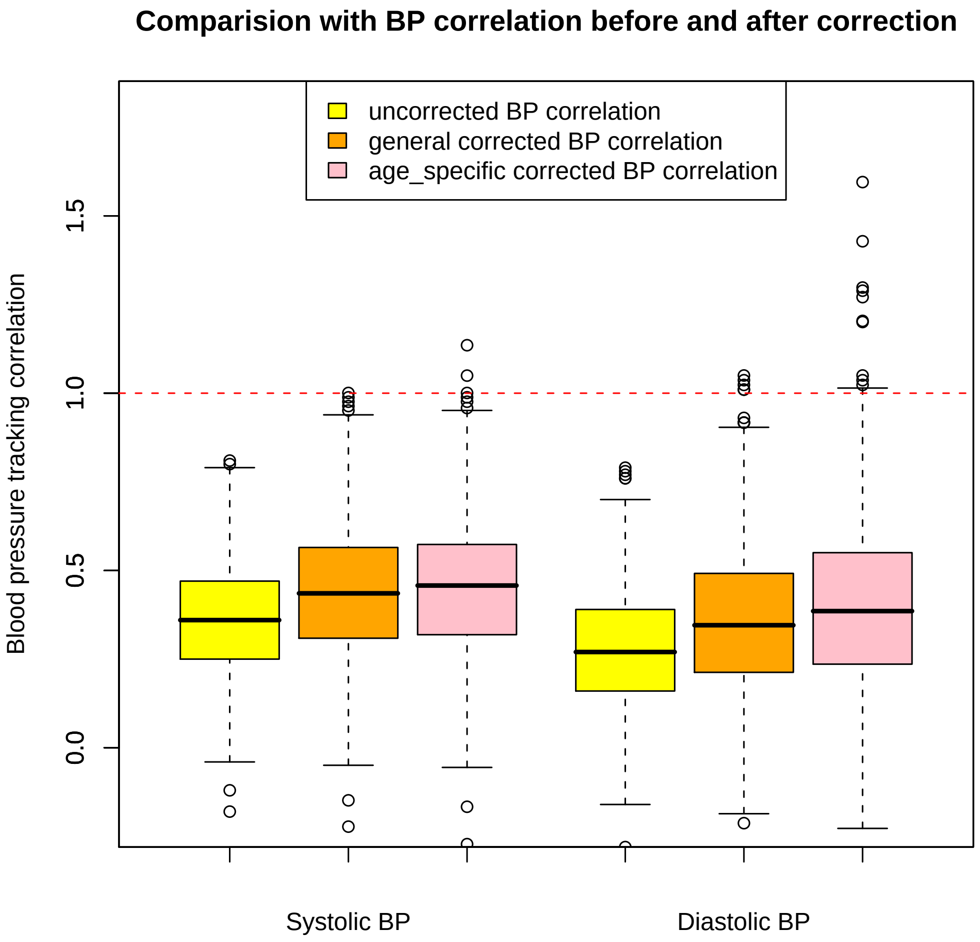


Figure 4.11: Comparision wtih BP tracking correlation before and after overall/age-specific correction (improved Reliability of diastolic pressure for pre-adolescent children)

Figure 4.11 visualizes the results of the corrected tracking correlations. The validity of correction is improvement. There are 13 (3.4%) correlations of diastolic pressure greater than one, but the proportion among all diastolic correlation excesses 1%. Because of absence of the original articles, we can not conclude that these correlations of diastolic pressure exceeding unity are overestimated. It may well be that these tracking correlation had been already corrected in the studies. Moreover, we find that the systolic BP measurements are more stable than diastolic ones. This pattern may explain why systolic blood pressure was generally a better predictor than diastolic pressure of coronary heart disease and cardiovascular disease.

4.4.2.3 Meta-regression

Toschke *et al.*[56] used meta-regression to estimate the effect of follow-up length on blood pressure tracking. They reported that a random intercept model by cohort nested within study was the most appropriate model and the follow-up time (FU) and mean age at baseline (Age_{i1}) were significantly associated with the correlation coefficients, while gender, method of blood pressure measurement and continent of study origin were not for both systolic and diastolic BP correlation. We carry out the same analyses to show the effect of the pooled correlation coefficient corrected due to BP measurement errors by contrast. The meta-regression models are expressed as follow:

$$\begin{cases} Y_{it} = \beta_0 + \beta_1 FU_{it} + \beta_2 Age_{i1} + b_i + \epsilon_{ij} \\ b_i \sim N(0, \sigma_b^2) \\ \epsilon_{ij} \sim N(0, \sigma_\epsilon^2), \end{cases}$$

where Y_{it} is the tracking correlation for systolic or diastolic blood pressure in ith cohort at the follow-up time t.

Table 4.5: Results of final meta-regression model including follow-up time and age at baseline (based on uncorrected BP measurement)

	Pooled correlation coefficient by baseline age		
	10 years at baseline	20 years at baseline	25 years at baseline
Systolic blood pressure			
Over 1 year	0. 4220	0. 4564	0. 4735
Over 5 years	0. 3908	0. 4251	0. 4423
Over 10 years	0. 3517	0. 3860	0. 4032
Diastolic blood pressure			
Over 1 year	0. 3030	0. 3427	0. 3626
Over 5 years	0. 2809	0. 3206	0. 3405
Over 10 years	0. 2533	0. 2930	0. 3128

Table 4.6: Results of final meta-regression model including follow-up time and age at baseline (based on age-specific corrected BP measurement)

	Pooled correlation coefficient by baseline age		
	10 years at baseline	20 years at baseline	25 years at baseline
Systolic blood pressure			
Over 1 year	0. 5356	0. 5704	0. 5877
Over 5 years	0. 4963	0. 5310	0. 5484
Over 10 years	0. 4472	0. 4819	0. 4993
Diastolic blood pressure			
Over 1 year	0. 4697	0. 4982	0. 5124
Over 5 years	0. 4368	0. 4653	0. 4795
Over 10 years	0. 3957	0. 4242	0. 4384

The Table 4.5 and Table 4.6 exhibit the uniform trend that weaker systolic and diastolic BP tracking with long follow-up. The predicted 1-year follow-up error-corrected BP tracking correlation coefficient (Table 4.6) at baseline age 10 years is about 0.54 for systolic BP and 0.47 for diastolic BP. The corresponding figures for 5-year and 10-year follow-up are 0.50 (0.44) and 0.45 (0.40) for systolic BP (diastolic BP), respectively. An another clear trends that the higher the age at baseline, the higher the tracking has been also shown in Table 4.5 and Table 4.6. The adjusted 1-yr follow-up pooled correlation (Table 4.6) for systolic BP in cohorts with baseline age of 20 years is 0.57. This adjusted correlation coefficient increased slightly over time to 0.59 for 25-year people. The age difference may be biologic, as tracking may be lower during the teenage years because of variable rates of growth and maturation among children. The overall estimates are slightly lower for diastolic compared with systolic measurement, yet present the same trend.

To sum up, as for uncorrected BP measurements, the systolic and diastolic BP corrected for measurement error show a better tracking effect. Lower correlation was found with longer intervals between two blood pressure measurements on the same group of people. Variability was a function of the time interval in which observations are made. Correlations were lower for diastolic than for systolic pressure, as had be anticipated, because within-person variance constitutes a larger proportion of the total population variance of diastolic than of systolic pressure.

Chapter 5

Correct Measurement Errors in Tracking of BMI

5.1 Sources of Error in Measurement of Body mass index

The body mass index (BMI), which is derived from two other measurements, will include the components of measurements of measurement error inherent in the constituent height and weight measurements. It is presumed that the measurements of stature and body mass are simple task and that provided sufficient care is taken, any error will be so small that it can be safely ignored. Is that presumption virtually true? To answer the question, we first find out the main sources of error in measuring body mass and stature. They can be summarized as the evitable and inevitable errors.

5.1.1 Measurements Errors of BMI due to Evitable Factors

The precision of height and weight measurements depends on instrument and their calibration, technique of the observers - the measuring and recording techniques, examination environment and individual factors. Besides individual factors, the other factors can be improved or be evitable through training and following recommended protocols. John H. Himes[60] summarized several crucial reminders for reducing errors in measuring height and weight, as shown in Table 5.1. Errors in instrument assembly, instrument reading, and data recording are common, but can be minimized in a straightforward manner by utilizing computerized data entry or editing at the measuring site[61]. In most settings, however, errors associated with the observers are the chief sources of measurement error in measurements of height and weight. Obviously, it is still important to have appropriate measuring equipment, but once they are installed and calibrated, little measurement error usually is due to the instruments. In a highly controlled research laboratory with experienced anthropometrists, the mean inter-observer (absolute) differences for standing height and weight are 0.3 cm and 0.02 kg, respectively[62]. Often, height and weight measurement for BMI are collected in clinical or other settings in which data collection may be hurried and observers may not have been trained as rigorously as observers in research settings. The extent of imprecision is likely to be increased if anthropometry is carried out by poorly trained individuals. Since anthropometry is often regarded as less complicated to carry out than many other measures of nutritional status, measurement is often delegated to lower-qualified staff.

Table 5.1: Data-collection practices for reducing errors for Height, Weight. (were summarized by John H. Himes[60])

Equipment and space
- Choose appropriate equipment
- Check and calibrate equipment regularly
- Keep extra batteries for scales
- Provide a private area for child measurements, if possible

Measurement protocols
- Chose a protocol that matches that used in the growth charts
- Have written copies of measurement protocols available for review
- Train and standardize data collectors
- Make sure data are recorded in the appropriate units (eg, kilograms, pounds)
- Make sure data are measured and recorded to the nearest unit specified in the protocol (eg, 0.1 cm for height, 0.1 kg for weight)
- Collect some replicate measurements for assessment of reliability, if feasible

Personnel
- Use as few observers as is feasible to take measurements, especially for research studies
- Identify observers on data-collection forms or data-entry programs

5.1.2 Measurements Errors of BMI due to Inevitable Factors

Through careful standardization can reduce the effects of the factors that undermine the precision of the measurement of height and weight by the greatest extent, such as well-calibrated instruments, standardized recording and reporting system, training and following recommended protocols. However, some factors can almost impossible to be eliminated due to the individual inherent physiological variability. One of the important but largely ignored measurement errors is diurnal variation. Likewise, the normal day-to-day variation within an individual also leads to component of measurement error. This inherent variation probably results from many sources including hydration, gastrointestinal and urinary bladder contents, diurnal hormonal fluctuations, salutatory growth, fidgeting, alterations in position and fatigue[63, 64].

It is well know that morning stature is greater than evening stature due to the compression of intervertebral cartilages[65]. Rodríguez *et al.*[66] evaluated the degree of differences in daily height and weight measurements, corresponding body mass index. 32 children aged between 7.1 and 14.9 years were measured at 8 A.M, 12 noon, 4 P.M and 8 P.M on the same day. The results are given in the Table 5.2 and Table 5.3.

Table 5.2: Mean values of anthropometric measurements at 8 A.M., 12 noon, 4 P.M., and 8 P.M. on the same day are expressed as means standard ± deviation.

	8 A.M.	12 noon	4 P.M.	8 P.M.
Weight (kg)	39.71 ± 12.5	39.78 ± 12.25	39.84 ± 12.39	39.98 ± 12.37
Height (cm)	144.69 ± 15.41	143.84 ± 15.39	143.71 ± 15.33	143.52 ± 15.28
BMI (kg/m^2)	18.50 ± 3.26	18.78 ± 3.26	18.87 ± 3.27	18.94 ± 3.23

Data adopted from Table 2 of Rodríguez *et al.*[66]

As shown in Table 5.2, during the childhood there is diurnal decrease in height and increase in weight and BMI.

Table 5.3: Mean variation and corresponding standard deviation of anthropometric measurements at 12 noon, 4 P.M., and 8 P.M. from the measurements taken at 8 A.M

	Variation 8 A.M. - 12 noon	Variation 8 A.M - 4 P.M.	Variation 8 A.M. - 8 P.M.
Weight (kg)	0.065 ± 0.68	0.223 ± 0.58	0.270 ± 0.61
Height (cm)	-0.83 ± 0.49	-0.96 ± 0.59	-1.15 ± 0.54
BMI (kg/m^2)	0.27 ± 0.34	0.36 ± 0.27	0.43 ± 0.29

Data adopted from Table 2 of Rodríguez *et al.*[66]

Height - In the study form Rodríguez *et al.*[66], the difference of height between 8 A.M. and 8 P.M. was -1.15 ± 0.54 cm. Kobayashi and Togo[67] measured stature and body weight for two children, 12.5 and 9.3 years, and their mother twice daily for 488 days, immediately after rising and just before bed. Stature decreased during the day, and the mean daytime loss was 1.78 cm in the older child, 1.61 cm in the younger child, and 1.43 cm in the adult. Stature increased during sleep hours at night, and the mean nighttime gain was 1.79 cm, 1.63 cm and 1.43 cm in each subject, respectively. Stature also increased after naps and a bath. Diurnal change of stature in Kobayashi and Togo's study were greater than those in other studies since the measurements were taken immediately after rising in the morning. The physiological factor that could explain this phenomenon is the diurnal loss of volume produced in intervertebral discs, mainly the lumbar ones[68]. When the individual is standing, rapid height loss occurs in the early hours of the day[69, 70] and continues throughout the day[66]. However, the process of height loss may be halted if an afternoon nap is taken[71]. Height measurement could therefore be made more accurate by standardizing the time of day at which measurements are made.

Weight - Diurnal weight variations may be affected by the circadian changed produced in total body water, food intake and anomalies in the individual's state of hydration. During the night, in supine position, and before breakfast, the processes of transpiration and metabolic expenditure (glycogen and fat) continue, producing a redistribution of body fluids from the extracellular compartment to the intracellular compartment and from the extremities toward the central circulation[72]. Furthermore, children have proportionally more total body water than adults and different body composition according to age and sex[73]. Irregularity of defaecation could be a source of variation of body weight. The weight of faeces, according to Hutchison and Hunter[74], is 120-180 g/day. However, Edholm *et al.*[75] recorded body weight changes from day-to-day in 140 young soldiers and concluded that irregularity of defaecation could be only a minor cause of weight irregularity, the weight of faeces varied from 75 to 210 g in their study. Moreover, they reported that there were significant correlations between change in body weight and food intake, and also with energy expenditure. Khosla and Billewicz[76] recorded daily weights in 19 subjects of both sexes of both sexes, their ages ranging from infancy to 58 years. Their main finding was that the extent of daily fluctuation of body weight was related to body weight itself. The maximum change of body weight from one to the next rarely exceeded 1.5% of body weight. Robinson and Waston[77] recorded day-to-day variation in body weight of young women and found that 13.4% of the daily variations exceeded 0.5 kg and 1.8% were greater than 1 kg. They considered it was likely that the daily fluctuations were primarily due to alterations in body water. This set of above factors may make it difficult to obtain satisfactory exactitude and precision when measuring body mass.

BMI - BMI may undergo changes in the course of the day if there are variations in either of the two determining variables. In Rodríguez *et al.*'s study, BMI is totally 2.44% greater at 8 P.M. than 8 A.M. Height decrease, raised to the square, produces an increase in BMI that is indirectly proportional. Moreover, weight increase, observed in the evening, also contributes to this BMI increases. Another issue that are worthy of our attention on estimate the diurnal error variance of BMI is the correlation between the diurnal error of height and weight. On the basis of above results, there are opposite changes of height and weight from morning to evening. Hence, we assume that the correlation between the diurnal error of height and weight is slightly -0.2 and the diurnal error SD of weight and height are 0.5 kg and 1 cm, respectively for the children group of Rodríguez *et al.*'s study[66]. And the anthropometric measurements in Table 5.2 at 8.A.M are used to compare the diurnal error variance of BMI and its corresponding reliability through simulations under different assumptions. The results of simulations presented in Figure 5.1 shows that the diurnal error variance of BMI is somewhat high if there are slight correlation between the diurnal error of height and weight. Nonetheless, the difference between the corresponding simulated reliabilities due to only diurnal errors of height and weight are very small. The median reliability based on the slight correlation between diurnal errors of height and weight is 0.988 and that based on no corresponding correlation is 0.986. That is to say, although there are possibly slight correlation between the diurnal error of height and weight, the effect of such a correlation upon the reliability might be ignored when the measurement error of BMI are corrected. However, the extent of diurnal error of height and weight are must be taken into account.

In conclusion, if an individual has been measured first in the morning and in the later exam in the afternoon, the measurements of height and weight would be slightly different and body mass index would be calculated incorrectly. Thus, when the results of height and weight are recorded, it is also important to record the time of day at which the measurements were made. To avoid the measurement with diurnal error, it can be suggested that, if an individual's height and weight measurements have been taken morning (or afternoon) consequent measurements should be taken at the same time of the day. However, in practice, it is difficult to standardize this physiologic within-individual variation when a large number of individuals are measured, so it is usually ignored for most purposes.

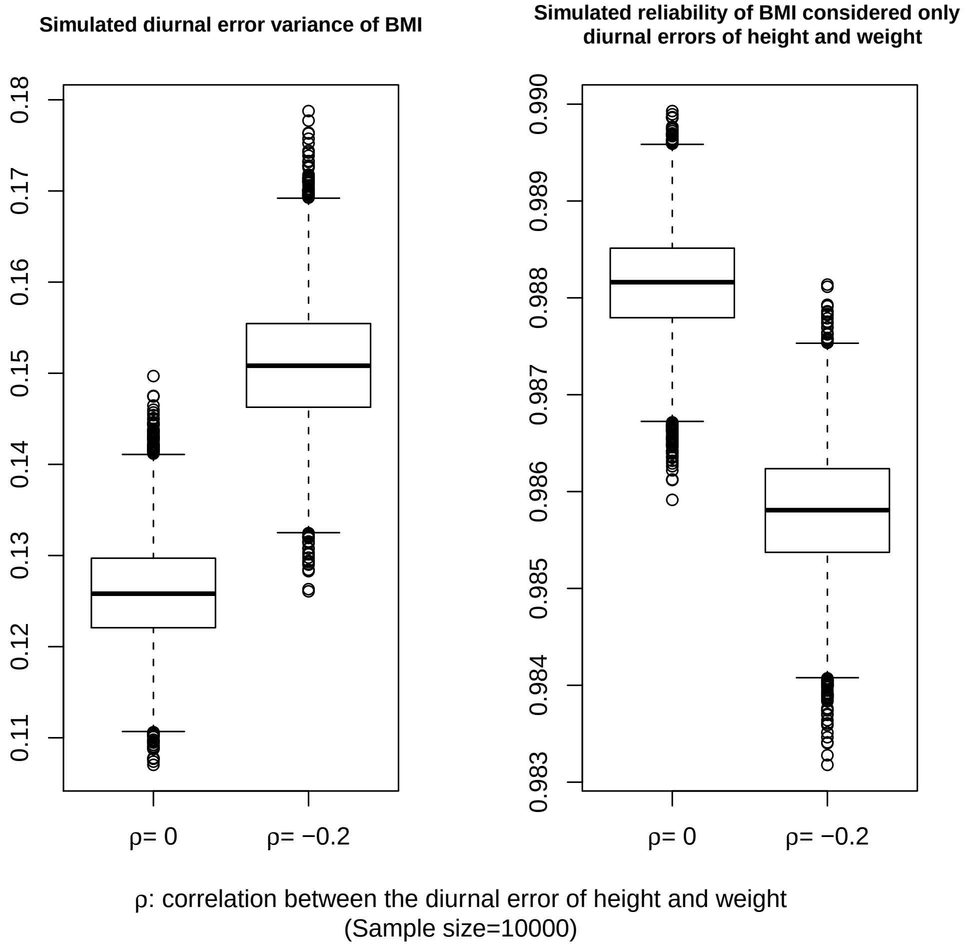


Figure 5.1: Comparision with simulated diurnal error variance of BMI and the corresponding reliability under different conditions of the correlation between the diurnal error of height and weight

5.2 Comparisons of Reported Reliability Coefficients for BMI

There are few studies reported the reliability of body mass index, which are present in Table 5.4 . Mueller *et al.*[78] and Mueller and Kaplowitz[79] estimated the intra and inter-observer reliability coefficients of BMI for children. These values are very high for height and weight and a composite index, the BMI is made up of the two former measures. But the time intervals between examinations in both studies are too short to reflect the within-individual physiological fluctuations in the reliability coefficients. That is to say, they can be regarded as the precisions of the BMI, which are only estimated the amount of the measuring errors in measurement of individuals' body mass, stature and the derived variable BMI. Comparing the intra-observer and inter-observer precision reliabilities in Table 5.4, it can be found that in the group of children, the inter-observer precision for height and weight are the same excellent as the intra-observer precision for them, and that the inter-observer precision (0.97) for BMI is slightly lower than intra-observer precision (0.99), nonetheless, 0.97 is still a highly precise level. The examiners in these studies had been well trained in measuring height and weight for children. It can be concluded that observers through regular training can minimize the imprecision in measurement of height and weight, at the same time reduce the difference between the examiners effectively. Furthermore, we can reasonably infer that because of well cooperation between adults and examiner, the precisions of the measuring of height, weight and derived BMI for adults might be better than those for children, at least not be worse; whereas, the imprecision for infants might be relatively high due to the lack of cooperation.

Table 5.4 shows that the reliabilities from Liu and Schutz's study[6] are generally slightly lower than those from Mueller *et al.*[78] and Mueller and Kaplowitz[79]. Anthropometric measurements were collected by Liu and Schutz one year apart in a 3-year-period investigation. The factor that the interval between repeated measurements was longer in Liu and Schutz's study (1 year as opposed < 1 day) may account for some of the differences, particularly in the case of weight that varies greatly from day to day. Although the reliability coefficients for one-year time interval could reflect both measuring errors and physiological fluctuations, such reliabilities might include additional variations due to some artificial factors. Particularly, women are keen on dieting to slim down. However, purposive control or reducing body weight leading to the change of body mass is not spontaneous physiological fluctuations. Thus, it is crucial to take the time interval between examinations into consideration when reliability coefficients are utilized to correct measurement errors in research.

Table 5.4: Reported values for intra-observer and inter-observer coefficient of reliability

Source	Observed subjects	Time interval between examinations	BMI		Height		Weight	
			intra[a]	inter[b]	intra[a]	inter[b]	intra[a]	inter[b]
Mueller *et al.* (1996) [78]	10-13yr Children	$<$ 1 day (or within hours)	0.99	0.99	0.99	0.99	0.99	0.99
Mueller and Kaplowitz (1994) [78]	8-9yr Children	$<$ 1 day (or within hours)	0.99	0.97	0.99	0.99	0.99	0.99
Liu and Schutz (2000) [6]	premenopausal females	1 year	-	0.94	-	0.98	-	0.95
Liu and Schutz (2000) [6]	premenopausal females	1 year	-	0.93	-	0.98	-	0.94
Nordhamm *et al.* (2000) [80]	adults	1-3 weeks apart	1.00	-	1.00	-	1.00	-

Intra[a] = Repeated measures by the same observer;
Inter[b] = Repeated measures by different observer.

Likewise, Nordhamm *et al.*[80] estimated the reliability of anthropometric measurements for adults group, where each individual was examined on two occasions 1-3 weeks apart. The reliability coefficients of weight, height and derived BMI in their study are perfect (1.00), which can reflect both measuring errors and short-term physiological fluctuations. Can we deduce a conclusion from that, it could be ignored the measurement errors when the body mass index are calculated for adults. We can not draw hasty conclusions through one research result alone, it requires more further studies to confirm the deduction.

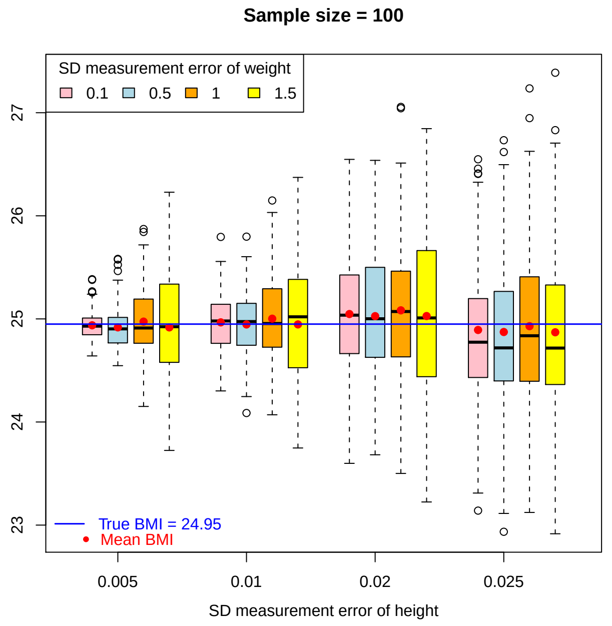
5.3 The Reliability of Ratio Variable

Another important issue to be discussed is the reliability of a ratio variable, recent research indicates that even when the component variables are reliable, it does not automatically guarantee a derived ratio variable appropriate reliability. The reliability of a ratio variable is more complex than the reliability of a raw score variable because it is affected by several factors, specifically, the reliability of the numerator and denominator variables, the correlation between the two component variables, and the relative variation of the two variables[81]. It is expected that a ratio variables is less reliable than its component variables in repeated measurements because both are the numerator and denominator variables. Is this so for the BMI? However, the BMI is a ratio with very high reliability from previously published papers as shown in Table 5.4. For the sake of verification that facticity, a small simulation would be carried out on a group of adult men aged from 25 to 29 years old, whose mean height is 176.7 cm with standard deviation (SD) 7.0 cm and mean weight is 77.9 kg with SD 14.6 kg. These data are taken from the National Health Examination surveys. Let it be supposed that the SD measurement error of height is 0.5 cm, 1 cm, 2 cm and 2.5 cm and the SD measurement error of height is 0.1 kg, 0.5 kg, 1 kg, and 1.5 kg, respectively. Their corresponding reliability coefficients and the simulated reliability for the derived ratio variable BMI are presented in Table 5.5. Despite some unrealistic assumed value for the SD measurement error of height (> 1cm) and weight (> 1 kg), the purpose is just to investigate whether the derived ratio variable BMI is the same reliable as its component variables.

Table 5.5: Simulated reliability coefficients of BMI (25-29 yr Males: weight 77.9 ± 14.6 kg; height 176.7 ± 7.0 cm)

Simulated reliability coefficients of BMI (sample size: 10000)					
Measurement error SD of weight	Reliability coefficients of weight	Measurement error SD of height			
		0.5 cm	1 cm	2 cm	2.5 cm
		Reliability coefficients of height			
		0.9945	0.9796	0.9184	0.8724
0.1 kg	0.9999	0.9561	0.9561	0.9047	0.8752
0.5 kg	0.9988	0.9184	0.9153	0.8757	0.8424
1.0 kg	0.9953	0.8696	0.8647	0.8061	0.7876
1.5 kg	0.9894	0.8188	0.7772	0.7553	0.7501

Table 5.5 shows that the reliability coefficients of BMI are generally lower than those of its component variables weight and height. When the height and weight are highly reliable, it can result in the high reliability coefficient of BMI. It may well be that the reliabilities of height and weight, the individual variables in the index, are themselves so high as to have little impact on the reliability of the BMI. However, if component variables have great error variance, it would bring much greater error variance on the derived ratio variable BMI. One of the possible reasons might be explained this phenomenon is the ratio transformation of height caused systematic error when calculating BMIs. Through a simulation once more, the results as shown in Figure 5.2 are beyond our expectation. Not the ratio transformation but rather the sample size distorts the distribution of BMIs. Sampling error determined by small sample size affects the true distribution of BMIs much more than a ratio transformation. That is to say, the ratio transformation in deriving BMIs do not cause the systematic error, but it might enlarge variation of the derived BMIs and reduces the reliability of BMI. The simulations also confirm that the individual variables in the body mass index with small error variations can guarantee the derived ratio variable BMI high reliability, which accounts for why the reliability coefficients of BMI in previously published data are so high (see Table 5.4). These results suggest that the BMI have well reliability to be used in assessment of physical activity and fitness for human.



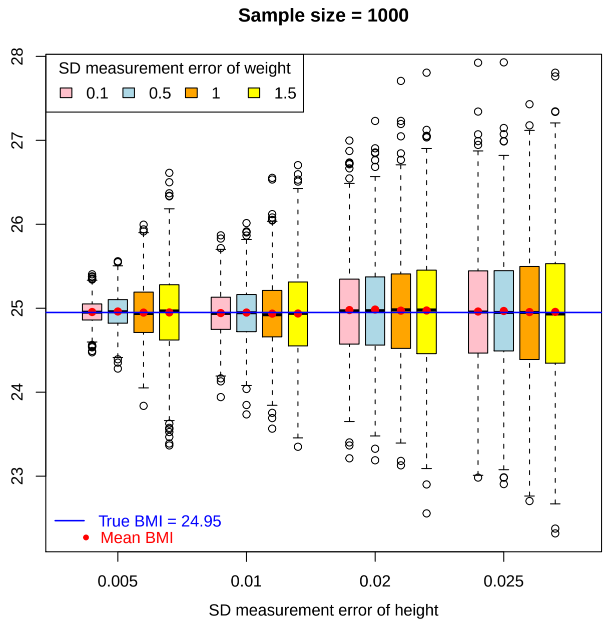


Figure 5.2: Comparison of the effects of sample size and ratio transformation on the distribution of observed BMI

5.4 Derivation of Reliability for BMI form its Components

5.4.1 Overview of Reliabilities for Components of BMI-Height and Weight

On account of the reported reliability of BMI from previously published studies that cannot always meet the requirements of reflecting the measuring errors and physiological fluctuations in a short-term interval, maybe we can derivate the reliability of BMI from their components: weight and height. Furthermore, only few studies directly published and analyzed the reliability coefficient of the BMI, but relatively more researches were assessed the reliability for weight and height measurements, which are given in Table 5.6.

For adults, the reliability in measuring body weight and stature are always excellent (> 0.96) except the reliability for stature in women (0.65) reported by Harrison *et al.*[82]. The difference might be accounted for an open-ended (indefinite) time interval for investigation. However, stature is an instable variable for adults, even though the observation interval is very long. This is can be proved from results from Liu and Schutz's study[6], where the reliability of height for woman during one year is 0.98. Thus, there must be other factors leading to so low reliability (0.65) in Harrison et al.'s study. Most subjects in Harrison *et al.*'s study[82] were measured in their homes during routine home visits, while some adults were taken in a clinic environment when they visited the clinic. Owing to the different instrument and technique of measurements in home and clinic environment, it might be results in greater measuring errors.

For children group, the reliability of weight and height measurements are very high (> 0.94) except the values published by Harrison *et al.*[82]. They measured weight and height within 2-3 months. It is probably that the 2-3 months time interval is too long to estimate the unreliability of measurements for children, particularly for toddler and children during the puberty and adolescence. Because in these periods children are at the peak of growth, they are much likely to become taller and heavier within 2-3 months spontaneously. Such factor of growth might be explained why the reliability coefficients in Harrison *et al.*'s study[82] are so low.

The intra-observer error is slightly smaller than inter-observer error with what we expect leading to the inter-observer reliabilities are generally slightly high than the intra-observer ones.

Table 5.6: Reported values for intra-observer and inter-observer reliability of height and weight

Source	Observed subjects	Time interval between examinations	Height (Length)		Weight	
			Intra^a	Inter^b	Intra^a	Inter^b
Infants						
Harrison *et al.* (1991) [82]	0-6 mothers infants	within 2 weeks	-	-	-	0.99
Children						
Pelletier *et al.* (1991) [83]	1-2 yr children	10-20 minutes	0.9803	0.9722	0.9896	0.9827
Harrison *et al.* (1991) [82]	1.5-2.5 yr Children	within 2 months	-	0.88	-	-
Harrison *et al.* (1991) [82]	1.5-2.5 yr Children	within 2 weeks	-	-	-	0.69
Martorell *et al.* (1976) [84]	1.5-2.5 yr children	5-9 day	-	0.99	-	0.94
Benefice and Malina (1996) [85]	5.5-6 yr children	within 1 day	-	0.98	-	0.95
Malina and Moriyama (1991) [86]	6-10 yr children	5-14 days	0.99	-	0.99	-
Lohman *et al.* (1975)[87]	6.3-12.9 yr boys	within 2 weeks	-	0.99	-	0.99
Harrison *et al.* (1991)[82]	7-9 yr Children	within 3 months	-	0.61	-	-
Harrison *et al.* (1991)[82]	7-9 yr Children	within 1 month	-	-	-	0.94
Benefice and Malina (1996) [85]	9-11 yr children	within 1 week	-	0.99	-	0.98
Zavaleta and Malina (1982) [88]	9-14 yr boys	1 day apart	0.9977	-	0.9972	-
Malina *et al.* (1973) [89]	12-17 yr	2-3 weeks	0.9982	0.9965	0.9811	0.9792
Adults						
Marks *et al.* (1989) [90]	Adult men	two week or more	-	0.9979	-	0.9984
Marks *et al.* (1989) [90]	Adult women	two week or more	-	0.9958	-	0.9980
Marks *et al.* (1989) [90]	Adult men	within 1 day	-	0.9988	-	1.00
Marks *et al.* (1989) [90]	Adult women	within 1 day	-	0.9974	-	1.00
Harrison *et al.* (1991) [82]	Adult men	any two measure-ments not on the same day	-	0.95	-	-
Harrison *et al.* (1991) [82]	Adult women	any two measure-ments not on the same day	-	0.65	-	-
Harrison *et al.* (1991) [82]	Adult men	within 2 months	-	-	-	0.97
Harrison *et al.* (1991) [82]	Adult women	within 2 months	-	-	-	0.96

Intra^a = Repeated measures by the same observer;
Inter^b = Repeated measures by different observer.

5.4.2 Methods and Procedures for Derivation the Reliability for BMI

5.4.2.1 Derivations

In order to derive the reliability of BMI from its components: height and weight, fist at all, it should be known how the measurement errors of height and weight combinatorially influence on the unreliability of measuring BMI.

Let $Weight^*$, $Height^*$ and BMI^* denote measured variables with respective measurement error ε, δ and η. Hence we have the following equations:

$$Weight^* = Weight + \varepsilon;$$

$$Height^* = Height + \delta;$$

$$BMI^* = BMI + \eta.$$

Now we assume that the measurement error of weight (ε) and the measurement error of height (δ) are independent. Although there are strong correlations between the height and weight, it is also reasonable to be assumed that there are no correlations between their measurement errors due to different measuring instruments and methods of them. But there is an exception: the diurnal error of height and weight are likely to be slightly correlated. Owing to the body mass index defined as weight (kg) divided by the square of height (m), it can be also expressed:

$$BMI^* = \frac{Weight^*}{Height^{*2}} = \frac{(Weight + \varepsilon)}{(Height + \delta)^2}, \tag{5.1}$$

which is considered as a function that depends on ε and δ, and then we obtain the approximation through the first order Taylor expansion at the point $(\varepsilon_0 = 0, \delta_0 = 0)$:

$$BMI^* \approx \frac{Weight}{Height^2} + \frac{\varepsilon}{Height^2} - \frac{2 \cdot Weight \cdot \delta}{Height^3} = BMI + f(\varepsilon, \delta), \tag{5.2}$$

if we neglect terms of the second order.
The equation (5.2) can also be expressed as

$$BMI^* \approx BMI(1 + \frac{\varepsilon}{Weight} - \frac{2 \cdot \delta}{Height}) = BMI(1 + RE_{Weight} - 2 \cdot RE_{Height}), \tag{5.3}$$

where the terms $\frac{\varepsilon}{Weight}$ and $\frac{\delta}{Height}$ are the relative measurement errors of weight and height, respectively. From the equation (5.3), we can find that the factor of measurement errors for height has double effects on derived BMI than that of weight if the relative measurement error of height and weight are equal. Hereby, we discover an interesting result that the relative measurement error of BMI (RE_{BMI}) could be obtained by estimating of the relative measurement error of height and weight. The mathematical expression see below:

$$BMI^* = BMI(1 \pm RE_{BMI}) \approx BMI(1 \pm RE_{Weight} \pm 2 \cdot RE_{Height}), \quad (5.4)$$

namely,$RE_{BMI} \approx RE_{Weight} \pm 2 \cdot RE_{Height}$.

5.4.2.2 Simulations

First, since the equation (5.4) is an approximate equation, it is necessary to check whether $RE_{Weight} \pm 2 \cdot RE_{Height}$ can be regarded as an estimator of RE_{BMI} before it is applied in practice. We select two typical groups of anthropometric measurements, one's true height is 1.75 m and weight is 80 kg, and the true derived BMI is 26.12, another's true height is 1.0 m and weight is 16 kg, and BMI is 16, which can be represented an adult and a child respectively. On the assumption that the relative measurement error of weight and height of 0.1%, 0.5%, 1% and 1.5%, simulation are carried out under different combinations of the relative measurement error of height and weight in two groups. The results of simulations are illustrated in Figure 5.3 and Figure 5.4.

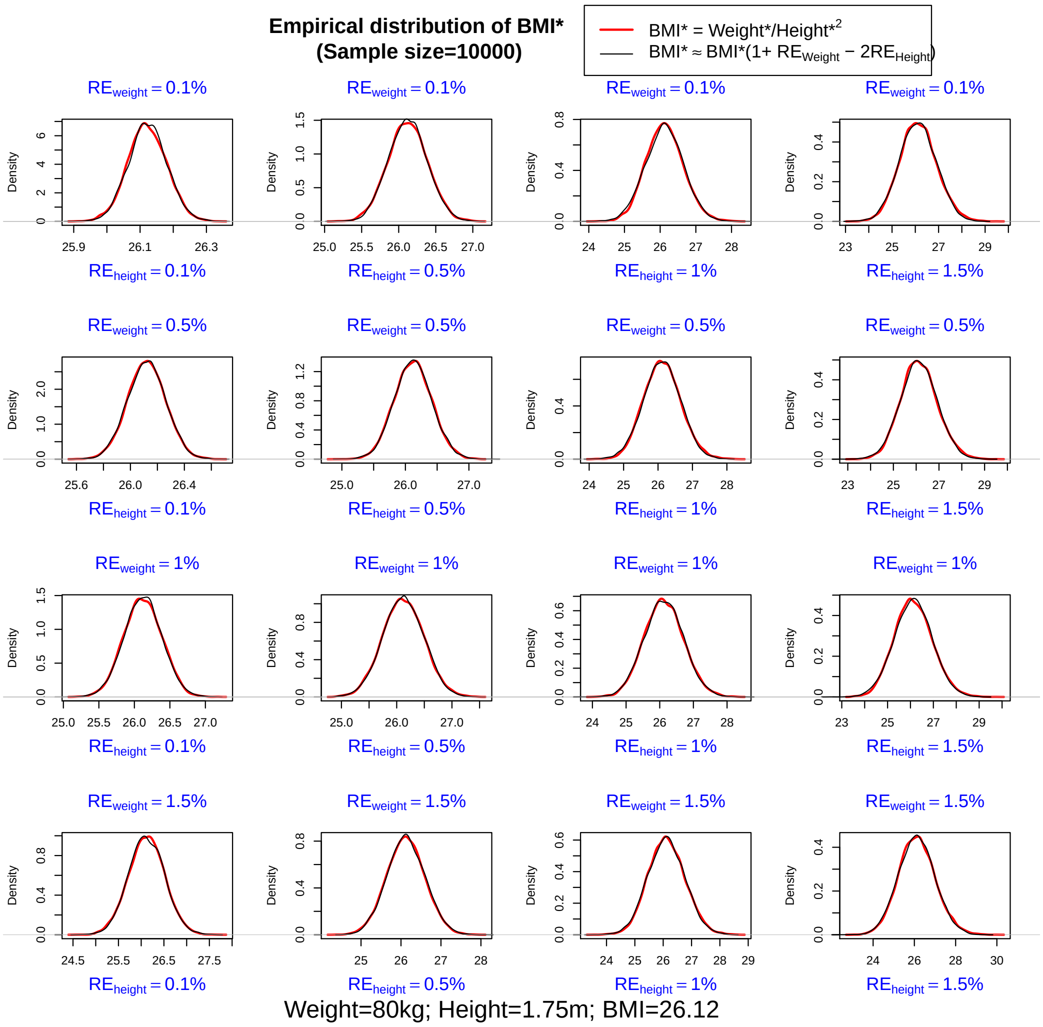


Figure 5.3: Empirical distribution of an adult's BMI under different relative measurement errors of height and weight

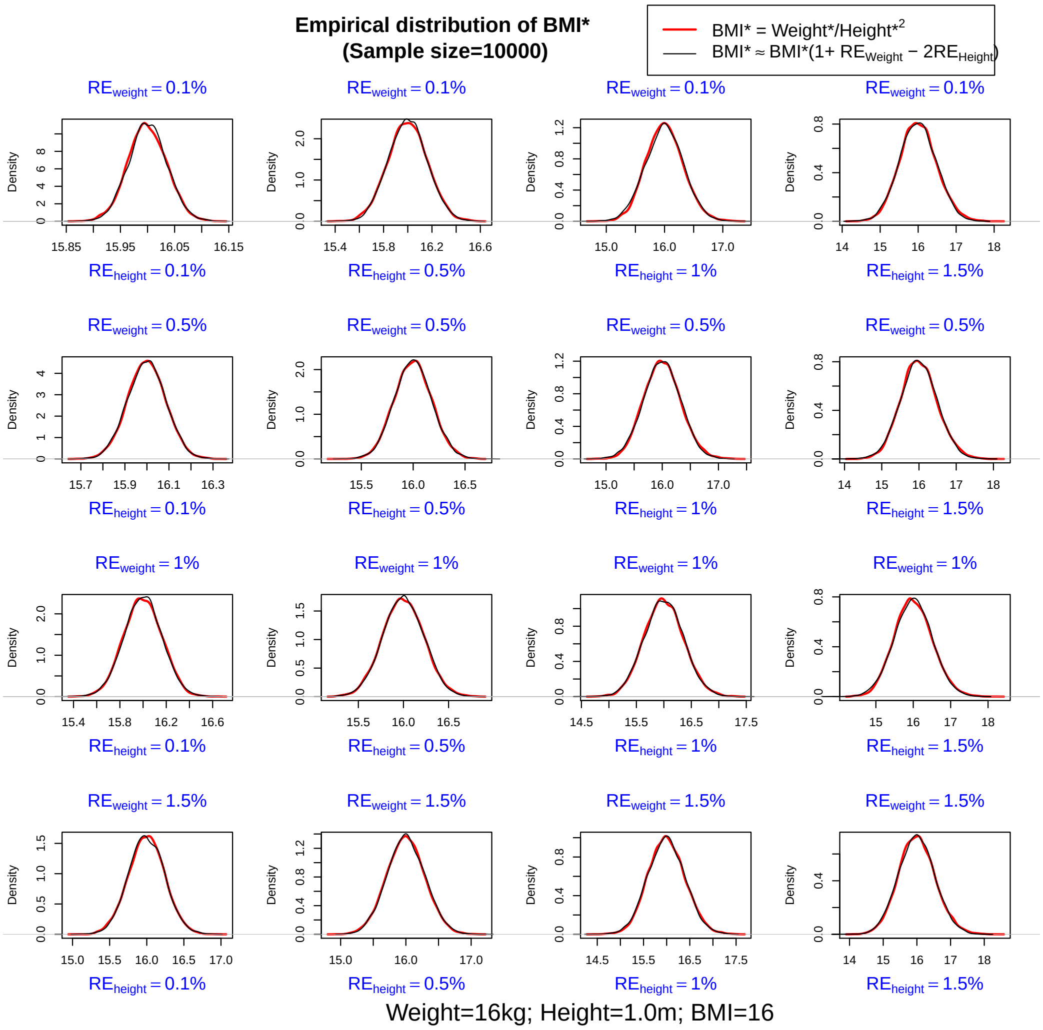


Figure 5.4: Empirical distribution of a child's BMI under different relative measurement errors of height and weight

The distribution curves in Figure 5.3 and Figure 5.4 show whether for an adult or a child, the empirical distributions of BMI^* with exact relative errors of height and weight and with approximate relative errors of height and weight are nearly identical. That is to say, the term $RE_{Weight} \pm 2 \cdot RE_{Height}$ can be regarded as a good approximation of the relative measurement error of BMI. This result would help us to estimate the variance for the measurement error of BMI and the corresponding reliability coefficients.

Previously, it has been assumed that the measurement error of weight (ε) and the measurement error of height (δ) are independent. Now a further assumption that fluctuations of the measurement errors of BMI (η) are only depend on the measurement error of weight (ε) and the measurement error of height (δ) are made to obtain an approximation of $Var(\eta)$. Namely, the magnitudes of height and weight are regarded as constants when estimating the variance of the measurement errors of BMI (η). The following mathematical expression is derived from the equation (5.2):

$$Var(\eta) = Var(f(\varepsilon, \delta)) \approx \frac{Var(\varepsilon)}{Height^4} + \frac{4 \cdot Weight^2 \cdot Var(\delta)}{Height^6}. \tag{5.5}$$

Likewise, we use above-mentioned two examples of an adult and a child to check the approximation equation (5.5). According to the mean diurnal differences (physiological fluctuations) for height and weight between 8 A.M. and 8 P.M., are about 0.01 m and 0.27 kg respectively among children between 7.1 and 14.9 years old (Table 5.3), we thus use $Var(\varepsilon)$ ranged from 0.1 to 0.5 and $Var(\delta)$ ranged from 0.00001 to 0.00005 to carry through the simulation. The results of simulations given in Figure 5.5 show that the approximation equation (5.5) can be thought of as a nearly exact estimator of variance of the measurement errors of BMI. Furthermore, it can be found that the variance of measurement errors of BMI for a child is affected by the measurement error of weight more apparently than that of height. However, for an adult the effects of the measurement error of weight and height influence closely on the measurement error of BMI. That is because the relative measurement error of weight for a child is much greater than that for an adult when body weights are measured with the same absolute errors. For instance, for an absolute measurement error of 0.5 kg, a 80-kg adult is measured with 0.625% relative error, however, a 16-kg child is measured with 3.125%.

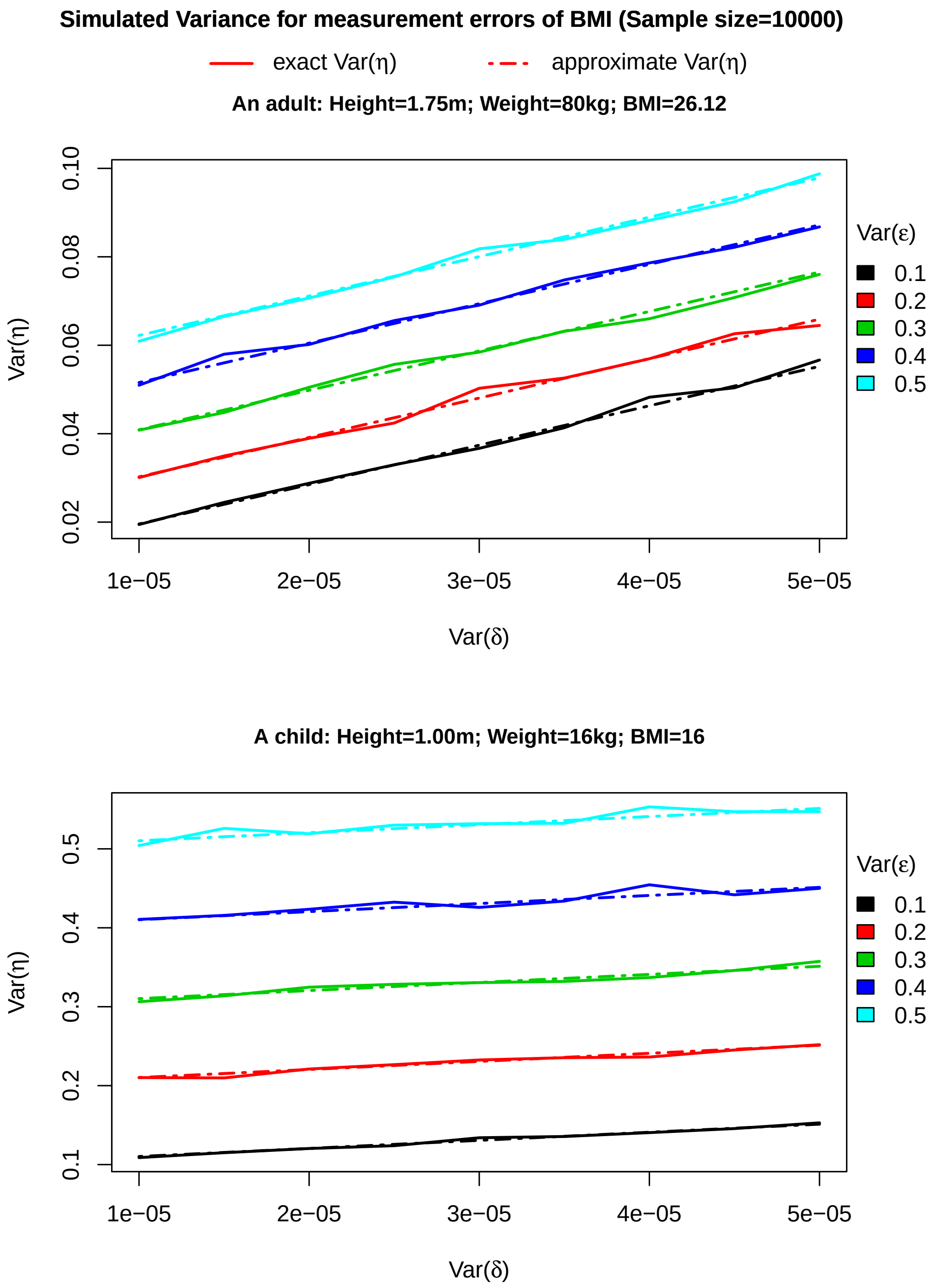


Figure 5.5: Comparison of the exact and approximate $Var(\eta)$ under different simulation conditions of $Var(\varepsilon)$ and $Var(\delta)$

5.4.2.3 Results

Next, we utilize the approximation equation (5.5) to observe the impacts of the measurement error of weight (ε) and the measurement error of height (δ) upon the measurement error of their derived BMI (η). And as for the extent to the height and weight, we use the mean height and weight by age from Frisancho[91], which are based on the largest database from National Health Examination surveys.

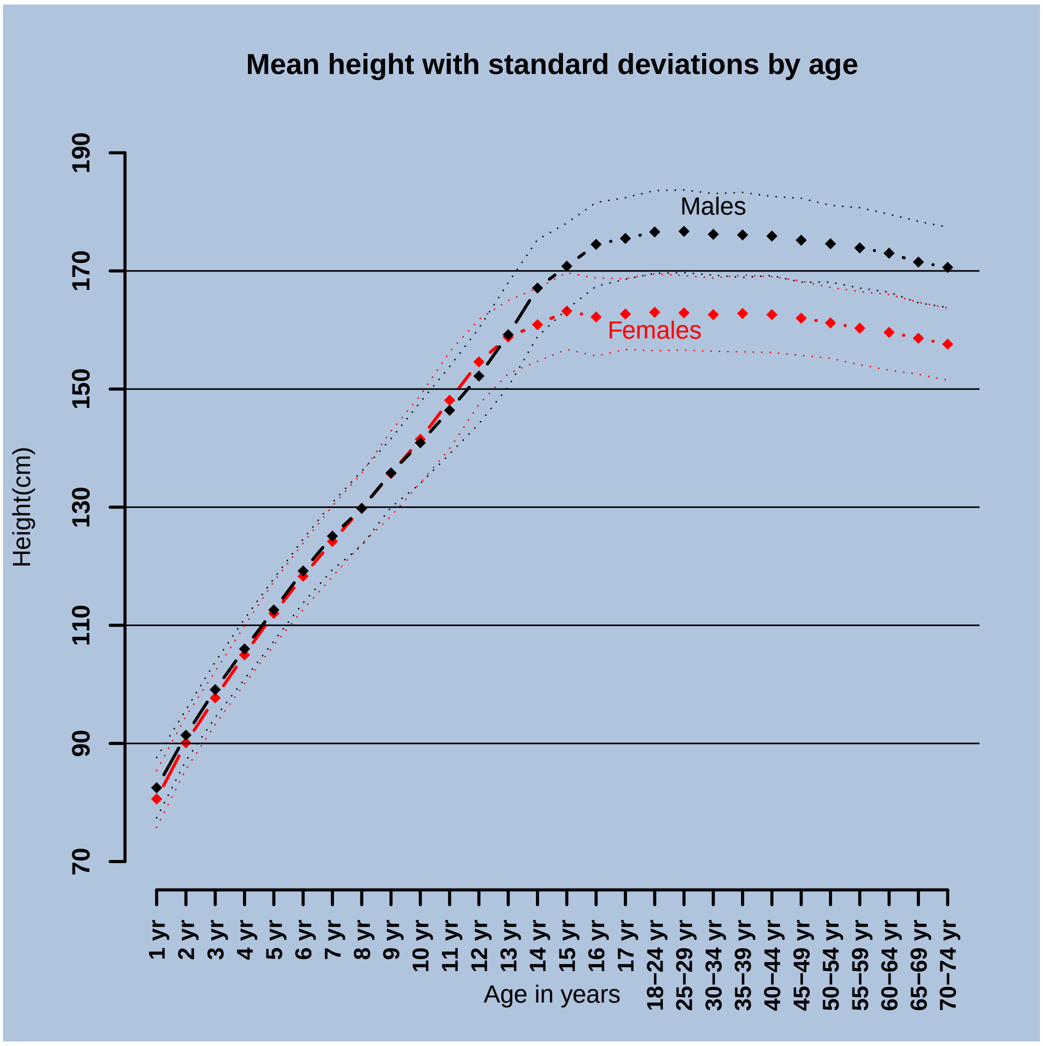


Figure 5.6: Mean height with standard deviations by age for males and females of 1 to 74 years
(Data adopted from Frisancho[91] Table IV.1)

Figure 5.6 shows that children grow taller year to year until 18 year olds and keep stable during adulthood, but up to the senectitude (> 50 yr) their mean height decreases slightly. Adult males are generally taller than adult females.

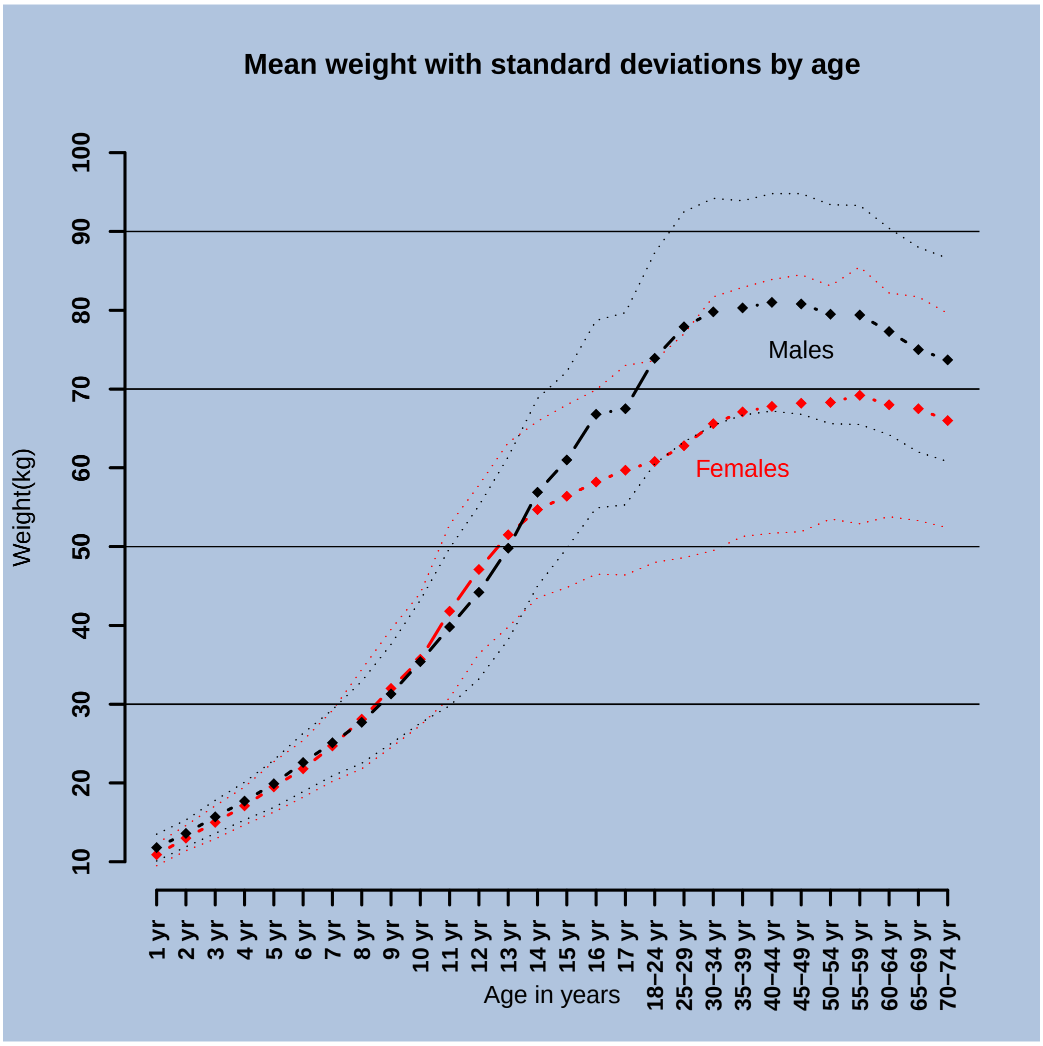


Figure 5.7: Mean weight with standard deviations by age for males and females of 1 to 74 years
(Data adopted from Frisancho[91] Table IV.2)

Figure 5.7 presents that children grow heavier year to year until 18 year olds and keep growing during adulthood, but up to the senectitude (> 50 yr) their mean weight decreases slightly. Form adolescence on, boys are generally heavier than girls until their late years.

Table A.1 in appendix shows that the variability of measurement errors for BMI (η) under different conditions of $Var(\varepsilon)$ and $Var(\delta)$. Comparisons across a row show that the variability increases slight with the variability of measurement errors of height. Comparisons down a column show that the variability increases with the variability of measurement errors of weight. Science the variation of measurement errors for weight is greater than those for height, the measurement error of weight have more influence than measurement error of height on measuring the BMI. Moreover, there are no obvious differences between males and females in all age groups.

Furthermore, we can also estimate the reliability for BMI through the above results from the A.1 for the variability of measurement errors of BMI by using the following equation:

$$R_{BMI} = \frac{Var(BMI)}{Var(BMI^*)} = \frac{Var(BMI^*) - Var(\eta)}{Var(BMI^*)} = 1 - \frac{Var(\eta)}{Var(BMI^*)},$$

where the total inter-individual variance for BMI ($Var(BMI^*)$) can be utilized the data from Frisancho[91], which are based on the largest database from National Health Examination surveys. Figure 5.8 illustrates the mean BMI with standard deviations by age for males and females of 1 to 74 years. From 5 years on, the body mass index continues to increase for boys and girls. And the variations of BMI become greater with age increasing. That is to say, the greater the magnitude of the body mass index, the greater their corresponding variability.

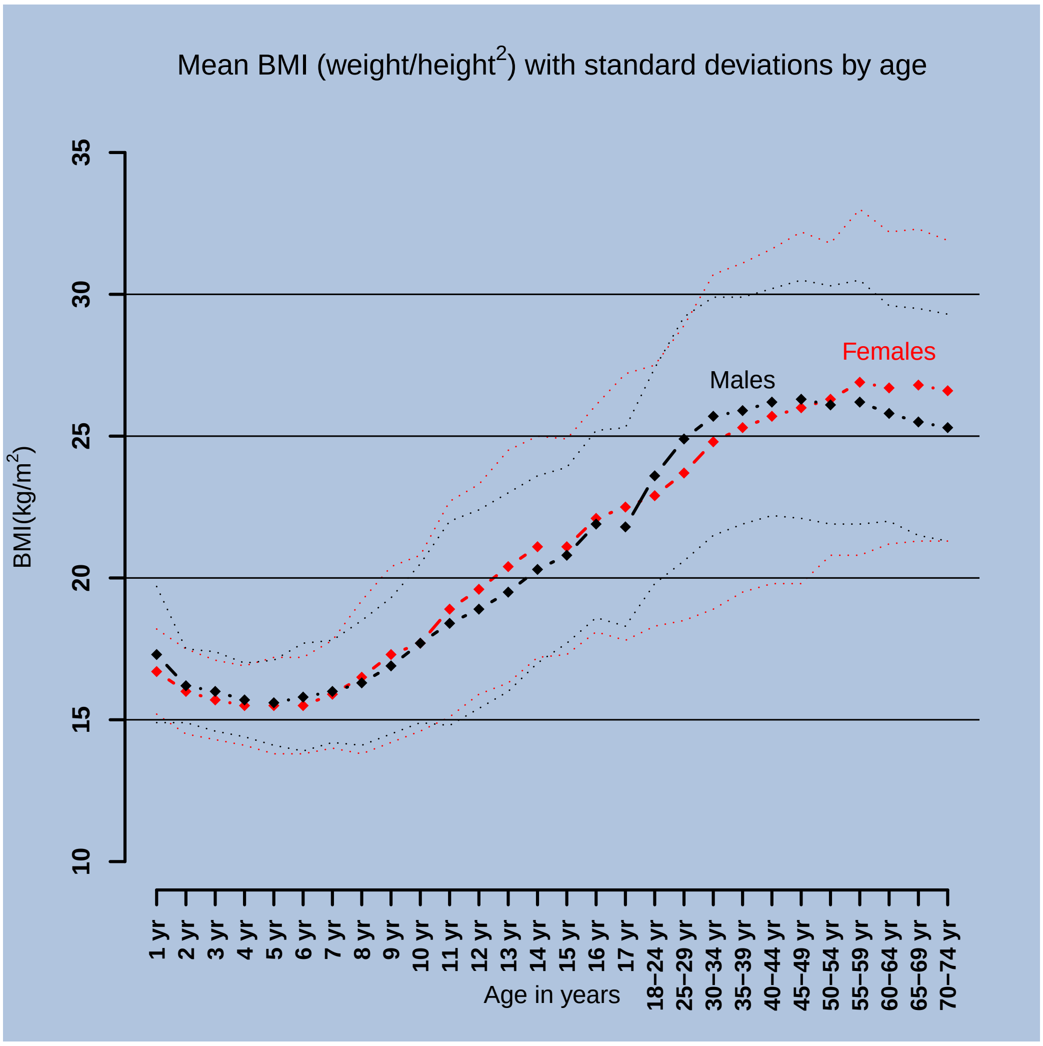


Figure 5.8: Mean BMI with standard deviations by age for males and females of 1 to 74 years
(Data adopted from Frisancho[91] Table IV.5)

The approximate coefficients of reliability of BMI are represented in A.2 in appendix. As a whole, the reliabilities of BMI are excellent (> 0.99) for individuals after passing into adolescence ($>= 13$ years old), which are in accordance with other previously reported results (Table 5.4). And for the pre-adolescent children (ages 8-12 years), the reliabilities for their measured body mass indexes are also quite high (> 0.95). However, the coefficients of reliability of BMI for the young children with the height under 1.2 m and weight lighter than 20 kg are relative lower if the variance of the measurement error of weights are comparatively greater ($Var(\varepsilon) > 0.3$), particularly, for the girls under 3 years old. One of possible causations is that the total inter-individual variances of BMI for children are remarkably lower in contrast with those for adults due to the small values of BMI for children in the nature of things, which has been shown in Figure 5.9. And because of that, the assumption that the variance for measurement errors of weight greater than 0.3 might not be in reason. For children younger than 3 years old, the mean weight is under 15 kg and the corresponding inter-individual variance is circa 4 kg. Moreover, it is easy to avoid measuring error when measuring children's body mass. Therefore, the measurement error variance of weight should be less than 0.3 for younger children. Another remarkable issue is that the measurement errors of height have less impact on accessing BMI than those of weight, which has been further observed in Figure 5.9 about the coefficients reliability of BMI.

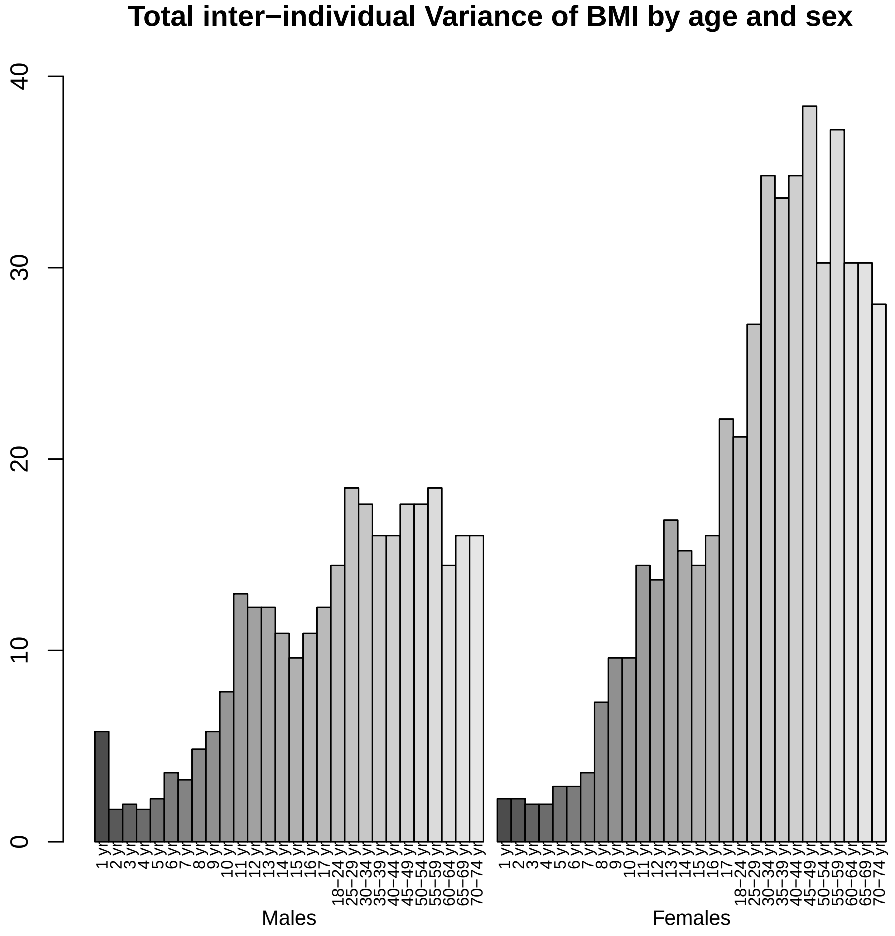


Figure 5.9: Comparison of the total inter-individual variance of BMI in different age and sex group (ages 1-74 years)
(Data adopted from Frisancho[91] Table IV.5)

5.4.2.4 Derivation of BMI ignored the Effect of Measurement Errors of Height

Through observing and comparing of coefficients of the reliability for weight and height from previously published data (Table 5.6), it can be found that whether for children or adults the reliability of stature in most cases is slightly higher than those of body weight. However, the equation (5.3) shows that the factor of measurement errors for height has double effects on derived BMI than that of weight if the relative measurement error of height and weight are equal. But in real life, the relative measurement error of height and weight might be not equal. To investigate the quantitative effects of measurement errors of height and weight upon the body mass index in real life, it would be assumed that BMIs are influenced only by one factor: the measurement error of weight or height. The mathematical expressions see below:

$$BMI^* \approx BMI(1 \pm RF_{Weight});$$

$$BMI^* \approx BMI(1 \pm 2 \cdot RF_{Height}).$$

We still apply above-mentioned practical examples. Supposing that the standard deviation of measurement error (including physiological variability) for height is 1 cm and for weight is 1 kg, the corresponding relative error of height for an adult is 0.57% (RF_{Height}) and that for a child is 1%, and the corresponding relative error of weight for and adult is 1.25% (RF_{Weight}) and that for a child 6.25%. The box-plot in Figure 5.10 shows that the simulated BMIs for a child only with measurement errors of weight have much greater fluctuations than those only with measurement errors of height. For an adult, the measurement error of weight affects the simulated BMIs slightly more than that of height. That is to say, in real life relative measurement error of weight is likely to be greater than that of height, consequently, the factor of measurement errors of weight influences more remarkable on derived BMI than the another factor of height, although the equation (5.3) in theory shows that the relative measurement error of height seems to has greater impact upon the BMI.

Through the simulation for combinations of the measurement error of height and weight, these finding in Table 5.6 are further confirmed. The variability of height measurement is more stable than that of weight, which is very useful to derive the reliability of BMI. It is supposed that humans' statures consider as being near to a constant, and then the reliability of BMI could approximate to the reliability of body mass. The procedure can be shown as following:

$$R_{BMI} = \frac{Var(BMI)}{Var(BMI^*)} = \frac{Var(Weight/Height^2)}{Var(Weight^*/Height^2)} = \frac{Var(Weight)/Height^4}{Var(Weight^*)/Height^4} = R_{Weight},$$

where * refers to a measurement with measurement errors. For the measurement of height with little measuring errors, the main source of short-term physiological fluctuations is diurnal variation. However, the diurnal difference between 8 A.M. and 8 P.M. is just about 1 cm [66], namely, 0.01 m. The BMI is defined as $Weight/Height^2$, where body weight is in kilograms and height is in meters. That is to say, the quantitative effect of the variability of height in short time upon the reliability of BMI is less than 0.0001 m. This value might be too small to influence the reliability of BMI, which has been observed from the simulation results (A.2). Therefore, it is reasonable to be assumed that height could be as a constant when deriving the reliability of the body mass index due to the information about the measurement error of height not available.

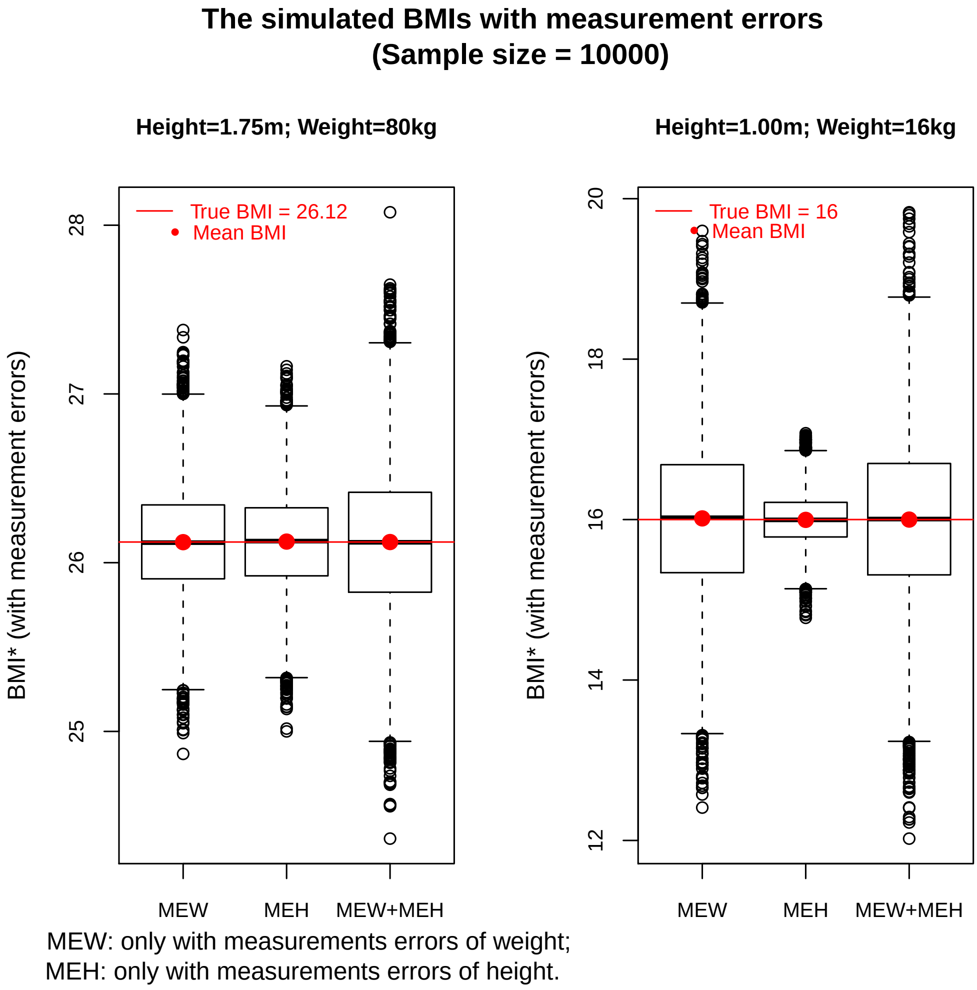


Figure 5.10: The Boxplot of simulated BMIs with different measurement errors

5.5 Methods and Design of the Practical Study

5.5.1 Data and Background

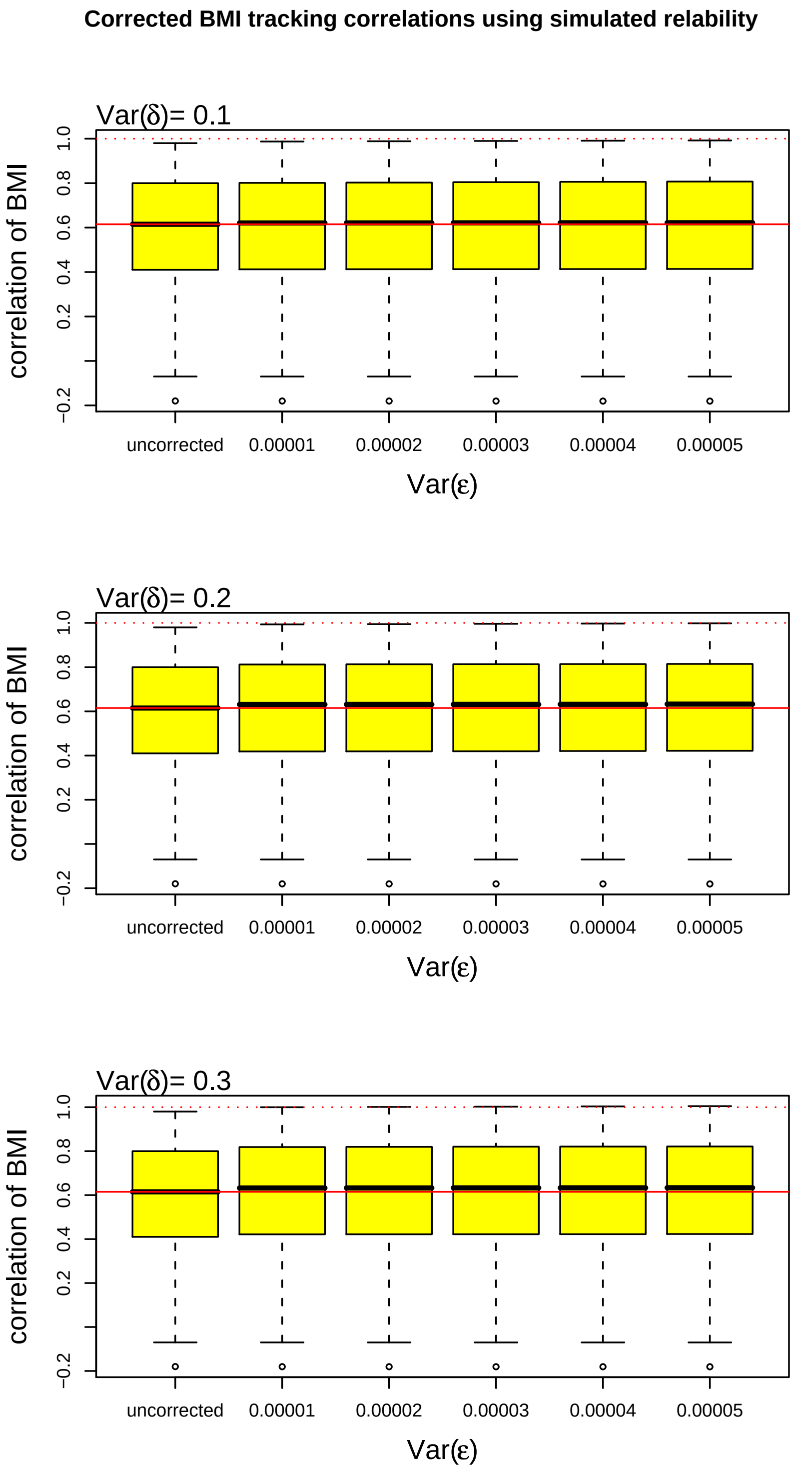
Toschke *et al.* have extracted the data about the tracking correlation of body mass index (BMI) from 48 publications with follow up times between 0.5 and 44 years. Duplicate articles of the same study were removed and only the article with most complete information, largest sample size, or earlier publication date was included. Basic information consisted of cohort size, (mean) age at baseline measurement and at follow up measurement, gender and origin of the studied population. The meta-regression analysis based on the extracted data showed a high degree of BMI tracking across all age groups and independent of BMI. In the present study, the short-term physiological fluctuations and measuring errors will be taken into account when we estimate the tracking correlation. We utilize the sub-data, from which the articles published spearman's rank correlation as the tracking correlation are excluded.

5.5.2 Statistical Analysis and Results

The primary concern is that how to select the appropriate reliability coefficients to correct the measurement error of tracking correlation. The factors that we should take into account are the age of subjects, the number of observers (single or more) and time interval between examinations. There are no researchers who had determined the optimal observed time interval, which can well and truly reflect the imprecision and short-term physiological fluctuations on measuring anthropometric measurements and derived BMI. Moreover, in meta-analysis there are no corresponding summary data available for estimating measurement intervals for weight and height of individuals throughout the whole age range. Although we are not able to archive that, we can select the reliability for BMI of the relatively reasonable time interval between examinations. They should meet the following criteria: a duplicate observation within a short term chosen to be long enough to capture short-term physiological variation in the actual measure but during which we would not expect functionally significant change (growth or change in body mass or composition) to occur. It is suggested as follow: for the adults group, it does not matter whether the observed time interval for measuring height is apart several months or weeks; but for measuring weight it should be remeasured within several weeks to guarantee no significant change by artificial factors;

for the children group, whether measuring height or weight the time interval between examinations should not exceed several weeks due to the factors of growth. Based on the above analysis, we chose the reliability of BMI from Table 5.4 and reliability of weight from Table 5.6 as the reliability of BMI, then the range for the reliability coefficients of BMI in the children group are 0.94 to 0.99 and it in the adults group is 0.99. At the same time, the simulate reliability coefficients of BMI from A.2 can also be as reference.

Figure 5.11 illustrates the BMI tracking correlation before and after correction under different conditions. The yellow box-plots in Figure 5.11 show the results of corrected BMI tracking correlations by using simulated reliability coefficients. When the measurement error variances of the weight (ε) are greater than 0.3, there are some corrected BMI tracking correlation exceeding one, nonetheless, their proportion among all correlation are less than 1%. The blue box-plots in Figure 5.11 visualize the results of corrected BMI tracking correlations according to the previously published reliability. When the reliability coefficients of weight as the reliability coefficients of BMI for children are smaller than 0.95, there are (3.6%) corrected correlation of BMI greater than one. On the whole, no obvious differences of the BMI tracking correlation before and after correction are observed in Figure 5.11. In contrast to blood pressures, the reliability of BMI is much higher. That is to say, the individuals' height and weight measurements and derived BMI have high precision and much less short-term variability of physiological fluctuation.


Corrected BMI tracking correlations using simulated relability
Var(δ)= 0.1
Var(δ)= 0.2
Var(δ)= 0.3
correlation of BMI
-0.2
0.2
0.4
0.6
0.8
1.0
uncorrected
0.00001
0.00002
0.00003
0.00004
0.00005
Var(ε)

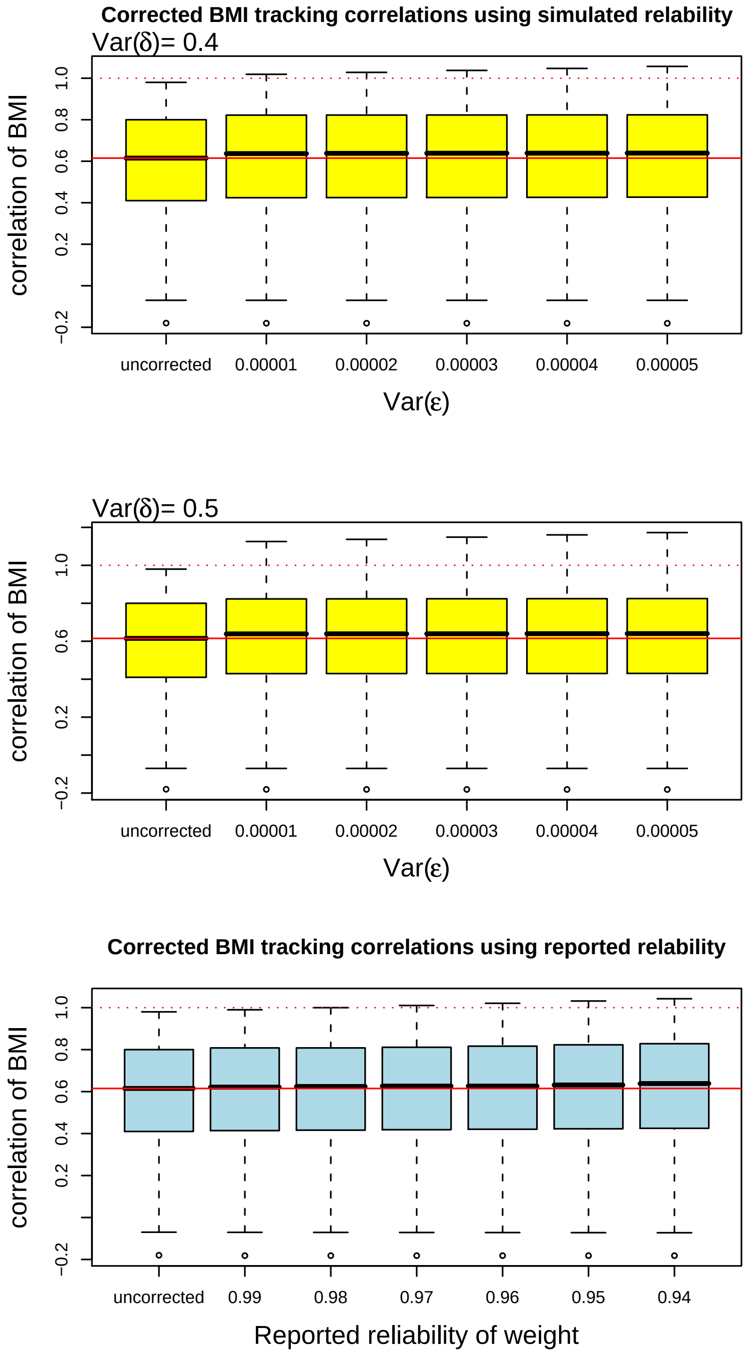


Figure 5.11: Comparison with BMI tracking correlation before and after correction under different conditions

Chapter 6

Summary

It is well know that all measurements are imperfect and always with some errors, whether the measurements be blood pressure, height, weight or other anthropometric measurements. If measurement errors are uncorrected before data analysis, they can affect the findings. In Section 2.3, we have showed the attenuation effect due to measurement errors upon the correlation coefficient. Therefore, in estimating tracking correlation in meta-analysis we must be aware of these problems, and careful to remove any sources of bias as far as we can. The classical additive measurement error model is used to analyze the measurement error in blood pressure, height and weight, which assumes that the measurement error is independent of true value. Although the other Berkson model allows the measurement error to be correlated with the true value and assumes the measurement error is independent of the observed value, the classical additive measurement error model is appropriate for our study, because true blood pressure, height and weight are fixed for an individual and the measured values are perturbed by error. To quantify the amount of error in measurement, the reliability of measurement is estimated, which measures the percentage of the observed variance that is true score variance. We can also correct the effect of measurement error in tracking correlation by using the reliability coefficient, but then it becomes more complicated in meta-analysis because of the necessary information to estimate reliability not available in each primary studies. To overcome the difficulty, the reliability is estimated by gathering of data from other studies that allows the useful information of measurement error to be reflected in the reliability coefficients.

The results of Meta-regression in Section 4.4.2.3 demonstrate that tracking correlations of blood pressure from childhood to manhood rise substantially after making correction procedure. These increases in tracking correlations after correction are caused by the factor that blood pressure varies in the same person for several readings at a particular visit days or weeks apart (within-visit variability) as well as over several visits days or weeks apart (between-visit variability). A number of authors have previously shown that the between-visit is large than the within-visit component[48, 52]. Therefore, the number of visits is more important than the number of measurements per visit in characterizing a person's true blood pressure and estimating tracking correlation relating blood pressure from one year to the next. Theoretically, the best estimate of tracking would derive from an infinite number of visits in each year. In practice, however, the optimal number of readings to estimate a person's annual blood pressure remains to be determined. From the data about reliability coefficients (Table 4.3) it appears that the greatest improvement in accuracy of measured blood pressures is from one to two visits, with progressively less improvement with three and four visits. In analysis of the BP reliability in childhood, these issues are particularly relevant because of the relatively larger inherent diastolic blood pressure variability over time in children compared with adults. That leads to the tracking correlations for diastolic pressure are less than those for systolic pressure. Thus, the characterization of a child's blood pressure is less precise for diastolic than for systolic pressure, resulting, in turn, in lower reliability. These differences in variability between systolic and diastolic may be a true biologic difference. Likewise, the reliability coefficients for systolic pressure is slightly high than those for diastolic pressure. That is to say, systolic blood pressure is generally a better risk predictor than diastolic pressure of cardiovascular diseases.

However, there are no obvious differences of BMI tracking correlation before and after correction of measurement errors because of the extremely high reliability of BMI. The previously published reliabilities of BMI in a less than one month time interval between examinations are excellent (>= 0.97). When using the reliability for children smaller than 0.95 to correct measurement errors in tracking of BMI, there are 3.6% tracking correlations greater than one. These results indicated that in contrast to blood pressure, the individuals' height and weight and derived BMI are measured with high precision and much less short-term variability of physiological fluctuation. At least, measurement errors are too small to influence the tracking effect of BMI. Although correcting measurement errors may not be necessary in tracking of BMI because of its very high reliability, we obtain a useful approximate formula to estimate relative error of BMI. This approximation formula based on first order Taylor expansion converts the measurement error of BMI that is ratio of the measurement error of height and weight into a linear combination of its components' measurement error, which have been checked in Section

5.4.2.2 through simulations. However, the first-order Taylor approximation may not always be appropriate, especially if the transformation is highly non-linear. In such cause, it may have to resort to higher-order approximations or other numerically intensive approaches. Fortunately, the results of simulations indicate that the fist order Taylor approximation can be furtherly used to estimate the measurement error variance of BMI and its corresponding reliability coefficient and it might be helpful to analysis the measurement error of BMI and correct them in meta-analysis or later research work.

Appendix A

Tables of Results

Table A.1: Variability of measurement errors for BMI(η) under different conditions

1-yr Males:
Height = 0.825 m ; Weight = 11.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.234	0.251	0.269	0.287	0.304
0.2	0.449	0.467	0.485	0.502	0.520
0.3	0.665	0.683	0.701	0.718	0.736
0.4	0.881	0.899	0.916	0.934	0.952
0.5	1.097	1.115	1.132	1.150	1.168

1-yr Females:
Height = 0.806 m ; Weight = 10.9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.254	0.272	0.289	0.306	0.324
0.2	0.491	0.509	0.526	0.543	0.561
0.3	0.728	0.746	0.763	0.780	0.798
0.4	0.965	0.982	1.000	1.017	1.034
0.5	1.202	1.219	1.237	1.254	1.271

2-yr Males:
Height = 0.914 m ; Weight = 13.6 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.156	0.169	0.181	0.194	0.207
0.2	0.299	0.312	0.325	0.337	0.350
0.3	0.443	0.455	0.468	0.481	0.493
0.4	0.586	0.599	0.611	0.624	0.637
0.5	0.729	0.742	0.755	0.767	0.780

2-yr Females:
Height = 0.901 m ; Weight = 13 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.164	0.177	0.190	0.202	0.215
0.2	0.316	0.329	0.341	0.354	0.367
0.3	0.468	0.480	0.493	0.506	0.518
0.4	0.620	0.632	0.645	0.658	0.670
0.5	0.771	0.784	0.797	0.809	0.822

3-yr Males:
Height = 0.991 m ; Weight = 15.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.114	0.125	0.135	0.145	0.156
0.2	0.218	0.228	0.239	0.249	0.259
0.3	0.321	0.332	0.342	0.353	0.363
0.4	0.425	0.436	0.446	0.456	0.467
0.5	0.529	0.539	0.550	0.560	0.570

3-yr Females:
Height = 0.977 m ; Weight = 15 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.120	0.130	0.141	0.151	0.161
0.2	0.230	0.240	0.251	0.261	0.271
0.3	0.340	0.350	0.360	0.371	0.381
0.4	0.449	0.460	0.470	0.480	0.491
0.5	0.559	0.569	0.580	0.590	0.601

4-yr Males:
Height = 1.06 m ; Weight = 17.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.088	0.097	0.106	0.115	0.123
0.2	0.167	0.176	0.185	0.194	0.203
0.3	0.246	0.255	0.264	0.273	0.282
0.4	0.326	0.335	0.343	0.352	0.361
0.5	0.405	0.414	0.423	0.431	0.440

4-yr Females:
Height = 1.05 m ; Weight = 17.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.091	0.100	0.108	0.117	0.126
0.2	0.173	0.182	0.191	0.199	0.208
0.3	0.256	0.264	0.273	0.282	0.290
0.4	0.338	0.347	0.355	0.364	0.373
0.5	0.420	0.429	0.438	0.446	0.455

5-yr Males:
Height = 1.126 m ; Weight = 19,9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.070	0.078	0.086	0.093	0.101
0.2	0.132	0.140	0.148	0.156	0.163
0.3	0.194	0.202	0.210	0.218	0.225
0.4	0.257	0.264	0.272	0.280	0.288
0.5	0.319	0.327	0.334	0.342	0.350

6-yr Males:
Height = 1.192 m ; Weight = 22.6 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.057	0.064	0.071	0.078	0.085
0.2	0.106	0.113	0.120	0.128	0.135
0.3	0.156	0.163	0.170	0.177	0.184
0.4	0.205	0.212	0.219	0.227	0.234
0.5	0.255	0.262	0.269	0.276	0.283

7-yr Males:
Height = 1.251 m ; Weight = 25.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.047	0.054	0.061	0.067	0.074
0.2	0.088	0.095	0.101	0.108	0.115
0.3	0.129	0.136	0.142	0.149	0.155
0.4	0.170	0.176	0.183	0.190	0.196
0.5	0.211	0.217	0.224	0.230	0.237

8-yr Males:
Height = 1.298 m ; Weight = 27.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.042	0.048	0.054	0.061	0.067
0.2	0.077	0.083	0.090	0.096	0.103
0.3	0.112	0.119	0.125	0.131	0.138
0.4	0.147	0.154	0.160	0.167	0.173
0.5	0.183	0.189	0.195	0.202	0.208

9-yr Males:
Height = 1.358 m ; Weight = 31.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.036	0.042	0.048	0.054	0.061
0.2	0.065	0.071	0.078	0.084	0.090
0.3	0.094	0.101	0.107	0.113	0.119
0.4	0.124	0.130	0.136	0.143	0.149
0.5	0.153	0.160	0.166	0.172	0.178

10-yr Males:
Height = 1.409 m ; Weight = 35.4 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.032	0.038	0.045	0.051	0.057
0.2	0.057	0.064	0.070	0.076	0.083
0.3	0.083	0.089	0.095	0.102	0.108
0.4	0.108	0.114	0.121	0.127	0.134
0.5	0.133	0.140	0.146	0.152	0.159

5-yr Females:
Height = 1.12 m ; Weight = 19,5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.071	0.079	0.087	0.094	0.102
0.2	0.135	0.143	0.150	0.158	0.166
0.3	0.198	0.206	0.214	0.221	0.229
0.4	0.262	0.270	0.277	0.285	0.293
0.5	0.325	0.333	0.341	0.349	0.356

6-yr Females:
Height = 1.183 m ; Weight = 21.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.058	0.065	0.072	0.079	0.086
0.2	0.109	0.116	0.123	0.130	0.137
0.3	0.160	0.167	0.174	0.181	0.188
0.4	0.211	0.218	0.225	0.232	0.239
0.5	0.262	0.269	0.276	0.283	0.290

7-yr Females:
Height = 1.242 m ; Weight = 24.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.049	0.055	0.062	0.069	0.075
0.2	0.091	0.097	0.104	0.111	0.117
0.3	0.133	0.139	0.146	0.153	0.159
0.4	0.175	0.181	0.188	0.195	0.201
0.5	0.217	0.223	0.230	0.237	0.243

8-yr Females:
Height = 1.298 m ; Weight = 28.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.042	0.048	0.055	0.062	0.068
0.2	0.077	0.084	0.090	0.097	0.103
0.3	0.112	0.119	0.126	0.132	0.139
0.4	0.148	0.154	0.161	0.167	0.174
0.5	0.183	0.189	0.196	0.203	0.209

9-yr Females:
Height = 1.357 m ; Weight = 32 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.036	0.043	0.049	0.056	0.062
0.2	0.066	0.072	0.079	0.085	0.092
0.3	0.095	0.102	0.108	0.115	0.121
0.4	0.125	0.131	0.138	0.144	0.151
0.5	0.154	0.161	0.167	0.174	0.180

10-yr Females:
Height = 1.415 m ; Weight = 35.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.031	0.038	0.044	0.050	0.057
0.2	0.056	0.063	0.069	0.075	0.082
0.3	0.081	0.088	0.094	0.100	0.107
0.4	0.106	0.112	0.119	0.125	0.132
0.5	0.131	0.137	0.144	0.150	0.156

11-yr Males:
Height = 1.464 m ; Weight = 39.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.028	0.035	0.041	0.048	0.054
0.2	0.050	0.056	0.063	0.069	0.076
0.3	0.072	0.078	0.085	0.091	0.097
0.4	0.094	0.100	0.106	0.113	0.119
0.5	0.115	0.122	0.128	0.135	0.141

12-yr Males:
Height = 1.522 m ; Weight = 44.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.025	0.031	0.037	0.044	0.050
0.2	0.044	0.050	0.056	0.062	0.069
0.3	0.062	0.068	0.075	0.081	0.087
0.4	0.081	0.087	0.093	0.100	0.106
0.5	0.099	0.106	0.112	0.118	0.125

13-yr Males:
Height = 1.592 m ; Weight = 49.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.022	0.028	0.034	0.040	0.046
0.2	0.037	0.043	0.049	0.056	0.062
0.3	0.053	0.059	0.065	0.071	0.077
0.4	0.068	0.074	0.081	0.087	0.093
0.5	0.084	0.090	0.096	0.102	0.108

14-yr Males:
Height = 1.671 m ; Weight = 56,9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.019	0.025	0.031	0.037	0.043
0.2	0.032	0.038	0.043	0.049	0.055
0.3	0.044	0.050	0.056	0.062	0.068
0.4	0.057	0.063	0.069	0.075	0.081
0.5	0.070	0.076	0.082	0.088	0.094

15-yr Males:
Height = 1.708 m ; Weight = 61 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.018	0.024	0.030	0.036	0.042
0.2	0.029	0.035	0.041	0.047	0.053
0.3	0.041	0.047	0.053	0.059	0.065
0.4	0.053	0.059	0.065	0.071	0.077
0.5	0.065	0.071	0.077	0.083	0.089

16-yr Males:
Height = 1.745 m ; Weight = 66.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.017	0.023	0.030	0.036	0.042
0.2	0.028	0.034	0.041	0.047	0.053
0.3	0.039	0.045	0.051	0.058	0.064
0.4	0.049	0.056	0.062	0.068	0.075
0.5	0.060	0.067	0.073	0.079	0.086

11-yr Females:
Height = 1.481 m ; Weight = 41.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.027	0.034	0.041	0.047	0.054
0.2	0.048	0.055	0.061	0.068	0.075
0.3	0.069	0.076	0.082	0.089	0.095
0.4	0.090	0.096	0.103	0.110	0.116
0.5	0.111	0.117	0.124	0.130	0.137

12-yr Females:
Height = 1.546 m ; Weight = 47.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.024	0.031	0.037	0.044	0.050
0.2	0.042	0.048	0.055	0.061	0.068
0.3	0.059	0.066	0.072	0.079	0.085
0.4	0.077	0.083	0.090	0.096	0.103
0.5	0.094	0.101	0.107	0.114	0.120

13-yr Females:
Height = 1.588 m ; Weight = 51.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.022	0.029	0.036	0.042	0.049
0.2	0.038	0.045	0.051	0.058	0.065
0.3	0.054	0.060	0.067	0.074	0.080
0.4	0.070	0.076	0.083	0.089	0.096
0.5	0.085	0.092	0.098	0.105	0.112

14-yr Females:
Height = 1.609 m ; Weight = 54.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.022	0.029	0.036	0.043	0.049
0.2	0.037	0.044	0.051	0.057	0.064
0.3	0.052	0.059	0.065	0.072	0.079
0.4	0.067	0.073	0.080	0.087	0.094
0.5	0.081	0.088	0.095	0.102	0.109

15-yr Females:
Height = 1.632 m ; Weight = 56.4 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.021	0.028	0.034	0.041	0.048
0.2	0.035	0.042	0.048	0.055	0.062
0.3	0.049	0.056	0.062	0.069	0.076
0.4	0.063	0.070	0.077	0.083	0.090
0.5	0.077	0.084	0.091	0.097	0.104

16-yr Females:
Height = 1.622 m ; Weight = 58.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.022	0.029	0.037	0.044	0.052
0.2	0.036	0.044	0.051	0.059	0.066
0.3	0.051	0.058	0.066	0.073	0.081
0.4	0.065	0.073	0.080	0.088	0.095
0.5	0.080	0.087	0.095	0.102	0.109

17-yr Males:
Height = 1.755 m ; Weight = 67.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.017	0.023	0.029	0.035	0.042
0.2	0.027	0.034	0.040	0.046	0.052
0.3	0.038	0.044	0.050	0.057	0.063
0.4	0.048	0.055	0.061	0.067	0.073
0.5	0.059	0.065	0.071	0.078	0.084

18-24-yr Males:
Height = 1.766 m ; Weight = 73.9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.017	0.025	0.032	0.039	0.046
0.2	0.028	0.035	0.042	0.049	0.057
0.3	0.038	0.045	0.052	0.060	0.067
0.4	0.048	0.056	0.063	0.070	0.077
0.5	0.059	0.066	0.073	0.080	0.087

25-29-yr Males:
Height = 1.767 m ; Weight = 77.9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.018	0.026	0.034	0.042	0.050
0.2	0.028	0.036	0.044	0.052	0.060
0.3	0.039	0.047	0.055	0.063	0.071
0.4	0.049	0.057	0.065	0.073	0.081
0.5	0.059	0.067	0.075	0.083	0.091

30-34-yr Males:
Height = 1.762 m ; Weight = 79.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.019	0.027	0.036	0.044	0.053
0.2	0.029	0.038	0.046	0.055	0.063
0.3	0.040	0.048	0.057	0.065	0.074
0.4	0.050	0.059	0.067	0.076	0.084
0.5	0.060	0.069	0.077	0.086	0.094

35-39-yr Males:
Height = 1.761 m ; Weight = 80.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.019	0.028	0.036	0.045	0.054
0.2	0.029	0.038	0.047	0.055	0.064
0.3	0.040	0.048	0.057	0.066	0.074
0.4	0.050	0.059	0.068	0.076	0.085
0.5	0.061	0.069	0.078	0.087	0.095

40-44-yr Males:
Height = 1.759 m ; Weight = 81 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.019	0.028	0.037	0.046	0.055
0.2	0.030	0.039	0.047	0.056	0.065
0.3	0.040	0.049	0.058	0.067	0.076
0.4	0.051	0.060	0.068	0.077	0.086
0.5	0.061	0.070	0.079	0.088	0.097

17-yr Females:
Height = 1.627 m ; Weight = 59.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.022	0.030	0.037	0.045	0.053
0.2	0.036	0.044	0.052	0.059	0.067
0.3	0.050	0.058	0.066	0.074	0.081
0.4	0.065	0.072	0.080	0.088	0.096
0.5	0.079	0.087	0.094	0.102	0.110

18-24-yr Females:
Height = 1.63 m ; Weight = 60.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.022	0.030	0.038	0.046	0.054
0.2	0.036	0.044	0.052	0.060	0.068
0.3	0.050	0.058	0.066	0.074	0.082
0.4	0.065	0.072	0.080	0.088	0.096
0.5	0.079	0.087	0.094	0.102	0.110

25-29-yr Females:
Height = 1.629 m ; Weight = 62.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.023	0.031	0.040	0.048	0.056
0.2	0.037	0.045	0.054	0.062	0.071
0.3	0.051	0.059	0.068	0.076	0.085
0.4	0.065	0.074	0.082	0.091	0.099
0.5	0.079	0.088	0.096	0.105	0.113

30-34-yr Females:
Height = 1.626 m ; Weight = 65.6 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.024	0.033	0.042	0.052	0.061
0.2	0.038	0.047	0.057	0.066	0.075
0.3	0.052	0.062	0.071	0.080	0.089
0.4	0.067	0.076	0.085	0.094	0.104
0.5	0.081	0.090	0.099	0.109	0.118

35-39-yr Females:
Height = 1.628 m ; Weight = 67.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.024	0.034	0.043	0.053	0.063
0.2	0.038	0.048	0.057	0.067	0.077
0.3	0.052	0.062	0.072	0.081	0.091
0.4	0.067	0.076	0.086	0.096	0.105
0.5	0.081	0.091	0.100	0.110	0.120

40-44-yr Females:
Height = 1.626 m ; Weight = 67.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.024	0.034	0.044	0.054	0.064
0.2	0.039	0.049	0.058	0.068	0.078
0.3	0.053	0.063	0.073	0.083	0.093
0.4	0.067	0.077	0.087	0.097	0.107
0.5	0.081	0.091	0.101	0.111	0.121

45-49-yr Males:
Height = 1.752 m ; Weight = 80.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.020	0.029	0.038	0.047	0.056
0.2	0.030	0.039	0.048	0.057	0.066
0.3	0.041	0.050	0.059	0.068	0.077
0.4	0.051	0.061	0.070	0.079	0.088
0.5	0.062	0.071	0.080	0.089	0.098

50-54-yr Males:
Height = 1.746 m ; Weight = 79.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.020	0.029	0.038	0.046	0.055
0.2	0.030	0.039	0.048	0.057	0.066
0.3	0.041	0.050	0.059	0.068	0.077
0.4	0.052	0.061	0.070	0.079	0.088
0.5	0.063	0.072	0.081	0.089	0.098

55-59-yr Males:
Height = 1.739 m ; Weight = 79.4 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.020	0.029	0.038	0.047	0.057
0.2	0.031	0.040	0.049	0.058	0.067
0.3	0.042	0.051	0.060	0.069	0.078
0.4	0.053	0.062	0.071	0.080	0.089
0.5	0.064	0.073	0.082	0.091	0.100

60-64-yr Males:
Height = 1.73 m ; Weight = 77.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.020	0.029	0.038	0.047	0.056
0.2	0.031	0.040	0.049	0.058	0.067
0.3	0.042	0.051	0.060	0.069	0.078
0.4	0.054	0.062	0.071	0.080	0.089
0.5	0.065	0.074	0.083	0.091	0.100

65-69-yr Males:
Height = 1.715 m ; Weight = 75 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.020	0.029	0.038	0.047	0.056
0.2	0.032	0.041	0.050	0.058	0.067
0.3	0.044	0.052	0.061	0.070	0.079
0.4	0.055	0.064	0.073	0.082	0.090
0.5	0.067	0.075	0.084	0.093	0.102

70-74-yr Males:
Height = 1.706 m ; Weight = 73.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.021	0.029	0.038	0.047	0.056
0.2	0.032	0.041	0.050	0.059	0.068
0.3	0.044	0.053	0.062	0.071	0.079
0.4	0.056	0.065	0.074	0.082	0.091
0.5	0.068	0.077	0.085	0.094	0.103

45-49-yr Females:
Height = 1.62 m ; Weight = 68.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.025	0.035	0.045	0.056	0.066
0.2	0.039	0.050	0.060	0.070	0.081
0.3	0.054	0.064	0.074	0.085	0.095
0.4	0.068	0.079	0.089	0.099	0.110
0.5	0.083	0.093	0.103	0.114	0.124

50-54-yr Females:
Height = 1.612 m ; Weight = 68.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.025	0.036	0.047	0.057	0.068
0.2	0.040	0.051	0.062	0.072	0.083
0.3	0.055	0.066	0.076	0.087	0.098
0.4	0.070	0.081	0.091	0.102	0.112
0.5	0.085	0.095	0.106	0.117	0.127

55-59-yr Females:
Height = 1.603 m ; Weight = 69.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.026	0.038	0.049	0.060	0.072
0.2	0.042	0.053	0.064	0.075	0.087
0.3	0.057	0.068	0.079	0.091	0.102
0.4	0.072	0.083	0.094	0.106	0.117
0.5	0.087	0.098	0.110	0.121	0.132

60-64-yr Females:
Height = 1.596 m ; Weight = 68 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.027	0.038	0.049	0.060	0.071
0.2	0.042	0.053	0.064	0.076	0.087
0.3	0.057	0.069	0.080	0.091	0.102
0.4	0.073	0.084	0.095	0.106	0.118
0.5	0.088	0.099	0.111	0.122	0.133

65-69-yr Females:
Height = 1.586 m ; Weight = 67.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.027	0.039	0.050	0.062	0.073
0.2	0.043	0.055	0.066	0.077	0.089
0.3	0.059	0.070	0.082	0.093	0.105
0.4	0.075	0.086	0.098	0.109	0.120
0.5	0.090	0.102	0.113	0.125	0.136

70-74-yr Females:
Height = 1.576 m ; Weight = 66 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.028	0.039	0.050	0.062	0.073
0.2	0.044	0.055	0.067	0.078	0.089
0.3	0.060	0.071	0.083	0.094	0.105
0.4	0.076	0.088	0.099	0.110	0.122
0.5	0.092	0.104	0.115	0.127	0.138

Table A.2: Coefficients of reliablility of BMI under different conditions

1-yr Males:
Height = 0.825 m ; Weight = 11.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9595	0.9564	0.9533	0.9503	0.9472
0.2	0.9220	0.9189	0.9158	0.9128	0.9097
0.3	0.8845	0.8814	0.8784	0.8753	0.8722
0.4	0.8470	0.8440	0.8409	0.8378	0.8348
0.5	0.8095	0.8065	0.8034	0.8003	0.7973

1-yr Females:
Height = 0.806 m ; Weight = 10.9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.8870	0.8793	0.8716	0.8639	0.8562
0.2	0.7817	0.7740	0.7663	0.7586	0.7509
0.3	0.6764	0.6687	0.6610	0.6532	0.6455
0.4	0.5710	0.5633	0.5556	0.5479	0.5402
0.5	0.4657	0.4580	0.4503	0.4426	0.4349

2-yr Males:
Height = 0.914 m ; Weight = 13.6 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9077	0.9002	0.8927	0.8852	0.8777
0.2	0.8229	0.8154	0.8079	0.8004	0.7929
0.3	0.7381	0.7306	0.7231	0.7156	0.7081
0.4	0.6533	0.6458	0.6383	0.6308	0.6233
0.5	0.5686	0.5610	0.5535	0.5460	0.5385

2-yr Females:
Height = 0.901 m ; Weight = 13 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9269	0.9213	0.9157	0.9101	0.9045
0.2	0.8595	0.8539	0.8483	0.8427	0.8370
0.3	0.7921	0.7864	0.7808	0.7752	0.7696
0.4	0.7246	0.7190	0.7134	0.7078	0.7022
0.5	0.6572	0.6516	0.6460	0.6403	0.6347

3-yr Males:
Height = 0.991 m ; Weight = 15.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9418	0.9365	0.9312	0.9259	0.9205
0.2	0.8889	0.8836	0.8783	0.8730	0.8676
0.3	0.8360	0.8307	0.8254	0.8201	0.8147
0.4	0.7831	0.7778	0.7725	0.7672	0.7618
0.5	0.7302	0.7249	0.7196	0.7143	0.7089

3-yr Females:
Height = 0.977 m ; Weight = 15 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9387	0.9334	0.9282	0.9229	0.9176
0.2	0.8827	0.8774	0.8722	0.8669	0.8616
0.3	0.8267	0.8214	0.8162	0.8109	0.8056
0.4	0.7707	0.7655	0.7602	0.7549	0.7496
0.5	0.7147	0.7095	0.7042	0.6989	0.6936

4-yr Males:
Height = 1.06 m ; Weight = 17.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9479	0.9427	0.9374	0.9322	0.9270
0.2	0.9010	0.8958	0.8906	0.8854	0.8801
0.3	0.8542	0.8489	0.8437	0.8385	0.8333
0.4	0.8073	0.8021	0.7968	0.7916	0.7864
0.5	0.7604	0.7552	0.7500	0.7447	0.7395

4-yr Females:
Height = 1.05 m ; Weight = 17.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9536	0.9491	0.9447	0.9402	0.9358
0.2	0.9116	0.9071	0.9027	0.8982	0.8938
0.3	0.8696	0.8652	0.8607	0.8563	0.8518
0.4	0.8276	0.8232	0.8187	0.8143	0.8098
0.5	0.7857	0.7812	0.7768	0.7723	0.7679

5-yr Males:
Height = 1.126 m ; Weight = 19,9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9689	0.9654	0.9620	0.9585	0.9551
0.2	0.9412	0.9378	0.9343	0.9309	0.9274
0.3	0.9136	0.9101	0.9067	0.9032	0.8998
0.4	0.8860	0.8825	0.8790	0.8756	0.8721
0.5	0.8583	0.8549	0.8514	0.8479	0.8445

5-yr Females:
Height = 1.12 m ; Weight = 19,5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9753	0.9727	0.970	0.9673	0.9647
0.2	0.9534	0.9507	0.948	0.9454	0.9427
0.3	0.9314	0.9287	0.926	0.9234	0.9207
0.4	0.9094	0.9067	0.904	0.9014	0.8987
0.5	0.8874	0.8847	0.882	0.8794	0.8767

6-yr Males:
Height = 1.192 m ; Weight = 22.6 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9843	0.9823	0.9804	0.9784	0.9764
0.2	0.9706	0.9686	0.9666	0.9647	0.9627
0.3	0.9569	0.9549	0.9529	0.9509	0.9490
0.4	0.9431	0.9412	0.9392	0.9372	0.9353
0.5	0.9294	0.9274	0.9255	0.9235	0.9215

6-yr Females:
Height = 1.183 m ; Weight = 21.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9799	0.9775	0.9751	0.9727	0.9703
0.2	0.9623	0.9599	0.9575	0.9551	0.9527
0.3	0.9446	0.9422	0.9398	0.9374	0.9350
0.4	0.9269	0.9245	0.9221	0.9197	0.9173
0.5	0.9093	0.9069	0.9045	0.9021	0.8997

7-yr Males:
Height = 1.251 m ; Weight = 25.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9854	0.9833	0.9813	0.9793	0.9773
0.2	0.9728	0.9707	0.9687	0.9667	0.9647
0.3	0.9602	0.9581	0.9561	0.9541	0.9520
0.4	0.9476	0.9455	0.9435	0.9415	0.9394
0.5	0.9350	0.9329	0.9309	0.9289	0.9268

7-yr Females:
Height = 1.242 m ; Weight = 24.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9865	0.9847	0.9828	0.9810	0.9792
0.2	0.9749	0.9730	0.9712	0.9694	0.9675
0.3	0.9632	0.9614	0.9596	0.9577	0.9559
0.4	0.9516	0.9498	0.9479	0.9461	0.9442
0.5	0.9400	0.9381	0.9363	0.9344	0.9326

8-yr Males:
Height = 1.298 m ; Weight = 27.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9914	0.9901	0.9887	0.9874	0.9861
0.2	0.9841	0.9828	0.9815	0.9801	0.9788
0.3	0.9768	0.9755	0.9742	0.9729	0.9715
0.4	0.9696	0.9682	0.9669	0.9656	0.9643
0.5	0.9623	0.9610	0.9596	0.9583	0.9570

8-yr Females:
Height = 1.298 m ; Weight = 28.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9943	0.9934	0.9924	0.9915	0.9906
0.2	0.9894	0.9885	0.9876	0.9867	0.9858
0.3	0.9846	0.9837	0.9828	0.9819	0.9810
0.4	0.9798	0.9789	0.9780	0.9770	0.9761
0.5	0.9749	0.9740	0.9731	0.9722	0.9713

9-yr Males:
Height = 1.358 m ; Weight = 31.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9938	0.9927	0.9916	0.9906	0.9895
0.2	0.9887	0.9876	0.9865	0.9855	0.9844
0.3	0.9836	0.9825	0.9814	0.9803	0.9793
0.4	0.9785	0.9774	0.9763	0.9752	0.9742
0.5	0.9734	0.9723	0.9712	0.9701	0.9691

9-yr Females:
Height = 1.357 m ; Weight = 32 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9962	0.9956	0.9949	0.9942	0.9935
0.2	0.9932	0.9925	0.9918	0.9911	0.9904
0.3	0.9901	0.9894	0.9887	0.9881	0.9874
0.4	0.9870	0.9864	0.9857	0.9850	0.9843
0.5	0.9840	0.9833	0.9826	0.9819	0.9812

10-yr Males:
Height = 1.409 m ; Weight = 35.4 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9959	0.9951	0.9943	0.9935	0.9927
0.2	0.9927	0.9919	0.9911	0.9903	0.9894
0.3	0.9895	0.9887	0.9878	0.9870	0.9862
0.4	0.9862	0.9854	0.9846	0.9838	0.9830
0.5	0.9830	0.9822	0.9814	0.9806	0.9797

10-yr Females:
Height = 1.415 m ; Weight = 35.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9967	0.9961	0.9954	0.9948	0.9941
0.2	0.9941	0.9935	0.9928	0.9922	0.9915
0.3	0.9916	0.9909	0.9902	0.9896	0.9889
0.4	0.9890	0.9883	0.9876	0.9870	0.9863
0.5	0.9864	0.9857	0.9850	0.9844	0.9837

11-yr Males:
Height = 1.464 m ; Weight = 39.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9978	0.9973	0.9968	0.9963	0.9958
0.2	0.9961	0.9956	0.9952	0.9947	0.9942
0.3	0.9945	0.9940	0.9935	0.9930	0.9925
0.4	0.9928	0.9906	0.9901	0.9896	0.9891

11-yr Females:
Height = 1.481 m ; Weight = 41.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9981	0.9976	0.9972	0.9967	0.9963
0.2	0.9967	0.9962	0.9957	0.9953	0.9948
0.3	0.9952	0.9948	0.9943	0.9938	0.9934
0.5	0.9923	0.9919	0.9914	0.9910	0.9905

12-yr Males:
Height = 1.522 m ; Weight = 44.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9980	0.9975	0.9969	0.9964	0.9959
0.2	0.9964	0.9959	0.9954	0.9949	0.9944
0.3	0.9949	0.9944	0.9939	0.9934	0.9929
0.4	0.9934	0.9929	0.9924	0.9919	0.9913
0.5	0.9919	0.9914	0.9909	0.9903	0.9898

12-yr Females:
Height = 1.546 m ; Weight = 47.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9982	0.9978	0.9973	0.9968	0.9963
0.2	0.9970	0.9965	0.9960	0.9955	0.9951
0.3	0.9957	0.9952	0.9947	0.9943	0.9938
0.4	0.9944	0.9939	0.9935	0.9930	0.9925
0.5	0.9931	0.9927	0.9922	0.9917	0.9912

13-yr Males:
Height = 1.592 m ; Weight = 49.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9982	0.9977	0.9972	0.9967	0.9962
0.2	0.9970	0.9965	0.9960	0.9955	0.9950
0.4	0.9944	0.9939	0.9934	0.9929	0.9924
0.5	0.9931	0.9927	0.9922	0.9917	0.9912

14-yr Males:
Height = 1.671 m ; Weight = 56,9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9983	0.9977	0.9972	0.9966	0.9961
0.2	0.9971	0.9966	0.9960	0.9955	0.9949
0.3	0.9959	0.9954	0.9948	0.9943	0.9937
0.4	0.9947	0.9942	0.9937	0.9931	0.9926
0.5	0.9936	0.9930	0.9925	0.9919	0.9914

15-yr Males:
Height = 1.708 m ; Weight = 61 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9982	0.9975	0.9969	0.9963	0.9957
0.2	0.9969	0.9963	0.9957	0.9951	0.9944
0.3	0.9957	0.9951	0.9945	0.9938	0.9932
0.4	0.9945	0.9939	0.9932	0.9926	0.9920
0.5	0.9933	0.9926	0.9920	0.9914	0.9908

16-yr Males:
Height = 1.745 m ; Weight = 66.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9984	0.9978	0.9973	0.9967	0.9961
0.2	0.9974	0.9969	0.9963	0.9957	0.9951
0.3	0.9964	0.9959	0.9953	0.9947	0.9941
0.4	0.9955	0.9949	0.9943	0.9937	0.9931
0.5	0.9945	0.9939	0.9933	0.9927	0.9921

17-yr Males:
Height = 1.755 m ; Weight = 67.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9986	0.9981	0.9976	0.9971	0.9966
0.2	0.9978	0.9973	0.9968	0.9962	0.9957
0.3	0.9969	0.9964	0.9959	0.9954	0.9949
0.4	0.9960	0.9955	0.9950	0.9945	0.9940
0.5	0.9952	0.9947	0.9942	0.9937	0.9932

18-24-yr Males:
Height = 1.766 m ; Weight = 73.9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9988	0.9983	0.9978	0.9973	0.9968
0.2	0.9981	0.9976	0.9971	0.9966	0.9961
0.3	0.9974	0.9969	0.9964	0.9959	0.9954
0.4	0.9967	0.9962	0.9957	0.9952	0.9947
0.5	0.9959	0.9954	0.9949	0.9944	0.9939

13-yr Females:
Height = 1.588 m ; Weight = 51.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9987	0.9983	0.9979	0.9975	0.9971
0.2	0.9977	0.9964	0.9960	0.9956	0.9952
0.4	0.9959	0.9955	0.9951	0.9947	0.9943
0.5	0.9949	0.9945	0.9941	0.9937	0.9934

14-yr Females:
Height = 1.609 m ; Weight = 54.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9986	0.9981	0.9977	0.9972	0.9968
0.2	0.9976	0.9971	0.9967	0.9962	0.9958
0.3	0.9966	0.9962	0.9957	0.9952	0.9948
0.4	0.9956	0.9952	0.9947	0.9943	0.9938
0.5	0.9946	0.9942	0.9937	0.9933	0.9928

15-yr Females:
Height = 1.632 m ; Weight = 56.4 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9986	0.9981	0.9976	0.9972	0.9967
0.2	0.9976	0.9971	0.9966	0.9962	0.9957
0.3	0.9966	0.9961	0.9957	0.9952	0.9947
0.4	0.9956	0.9952	0.9947	0.9942	0.9938
0.5	0.9947	0.9942	0.9937	0.9933	0.9928

16-yr Females:
Height = 1.622 m ; Weight = 58.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9986	0.9982	0.9977	0.9972	0.9968
0.2	0.9977	0.9973	0.9968	0.9963	0.9959
0.3	0.9968	0.9964	0.9959	0.9954	0.9950
0.4	0.9959	0.9955	0.9950	0.9945	0.9941
0.5	0.9950	0.9946	0.9941	0.9936	0.9932

17-yr Females:
Height = 1.627 m ; Weight = 59.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9990	0.9987	0.9983	0.9980	0.9976
0.2	0.9984	0.9980	0.9977	0.9973	0.9970
0.3	0.9977	0.9974	0.9970	0.9967	0.9963
0.4	0.9971	0.9967	0.9964	0.9960	0.9957
0.5	0.9964	0.9961	0.9957	0.9954	0.9950

18-24-yr Females:
Height = 1.63 m ; Weight = 60.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9990	0.9986	0.9982	0.9978	0.9975
0.2	0.9983	0.9979	0.9975	0.9972	0.9968
0.3	0.9976	0.9972	0.9969	0.9965	0.9961
0.4	0.9969	0.9966	0.9962	0.9958	0.9955
0.5	0.9963	0.9959	0.9955	0.9952	0.9948

25-29-yr Males:
Height = 1.767 m ; Weight = 77.9 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9990	0.9986	0.9982	0.9977	0.9973
0.2	0.9985	0.9980	0.9976	0.9972	0.9967
0.3	0.9979	0.9975	0.9970	0.9966	0.9962
0.4	0.9973	0.9969	0.9965	0.9961	0.9956
0.5	0.9968	0.9964	0.9959	0.9955	0.9951

30-34-yr Males:
Height = 1.762 m ; Weight = 79.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9989	0.9984	0.9980	0.9975	0.9970
0.2	0.9983	0.9979	0.9974	0.9969	0.9964
0.3	0.9978	0.9973	0.9968	0.9963	0.9958
0.4	0.9972	0.9967	0.9962	0.9957	0.9952
0.5	0.9966	0.9961	0.9956	0.9951	0.9946

35-39-yr Males:
Height = 1.761 m ; Weight = 80.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9988	0.9983	0.9977	0.9972	0.9966
0.2	0.9982	0.9976	0.9971	0.9965	0.9960
0.3	0.9975	0.9970	0.9964	0.9959	0.9953
0.4	0.9969	0.9963	0.9958	0.9952	0.9947
0.5	0.9962	0.9957	0.9951	0.9946	0.9940

40-44-yr Males:
Height = 1.759 m ; Weight = 81 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9988	0.9982	0.9977	0.9971	0.9966
0.2	0.9981	0.9976	0.9970	0.9965	0.9959
0.3	0.9975	0.9969	0.9964	0.9958	0.9953
0.4	0.9968	0.9963	0.9957	0.9952	0.9946
0.5	0.9962	0.9956	0.9951	0.9945	0.9940

45-49-yr Males:
Height = 1.752 m ; Weight = 80.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9989	0.9984	0.9979	0.9974	0.9968
0.2	0.9983	0.9978	0.9973	0.9967	0.9962
0.3	0.9977	0.9972	0.9967	0.9961	0.9956
0.4	0.9971	0.9966	0.9961	0.9955	0.9950
0.5	0.9965	0.9960	0.9955	0.9949	0.9944

50-54-yr Males:
Height = 1.746 m ; Weight = 79.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9989	0.9984	0.9979	0.9974	0.9969
0.2	0.9983	0.9978	0.9973	0.9968	0.9963
0.3	0.9977	0.9972	0.9967	0.9961	0.9956
0.4	0.9971	0.9965	0.9960	0.9955	0.9950
0.5	0.9964	0.9959	0.9954	0.9949	0.9944

25-29-yr Females:
Height = 1.629 m ; Weight = 62.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9992	0.9989	0.9985	0.9982	0.9979
0.2	0.9986	0.9983	0.9980	0.9977	0.9974
0.3	0.9981	0.9978	0.9975	0.9972	0.9969
0.4	0.9976	0.9973	0.9970	0.9967	0.9963
0.5	0.9971	0.9967	0.9964	0.9961	0.9958

30-34-yr Females:
Height = 1.626 m ; Weight = 65.6 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9993	0.9991	0.9988	0.9985	0.9983
0.2	0.9989	0.9986	0.9984	0.9981	0.9978
0.3	0.9985	0.9982	0.9980	0.9977	0.9974
0.4	0.9981	0.9978	0.9976	0.9973	0.9970
0.5	0.9977	0.9974	0.9971	0.9969	0.9966

35-39-yr Females:
Height = 1.628 m ; Weight = 67.1 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9993	0.9990	0.9987	0.9984	0.9981
0.2	0.9989	0.9986	0.9983	0.9980	0.9977
0.3	0.9984	0.9982	0.9979	0.9976	0.9973
0.4	0.9980	0.9977	0.9974	0.9972	0.9969
0.5	0.9976	0.9973	0.9970	0.9967	0.9964

40-44-yr Females:
Height = 1.626 m ; Weight = 67.8 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9993	0.9990	0.9987	0.9984	0.9982
0.2	0.9989	0.9986	0.9983	0.9980	0.9977
0.3	0.9985	0.9982	0.9979	0.9976	0.9973
0.4	0.9981	0.9978	0.9975	0.9972	0.9969
0.5	0.9977	0.9974	0.9971	0.9968	0.9965

45-49-yr Females:
Height = 1.62 m ; Weight = 68.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9994	0.9991	0.9988	0.9986	0.9983
0.2	0.9990	0.9987	0.9984	0.9982	0.9979
0.3	0.9986	0.9983	0.9981	0.9978	0.9975
0.4	0.9982	0.9980	0.9977	0.9974	0.9972
0.5	0.9978	0.9976	0.9973	0.9970	0.9968

50-54-yr Females:
Height = 1.612 m ; Weight = 68.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9992	0.9988	0.9985	0.9981	0.9978
0.2	0.9987	0.9983	0.9980	0.9976	0.9973
0.3	0.9982	0.9978	0.9975	0.9971	0.9968
0.4	0.9977	0.9973	0.9970	0.9966	0.9963
0.5	0.9972	0.9968	0.9965	0.9961	0.9958

55-59-yr Males:
Height = 1.739 m ; Weight = 79.4 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9989	0.9984	0.9979	0.9974	0.9969
0.2	0.9983	0.9978	0.9973	0.9968	0.9964
0.3	0.9977	0.9972	0.9967	0.9963	0.9958
0.4	0.9971	0.9966	0.9962	0.9957	0.9952
0.5	0.9965	0.9961	0.9956	0.9951	0.9946

55-59-yr Females:
Height = 1.603 m ; Weight = 69.2 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9993	0.9990	0.9987	0.9984	0.9981
0.2	0.9989	0.9986	0.9983	0.9980	0.9977
0.3	0.9985	0.9982	0.9979	0.9976	0.9973
0.4	0.9981	0.9978	0.9975	0.9972	0.9969
0.5	0.9977	0.9974	0.9971	0.9968	0.9964

60-64-yr Males:
Height = 1.73 m ; Weight = 77.3 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9986	0.9980	0.9974	0.9968	0.9961
0.2	0.9978	0.9972	0.9966	0.9960	0.9954
0.3	0.9971	0.9964	0.9958	0.9952	0.9946
0.4	0.9963	0.9957	0.9951	0.9944	0.9938
0.5	0.9955	0.9949	0.9943	0.9937	0.9930

60-64-yr Females:
Height = 1.596 m ; Weight = 68 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9991	0.9988	0.9984	0.9980	0.9976
0.2	0.9986	0.9982	0.9979	0.9975	0.9971
0.3	0.9981	0.9977	0.9974	0.9970	0.9966
0.4	0.9976	0.9972	0.9969	0.9965	0.9961
0.5	0.9971	0.9967	0.9963	0.9960	0.9956

65-69-yr Males:
Height = 1.715 m ; Weight = 75 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9987	0.9982	0.9976	0.9971	0.9965
0.2	0.9980	0.9974	0.9969	0.9963	0.9958
0.3	0.9973	0.9967	0.9962	0.9956	0.9951
0.4	0.9966	0.9960	0.9955	0.9949	0.9943
0.5	0.9958	0.9953	0.9947	0.9942	0.9936

65-69-yr Females:
Height = 1.586 m ; Weight = 67.5 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9991	0.9987	0.9983	0.9980	0.9976
0.2	0.9986	0.9982	0.9978	0.9974	0.9971
0.3	0.9981	0.9977	0.9973	0.9969	0.9965
0.4	0.9975	0.9972	0.9968	0.9964	0.9960
0.5	0.9970	0.9966	0.9963	0.9959	0.9955

70-74-yr Males:
Height = 1.706 m ; Weight = 73.7 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9987	0.9982	0.9976	0.9971	0.9965
0.2	0.9980	0.9974	0.9969	0.9963	0.9958
0.3	0.9972	0.9967	0.9961	0.9956	0.9950
0.4	0.9965	0.9959	0.9954	0.9948	0.9943
0.5	0.9958	0.9952	0.9947	0.9941	0.9936

70-74-yr Females:
Height = 1.576 m ; Weight = 66 kg

	$Var(\delta)$				
$Var(\varepsilon)$	0.0001	0.0002	0.0003	0.0004	0.0005
0.1	0.9990	0.9986	0.9982	0.9978	0.9974
0.2	0.9984	0.9980	0.9976	0.9972	0.9968
0.3	0.9979	0.9975	0.9971	0.9966	0.9962
0.4	0.9973	0.9969	0.9965	0.9961	0.9957
0.5	0.9967	0.9963	0.9959	0.9955	0.9951

Appendix B

R-Code of Simulations

Simulation:the effect of the correlation between the diurnal error of height and weight upon the diurnal error variance of BMI and its reliablity

```
> library(MASS)
> vbmifc <- function(n) {
+   sigma <- matrix(c(0.5^2,-0.2*0.5*0.01,-0.2*0.5*0.01,0.01^2),ncol = 2)
+   varbmifc <- array(NA, dim = n)
+    for (i in 1:n) {
+     fc <- mvrnorm(n = 1000, mu = c(0, 0), Sigma = sigma)
+     fwc <- fc[, 1]
+     fhc <- fc[, 2]
+     bmifc <- (39.71 + fwc)/(1.4469 + fhc)^2
+     varbmifc[i] <- var(bmifc)
+     }
+   return(varbmifc)
+ }
> vbmif <- function(n) {
+   varbmif <- array(NA, dim = n)
+    for (i in 1:n) {
+     fw <- rnorm(1000, 0, 0.5)
+      fh <- rnorm(1000, 0, 0.01)
+       bmif <- (39.71 + fw)/(1.4469 + fh)^2
+       varbmif[i] <- var(bmif)
+     }
+   return(varbmif)
+ }
```

```
#Results see Figiure 5.1
```

Simulation: check whether the reliability of BMI lower than its components- height and weight for 25-29 yr Males: weight 77.9 ± 14.6 kg; height 176.7 ± 7.0 cm

```
#assume sd error of height and weight
> sdfh <- c(0.005, 0.01, 0.02, 0.025)
> sdfw <- c(0.1, 0.5, 1, 1.5)
#reliability of height
> 1 - sdfh^2/0.07^2

[1] 0.9948980 0.9795918 0.9183673 0.8724490

#reliability of weight
> 1 - sdfw^2/14.6^2

[1] 0.9999531 0.9988272 0.9953087 0.9894445

#true inter-individual variance of height and weight
> tsdw <- 14.6 - sdfw
> tsdh <- 0.07 - sdfh
#randomly generate observed height and weight measurements with error
> hst <- 1.767 + rnorm(10000, 0, 0.07)
> wst <- 77.9 + rnorm(10000, 0, 14.6)
#total inter-individual variance (with error)of BMI
> bmist <- var(wst/hst^2)
> vbmist <- array(bmist, dim = c(4, 4))
#true inter-individual variance (without error) of BMI
> vbmi <- array(0, dim = c(4, 4))
> for (i in 1:4) {
+  for (j in 1:4) {
+   vbmi[i, j]<-var((77.9+rnorm(10000,0,tsdw[i]))/(1.767+rnorm(10000,0,tsdh[j]))^2)
+    }
+ }
#reliability of BMI
> relbmi <- vbmi/vbmist
> relbmi

          [,1]      [,2]      [,3]      [,4]
[1,] 0.9511102 0.9362702 0.9144035 0.8973316
[2,] 0.9079177 0.9194381 0.8553021 0.8363293
[3,] 0.8478428 0.8231281 0.8039749 0.7864963
[4,] 0.8286526 0.8069595 0.7467973 0.7391669

#Results see Table 5.5
```

Simulation: check the approximation equation (5.4)

```
#assume relative error of height and weight
> rew <- c(0.001, 0.005, 0.01, 0.015)
> reh <- c(0.001, 0.005, 0.01, 0.015)
#true height, weight and BMI for an adult
> wa <- 80
> ha <- 1.75
> bmia <- wa/ha^2
> bmia

[1] 26.12245

#randomly generate observed height and weight measurements with error for an adult
> N <- 10000
> wast <- array(0, dim = c(4, N))
> for (i in 1:4) {
+     wast[i, ] <- wa * (1 + rnorm(N, 0, rew[i]))
+ }
> hast <- array(0, dim = c(4, N))
> for (i in 1:4) {
+     hast[i, ] <- ha * (1 + rnorm(N, 0, reh[i]))
+ }
#directly observed BMI (with error) for an adult
> bmiast <- array(0, dim = c(4, N, 4))
> for (j in 1:4) {
+     for (i in 1:4) {
+         bmiast[i, , j] <- wast[j, ]/hast[i, ]^2
+     }
+ }
#approximate observed BMI (with error) for an adult
> bmiaappst <- array(0, dim = c(4, 10000, 4))
> for (j in 1:4) {
+  for (i in 1:4) {
+   bmiaappst[i,,j]<-bmia*(1+rnorm(10000,0,rew[j])-2*rnorm(10000,0,reh[i]))
+     }
+ }

#Results see Figure 5.3
```

```
#true height, weight and BMI for a child
> wc <- 16
> hc <- 1
> bmic <- wc/hc^2
> bmic

[1] 16

#randomly generate observed height and weight measurements with error for a child
> wcst <- array(0, dim = c(4, N))
> for (i in 1:4) {
+     wcst[i, ] <- wc * (1 + rnorm(N, 0, rew[i]))
+ }
> hcst <- array(0, dim = c(4, N))
> for (i in 1:4) {
+     hcst[i, ] <- hc * (1 + rnorm(N, 0, reh[i]))
+ }
#directly observed BMI (with error) for a child
> bmicst <- array(0, dim = c(4, N, 4))
> for (j in 1:4) {
+     for (i in 1:4) {
+         bmicst[i, , j] <- wcst[j, ]/hcst[i, ]^2
+     }
+ }
#approximate observed BMI (with error) for a child
> bmicappst <- array(0, dim = c(4, 10000, 4))
> for (j in 1:4) {
+  for (i in 1:4) {
+   bmicappst[i,,j]<-bmic*(1+rnorm(10000,0,rew[j])-2*rnorm(10000,0,reh[i]))
+     }
+ }

#Results see Figure 5.4
```

Simulation: check the approximation equation (5.5)

```
> n <- 10000
#assume error variance of height and weight
> vw1 <- seq(0.1, 0.5, 0.05)
> vh1 <- seq(1e-05, 5e-05, 5e-06)
#exact error variance of BMI from randomly sampling
> varfb <- function(w, h, vw, vh, N) {
+   nvw <- length(vw)
+   nvh <- length(vh)
+   bmist <- array(NA, dim = c(nvh, N, nvw))
+    for (k in 1:nvw) {
+     for (i in 1:nvh) {
+      bmist[i,,k]<-(w+rnorm(N,0,sqrt(vw[k])))/(h+rnorm(N,0,sqrt(vh[i])))^2
+         }
+     }
+     varfb <- apply(bmist, c(1, 3), var)
+     return(varfb)
+ }
> varfb1 <- varfb(wa, ha, vw1, vh1, n) #for an adult
> varfb2 <- varfb(wc, hc, vw1, vh1, n) #for a child
#arpproximate error variance of BMI from randomly sampling
> varfbapp <- function(w, h, vw, vh) {
+   nvw <- length(vw)
+   nvh <- length(vh)
+   vbmiapp <- array(NA, dim = c(nvw, nvh))
+    for (j in 1:nvw) {
+     for (i in 1:nvh) {
+      vbmiapp[i, j] <- vw[j]/h^4 + 4 * w^2 * vh[i]/h^6
+         }
+     }
+     return(vbmiapp)
+ }
> varfbapp1 <- varfbapp(wa, ha, vw1, vh1) #for an adult
> varfbapp2 <- varfbapp(wc, hc, vw1, vh1) #for a child
#Results see Figure 5.5
```

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Declaration for the Thesis

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text.

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