4
Methods to Determine Dietary Intake

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Key messages

- We are living through major nutritional, methodological and technological transitions that raise new challenges and new opportunities to measure, monitor and compare dietary intakes.
- Different traditional dietary intake assessment methods are being used in various study settings. Each method has its unique features with its strengths and limitations.
- Dietary methodologies should benefit from new technologies. However, a clear distinction should be made between (new) dietary methodologies and (new) technologies. While existing dietary methodologies are relatively limited, the increasing development of different new technologies might confuse users' evaluation of their respective features and challenge the choices made.
- Dietary methodologies are prone to measurement errors, which should be carefully evaluated and minimised as much as possible.
- Dietary patterns aim to combine a large number of correlated dietary variables, estimated at the food, nutrient and/or related biomarker levels, into fewer independent (uncorrelated) components (i.e. patterns).
- Frontline nutritional research increasingly favours the use of integrated approaches to measure dietary intake. This includes (repeated) open-ended dietary methods (24-hour dietary recalls or food records) complemented by a food propensity questionnaire (for infrequently consumed foods) and biological markers (including metabolomics).

4.1 Challenges to assessing and monitoring dietary intake

Among the different environmental and lifestyle risk factors, diet is one of the most complex exposures to investigate in relation to some diseases. Indeed, diet is a universal exposure consumed in infinite combinations of foods and recipes, with large variations within and between individuals and over the whole life span. In addition, the several thousand chemicals (including contaminants) present in the diet may have complex synergistic or antagonistic bioactive effects. As a consequence, it makes it difficult to disentangle individual chemical and nutrient effects as well as to remove confounding completely when investigating diet–disease relationships and their underlying biological mechanisms. Diet may also have strong social, religious and psychological features that have impacts on study and questionnaire designs, logistics and ultimately the individual's dietary intakes.

The 'nutrition transition', characterised by a moving away from traditional diets towards more Western diets (rich in energy, fats, salt and sugar), is consistently observed with accelerated phenomena worldwide. This is another major challenge in measuring, monitoring and investigating diet and its associations with diseases, particularly cancer and cardiovascular disease. Indeed, cancer is a multiphasic and multifactorial disease, often occurring late in life. However, the lifelong cumulated risks might be affected by different (early) 'exposure windows', which are difficult to evaluate through single (or limited) repeated dietary measurements collected in nutritional epidemiology. Furthermore, the food frequency questionnaire (FFQ) assessment method predominantly used in large study settings has been repeatedly challenged with respect to its validity and reliability for measuring individual dietary intake. As a consequence, nutritional research has increasingly favoured approaches integrating traditional and more innovative measurements of dietary exposure (including biological and

Nutrition Research Methodologies, First Edition. Edited by Julie A Lovegrove, Leanne Hodson, Sangita Sharma and Susan A Lanham-New.

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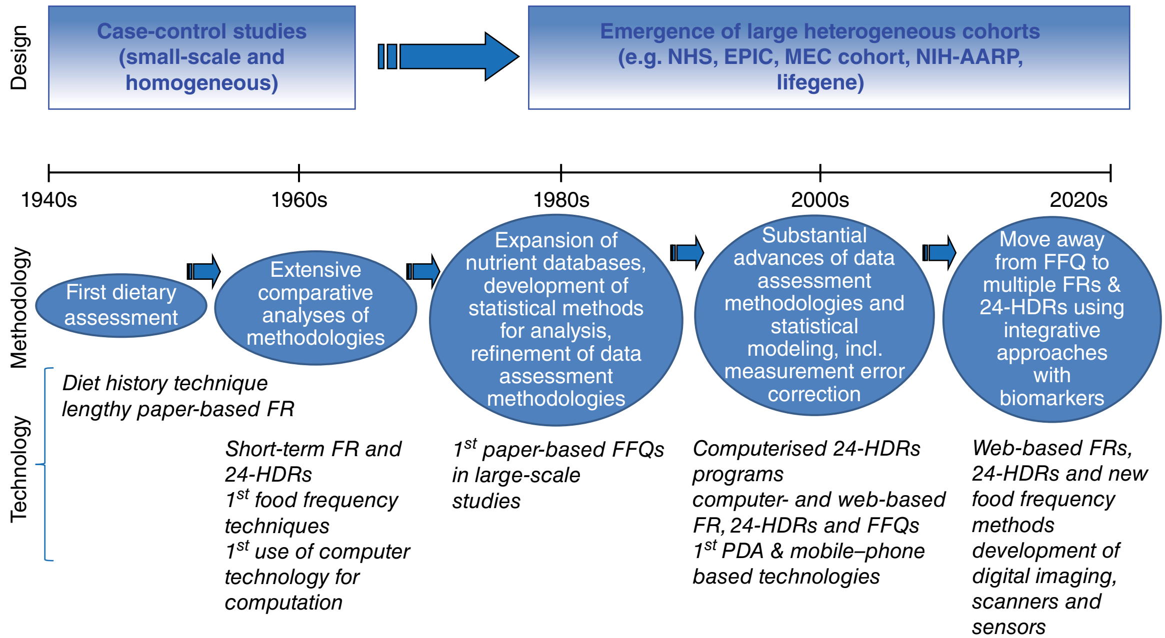


Figure 4.1 Evolution of design, methodology and technology in dietary assessment.

metabolite – intermediate or surrogate – markers) to improve the individual and population mean intakes and distribution.

This chapter reflects the major methodological and technological transitions in measuring individual dietary intake that have occurred over the last two to three decades by reporting both traditional and more innovative dietary assessment methodologies (or technologies), including combined approaches (Figure 4.1). A better understanding of their respective strengths and limitations as well as their comprehensive integration should pave the way for a more holistic and reliable estimation of individual (or population) dietary exposure, as an essential prerequisite for cost-effective and front-line nutritional research and monitoring.

4.2 Traditional dietary assessment methods

Dietary assessment methodologies can be classified according to different criteria, including the *duration of the period of registration* (short-term versus long-term dietary assessment methods) and the *time frame of the data collected* (e.g. past/retro versus current/prospective dietary intake assessment). Although the dietary assessment methods described in this chapter do not use any arbitrary categorisation, these notions are important to have in mind when evaluating and selecting the most appropriate dietary assessment method according to the study-specific aims and designs, as well as the logistical conditions and constraints. In this section, the dietary assessment methods and their respective strengths and weaknesses will be described in turn. The main results are summarised in Table 4.1 to facilitate comparison.

Description of methodologies

Observation methods

When using the observation method to assess participants' dietary intake, fieldworkers visit homes or school canteens to observe meal times and record dietary intake. Observation is an objective method to assess dietary intake, although in practice it can only be done in settings such as canteens or school dinner halls and for discrete time periods. However, new and existing technologies like cameras also allow the observation of subjects' dietary intake in different settings (see Section 4.3).

An important strength of the observation method is the fact that it provides an objective assessment of dietary intake. However, this method is highly intensive for researchers and is therefore expensive. When not performed covertly, the observation may alter individuals' usual eating patterns. Furthermore, this method is not feasible for obtaining habitual dietary data at either a group or an individual level. Observation of dietary intake is most commonly undertaken as a reference method for validating other dietary assessment methods.

Table 4.1 Traditional dietary assessment methods (comparison of important characteristics, errors and potential for standardisation).

	Food records	24-hour dietary recall	FFQ	Diet history	Screener
Type of information available					
Detailed information about foods/recipes	x	x		x	
Not detailed information about food groups			x		x
Scope of information sought					
Total diet	x	x	x	x	
Specific components					x
Time frame of single administration					
Short term (e.g. yesterday, today)	x	x		x	x
Long term (e.g. last month, last year)			x	x	x
Adaptable to diet in distant past					
Yes			x	x	x
No	x	x			
Cognitive requirements					
Measurement or estimated recording of foods and drinks as they are consumed	x				
Memories of recent consumption		x		x	x
Ability to make judgements of long-term diet			x	x	x
Potential for reactivity					
Low		x	x	x	x
High	x				
Time required to complete					
Low			x		x
High	x	x	(x)*	x	
Respondent burden					
Low		x	x		x
High	x			x	
Investigator cost					
Low			x		x
High	x	x		x	
Affecting food choices					
Yes	x				
No		x	x	x	x
Possibility for automated data entry					
Yes	x	x	x	x	x
No					
Literacy required#					
Yes	x		x	x	x
No		x			
Usable for retrospective data collection					
Yes			x	x	x
No	x	x			
Potential for standardisation					
High potential	x	x			
Low potential			x	x	x
Error					
Systematic under-reporting of intake	x	x	x	?	x
Systematic over-reporting of intake			x (detailed FFQ)		
Person-specific biases associated with gender, obesity etc.	x	x	x		x

*high amount of time required to complete very detailed FFQs.
#depending on administration method (e.g. interview versus self-administration).

(a)

(b)

Breakfast

Place: at home / outdoor[1]

Product group	Food item	Brand name and/description	Quantity	Coding (for dietician)
Breakfast cereals E.g. muesli, cornflakes				
Bread E.g. cereal bread toast, ...	Cereal bread	Large, round bread	2 slices of the middle	
Sandwich filling E.g. cheese, jam, bacon, ...	Gouda cheese, Strawberry jam	Ripe gounda cheese, materne light jam	1 slice (10 – 10 cm) 1 teaspoon	
Fat E.g. low-fat spread, margarine, butter	Margarine	Becel, control	1 teaspoon per slice of bread	
Drinks E.g. water, milk, fruit juice, soft-drinks, ...	Orange juice Milk	Freshly squeezed Skimmed milk	1 orange 1 beaker	
Other foods E.g. egg, yoghurt, fruit, porridge, ...				

Figure 4.2 Food diaries. (a) Example of a food diary from the UK EPIC study. (b) Example of a Belgian food diary.

Food diary or food record methods

The food record or food diary (Figure 4.2) is an open-ended method that requires that the subject (or observer) reports all foods and beverages consumed at the time of consumption, to minimise reliance on memory. These records can be kept over one or more days and portion sizes may be determined by weighing or by estimating volumes (e.g. using visual aids like pictures, food models or food packets). In some situations, only those foods of particular study interest are recorded. For example, to estimate the intake of a certain food component (e.g. cholesterol, which is found in animal products only), food records might be limited to meat, poultry, fish, eggs or dairy products. However, if total energy intake or total diet estimates are required, the food record must include all foods and beverages consumed. Food records are generally completed by the subjects themselves using paper-based or more innovative (web/IT) technological supports (see Section 4.3), though in some situations a proxy might be employed (e.g. for children, the elderly or when literacy is too limited). To complete a food record, each respondent must be trained in the level of detail required to describe adequately the foods and portion sizes consumed, including the name of the food (brand name if possible), preparation methods, recipes for food mixtures and portion sizes. Reviewing the food records with the participants right after data collection is desirable in order to capture adequate detail.

The most important strength of the food record is its level of detail, given its open-ended nature and the fact that it refers to the current diet (i.e. dietary intake estimated at time of consumption). In addition, the report of actually consumed foods contributes to increasing the accuracy of portion sizes. As this method does not require recall of foods eaten, there is no memory problem. However, participants who keep food records sometimes delay recording their intakes for several hours or days, in which case they rely on memory. The most important disadvantages of the food record are its high investigator cost and respondent burden and the fact that it might affect the respondents' eating behaviour (subjects might change their eating behaviour due to the recording). Extensive respondent training and motivation are required and several repeated days are needed to capture individuals' usual intake. The intake often tends to be under-reported and the number of food items regularly decreases with time. Drop-out increases with the number of daily records requested, and the fact that literacy and high respondent motivation and compliance are required may lead to a non-representative sample and subsequent non-response bias.

The food record is often used in dietary programmes, as writing down all food and drinks consumed could enhance self-monitoring for weight control or other behaviour change (see Section 4.3). Furthermore, multiple food records (usually between three and seven days) are often used as a reference method in relative validation studies (e.g. for validating FFQs).

24-hour dietary recall methods

The 24-hour dietary recall method (Figure 4.3) is an open-ended method asking the respondent to remember and report all the foods and beverages consumed in the preceding 24 hours or over the previous day. The recall is often structured (e.g. per meal occasion), using specific probes and cognitive processes, to help respondents recall their diet. Probing is especially useful in collecting the necessary details, such as how foods were prepared. The recall typically is conducted by interview (in person or by telephone), either using a paper-and-pencil form or through computer-assisted interview. However, self-administered electronic forms of administration have also recently become available (see Section 4.3). When the recall is interviewer administered, well-trained interviewers are crucial. However, non-nutritionists with sufficient training on foods and recipes available in the study region and in interview techniques can be cost-effective.

Important strengths of the 24-hour dietary recall method are its relatively low respondent burden and the fact that it does not affect respondents' eating behaviour. This method is appropriate for most population groups, which reduces the potential for non-response bias and facilitates comparisons between populations. Another advantage is the fact that portion sizes are being recalled for all foods and beverages (using different quantification means), allowing estimation of individual intake. Disadvantages of the 24-hour dietary recall method are its high investigator cost (when interviewer administered) and the fact that repeated measurements are needed to capture individuals' usual intake (see also the section on food records earlier in this chapter). Furthermore, the fact that 24-hour dietary recall relies on subjects' short-term memory should also be considered as a relative disadvantage compared to food records (but not FFQs). In addition, socially desirable answers could introduce some recall bias during the a 24-hour dietary recall interview. As for food records, a 24-hour dietary recall tends also to under-report individual intakes.

Two repeated 24-hour dietary recall interviews are often used in large-scale dietary monitoring surveys, because of the low respondent burden and high level of standardisation. Furthermore, this method has also been applied as a reference calibration method in large-scale surveys to estimate population mean intake and correct for the measurement error of less accurate methods (e.g. FFQs).

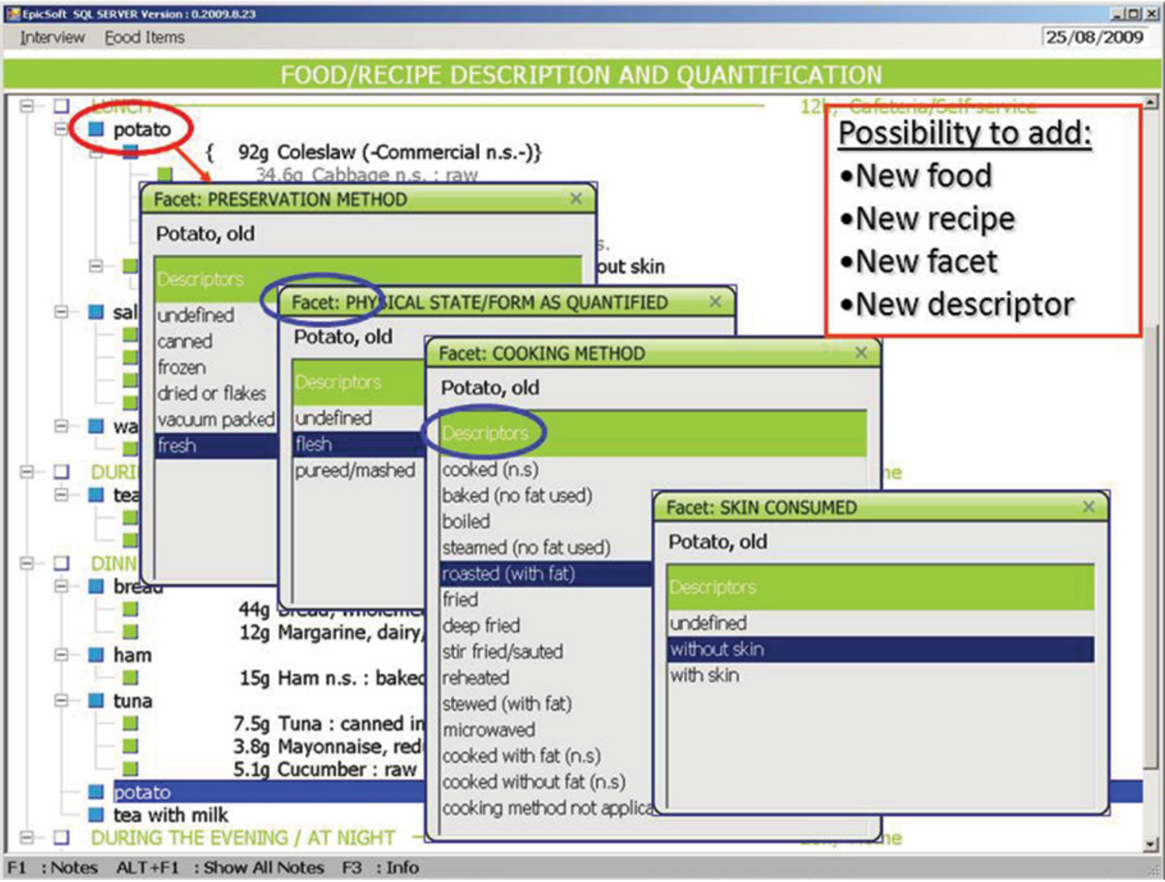


Figure 4.3 Food descriptions in the standardised EPIC-Soft 24-hour dietary recall method. (EPIC-Soft has since been renamed GloboDiet.)

Diet history methods

In 1947, Burke developed a dietary history interview and attempted to assess an individual's usual diet. This original dietary history interview included 24-hour dietary recall, a menu recorded for 3 days and a checklist of foods consumed over the preceding month. This checklist consisted of a detailed listing of the types of foods and beverages commonly consumed at each eating occasion over a defined time period, most often a 'typical' week. A trained interviewer probed for the respondent's customary pattern of food intake on each day of the typical week. The reference time frame could also be the past month or the past several months, or might reflect seasonal differences if the time frame was the past year. This checklist was the forerunner of the more structured dietary questionnaires in use today (e.g. FFQs, described below). A highly skilled and trained professional is needed for both the interview and the processing of the information.

An important strength of the diet history is that it assesses the individual subject's usual intake while not affecting eating behaviour. This method is very detailed, which means that information on the total diet can be obtained.

An important disadvantage of this detailed method is its high respondent and investigator burden. It is a difficult cognitive task for respondents to recall their usual individual intake and the estimation of usual portion sizes remains a challenge.

Due to its significant respondent and investigator burden and high costs, the dietary history is seldom applied in current or recent dietary surveys.

Food frequency questionnaire (FFQ) methods

The basic *food frequency questionnaire* (FFQ) consists of two components: a closed food list and a frequency response section for subjects to report how often each food (e.g. banana) or food group (e.g. fruit) was eaten. For each item on the food list, the respondent is asked to estimate the frequency of consumption based on open or specified frequency categories, which indicate the number of times the food is usually consumed per day, week, month or year. The number and/or types of food items and frequency categories may vary according to the study objectives and designs. Brief FFQs may focus on one or several specific nutrients. FFQs generally include between 50 and 150 (mostly generic) food items.

Different types of FFQ are usually considered: *non-quantitative* (alternatively called qualitative), *semi-quantitative* or completely *quantitative FFQs*. Non-quantitative questionnaires do not specify any portion sizes (standard portions derived from other study populations or data sets might be added afterwards), whereas semi-quantified instruments provide a combination of individual or typical/standard portion sizes to estimate food quantities (standard portions are part of the food item line). A quantitative FFQ allows the respondent to indicate any amount of food typically consumed. FFQs are commonly used to rank individuals by intake of selected foods or nutrients. Although FFQs are not designed for estimating absolute nutrient intakes, the method is often used for estimating average intake of those nutrients that have large day-to-day variability and for which there are relatively few significant food sources (e.g. alcohol, vitamin A and vitamin C).

Some FFQs also include questions regarding usual food preparation methods, trimming of meats and identification of the brand of certain types of foods, such as margarines or ready-to-eat cereals.

FFQs are generally self-administered (see Figure 4.4), but may also be interviewer administered. Proxies can be used to complete the FFQ in particular situations (e.g. for children, elderly, hospitalised patients and so on).

The most important strengths of the FFQ are its low investigator burden and cost and the fact that it does not affect the respondent's eating behaviour. Furthermore, it has the advantage that usual individual intake is being requested (over a long time frame), which avoids the need for repeated measurements. The completion of an FFQ remains a difficult cognitive task for respondents and this should be considered as an important limitation of this dietary intake assessment method. Usual portion sizes are difficult to estimate precisely and the intake estimates may be misreported.

Because of its low respondent burden and rather reduced cost (compared to more detailed methods like food records or 24-hour recalls), the FFQ is often the method of choice for large-scale dietary studies

(a)

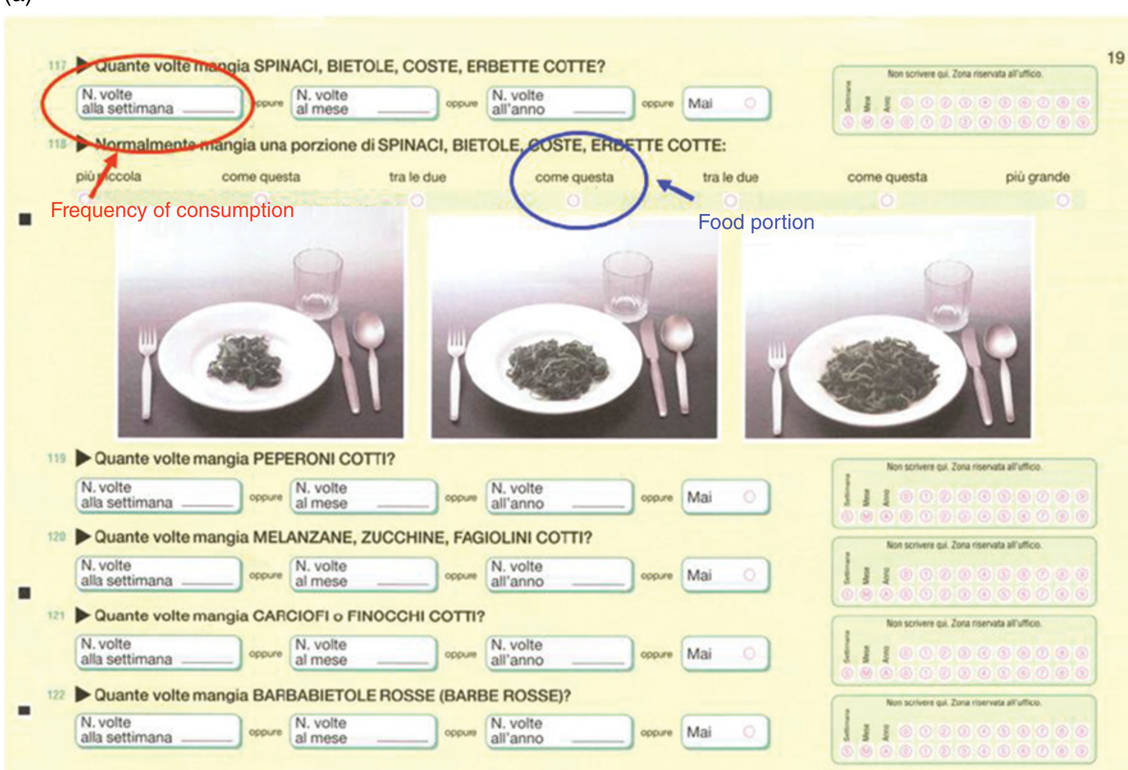


Figure 4.4 Self-reported FFQs. (a) A self-reported FFQ from the Italy EPIC study.

(b)

Food groups	How often do you consume the following product?	And what is the average portion per day?	Example portion sizes	Which type do you usually use?
Coffee	○ Never or less than once a month ○ 1–3 days per month ○ 1 day per week ○ 2–4 days per week ○ 5–6 days per week ● Every day	● 200 mL or less ○ Between 200 – 400 mL ○ Between 400 – 600 mL ○ 600 mL or more	*1 cup*: *125 mL* *1 beaker*: *225 mL*	● With caffeine ○ With reduced caffeine ○ Without caffeine
Tea	○ Never or less than once a month ○ 1 – 3 days per month ○ 1 day per week ○ 2 – 4 days per week ○ 5 – 6 days per week ● Every day	● 200 mL or less ○ Between 200 – 400 mL ○ Between 400 – 600 mL ○ 600 mL or more	*1 cup*: *125 mL* *1 beaker*: *225 mL*	○ Regular english tea ○ Green tea ● Herbal tea

Food groups	**How often** Does your child consume the following products?	And what is **the average** portion per day?	Example portion sizes
Water (*tap water, bottled water,...*)	○ Never or less than once per month ○ 1 – 3 days per month ○ 1 day per week ○ 2 – 4 days per week ○ 5 – 6 days per week ○ every day	○ 200 ml or less ○ Between 200 and 400 ml ○ Between 400 and 600 ml ○ 600 ml or more	*1 glass = 150 ml* *1 beaker = 150 ml*
Coffee and tea without sugar	○ Never or less than once per month ○ 1 – 3 days per month ○ 1 day pet week ○ 2 – 4 days per week ○ 5 – 6 days per week ○ every day	○ 200 ml or less ○ Between 200 and 400 ml ○ Between 400 and 600 ml ○ 600 ml or more	*1 cup= 125 ml* *1 beaker = 225 ml*
Coffee and tea with sugar	○ Never or less than once per month ○ 1 – 3 days per month ○ 1 day pet week ○ 2 – 4 days per week ○ 5 – 6 days per week ○ every day	○ 200 ml or less ○ Between 200 and 400 ml ○ Between 400 and 600 ml ○ 600 ml or more	*1 cup= 125 ml* *1 beaker = 225 ml*

Figure 4.4 (*Continued*) (b) An example of a Belgian FFQ.

investigating subjects' usual/habitual dietary intake, for instance large-scale cohort or intervention studies. However, its limited accuracy for assessing usual individual intakes increasingly means that complementary or alternative approaches are required (see Section 4.3).

Screeners or brief dietary assessment methods

In a variety of settings, comprehensive dietary assessments are not necessary or practical, for instance in studies where diet is not the main focus or is only considered as a covariate, as in health interview surveys. This has led to the development of diverse brief dietary assessment instruments, often called 'screeners', aiming to measure a limited number of foods and/or nutrients. Short questionnaires are often used to assess the intake of particular food items like fruit and vegetables in surveillance and intervention research. As mentioned in the previous section, complete FFQs typically contain between 50 and 150 food items to capture the range of foods contributing to the many nutrients in the diet. If an investigator is interested only in estimating the intake of a single nutrient or food group, however, then fewer foods need to be assessed. Often, only 15 to 30 foods might be required to account for most of the intake of a particular nutrient.

The most important strengths of brief instruments or screeners are their low respondent burden and low investigator cost. Screeners generally assess usual individual (specific food group) intakes, though often only for a limited number of food items (e.g. fruit and vegetables). Like other retrospective dietary assessment instruments (e.g. FFQs), they do not affect the subject's eating behaviour. The disadvantages of these brief instruments are very similar to those reported for FFQs, namely a difficult cognitive task for the respondent and a challenge to quantify usual portion sizes. Furthermore, screeners often only assess a limited number of nutrients/foods.

These brief instruments may have utility in clinical settings or in situations where health promotion and health education are the goals. They can also be used to examine relationships between some specific aspects of diet and other exposures, as in the National Health Interview Survey. Finally, some groups use short screeners to evaluate the effectiveness of policy initiatives.

Specific tools for dietary supplement intake assessments

Dietary supplements contribute to the total intakes of some nutrients, such as calcium, magnesium, iron and vitamins C, D and E. Failure to include these nutrient sources would lead to a serious underestimation of intakes. Therefore, dietary supplement information is increasingly collected via the traditional dietary intake assessment methods described above. However, precise information on product names and brand names as well as related quantities consumed (e.g. number and frequency of consumption of pills, drops, tablets) is required to assess accurately the nutrient intakes derived from dietary supplements. Furthermore, many formulations are now available over the internet and validation of the nutrient content can be difficult. Another method applicable to supplements but not to foods is the use of pill inventories, which are widely employed in obtaining information about other medications. For some supplements, inferences about use can be made from blood or urine biomarkers, if available, although they provide only qualitative rather than quantitative information.

Because most of the methods for assessing the intake of dietary supplements are similar to (or part of) those used for assessing dietary intake, they have the same strengths and limitations as the other methods mentioned in this chapter.

Main applications of traditional dietary assessment methods

The choice of the most appropriate dietary assessment method depends on many factors and requires careful consideration. The following questions should be answered in selecting the method that will best meet the study objectives:

- Is information needed about foods, nutrients, other food components (e.g. bioactive components) and/or specific dietary behaviours and which items are of primary interest according to the research question?
- Is the focus of the research question on the group or individual data level and are absolute or relative intake estimates required?
- What are the population characteristics (age, sex, education, literacy, cultural diversity, motivation) and the time frame of interest?
- What level of accuracy and precision is needed?
- What are the available resources, including money, logistical conditions and constraints, interview time, staff and food composition data (if nutrients are to be calculated)?

Based on the answers to these questions, one can decide on the most appropriate dietary intake assessment method to be used for the particular study design and conditions.

Although these traditional methods are also used in *clinical settings*, the methods to be employed depend on the clinical conditions, which go beyond the scope of this chapter.

In *epidemiological settings*, at least three important study designs can be considered: cross-sectional/ monitoring surveys, case-control studies and cohort studies. Any of the dietary instruments discussed in this chapter can be used in cross-sectional studies. Some of the instruments, such as 24-hour dietary recall, are appropriate when the study purpose requires detailed and reliable quantitative estimates of intake, and frequently as a substitute for food-weighted or recorded methods. In addition, the 24-hour dietary recall method has the advantage that it does not require literacy, which in large-scale surveys increases the number of respondents, including those of lower socio-economic status. Other instruments, such as FFQs or behavioural indicators, are appropriate when qualitative estimates are sufficient for ranking individuals according to their (low, medium or high) level of consumption, for example frequency of consuming soda/fizzy drinks.

For case-control studies, the period of interest for dietary exposure could be either the recent past (e.g. the year before diagnosis) or the distant past (e.g. 10 years ago or in childhood). Because information about diet before the onset of disease is needed, dietary assessment methods that focus on current behaviour, such as food diaries or 24-hour dietary recalls, are not useful in retrospective studies. The food frequency (and diet history) methods are well suited for assessing past diet and are therefore the only viable choices for case-control (retrospective) studies (unless more accurate information from the past is available, as for instance in nested cohort case-control studies). However, the accuracy of such distant past dietary intake estimations is lower than for recent dietary intake assessment methods (e.g. food diaries or 24-hour dietary recalls) due to the significance of recall bias.

In cohort studies or prospective dietary studies, dietary intake and/or status are measured at baseline, when study subjects are free of diseases, and are then related to later incidence of disease. A broad assessment of diet is usually desirable in prospective studies because many dietary exposures and many (intermediate) disease endpoints will ultimately be investigated and areas of interest may not even be recognised at the beginning of a cohort study. In order to relate diet at baseline to the eventual occurrence of disease, a measure is needed of the usual intake of foods by study subjects. Multiple 24-hour dietary recalls or food records, diet histories and food frequency methods have all been used effectively in prospective studies. Cost and logistical issues tend to favour food frequency methods because many prospective studies require thousands of respondents. However, because of concern about significant measurement error and attenuation attributed to the FFQ, other approaches are being considered (see Section 4.3). Incorporating emerging technological advances in administering dietary records, such as using mobile phones, increases the feasibility of such approaches in prospective studies (again, see Section 4.3). If an FFQ is used in a cohort, it is desirable to include multiple recalls or records in subsamples of the population (preferably before beginning the study) to design the FFQ in the best way and to calibrate it (see Section 4.4).

Measurement in *public health settings* of the effects of nutrition promotion and education requires a valid measure of change from baseline to the conclusion of the intervention period. Researchers have found that dietary records and scheduled 24-hour dietary recalls were associated with changed eating behaviour during the recording days. However, because of resource constraints, large intervention studies have often relied on less precise measures of diet, including FFQs and brief instruments.

The choice of the most optimal dietary intake assessment method to be used also frequently depends on the population characteristics, for instance the age group (diaries are often used for children, while 24-hour dietary recalls are recommended for adults). FFQs and screeners have been applied in all age groups, although proxy reported in certain population groups (e.g. in children). Furthermore, a better understanding of various instruments' strengths and weaknesses has led to the creative blending of approaches, with the goal of maximising the strengths of each instrument. For example, a record-assisted 24-hour dietary recall has been used in several studies with children. The children keep notes of what they have eaten and then use these notes as memory prompts in a later 24-hour dietary recall.

4.3 Innovative dietary assessment methods and technologies

Description of innovative dietary assessment methods and technologies

Innovation in dietary assessment includes two basic conceptual notions: *new methodologies,* substantially different approaches for collecting dietary information (e.g. integrating and combining different types of self-reports, or self-reports and biomarkers; see Section 4.6) versus *new technologies*, related to the way in which dietary data are collected, handled and disseminated or exchanged. In particular, the growing prominence of internet and telecommunication technologies has allowed for a rapid evolution in ways of assessing and processing dietary intakes that has previously not been possible. The use of new technologies to collect and process dietary data is especially but not exclusively promising for children, adolescents and younger adults who are familiar with such technologies in their daily lives. Since the early

2000s, innovative technologies reported in the literature have included both technically advanced approaches to traditional (self-report) methods (e.g. web-based FFQs) and technically new devices integrating objective measurement features (e.g. digital imaging for portion size estimation). It is therefore sometimes difficult to disentangle from the innovative technologies what are methodological features of the dietary assessment methods (see Section 4.2) and what are actually new approaches to assessing and processing dietary intake. This misconception contributes to obscuring the understanding and proper evaluation and use of the new technologies.

Table 4.2 gives an overview of the six main groups of innovative technologies that show promise for improving, complementing or replacing the traditional dietary assessment methods, including a description of their group-specific technology-related strengths and weaknesses. The examples provided reflect the different existing variants of the same technology and the currently ongoing developments of such new tools for different purposes and populations. The classification applied is rough and requires regular revisions to reflect the extremely dynamic development of new dietary technologies. The main technological groups can have overlapping technological features, which are highlighted.

Validity and reproducibility of innovative dietary assessment methods and technologies

Research to investigate the validity and reproducibility of innovative technologies is crucial, but science-based evidence is still missing. Well-designed validation studies that include biomarkers are lacking for most of the technology groups, particularly for personal digital assistant technologies, mobile phone–based technologies and technically new 24-hour dietary recalls. Moreover, the bias inherent in self-reported dietary data by individuals (that is, individual and population bias, such as BMI, socio-economic position and so on) remains a problem that even innovative technologies may not eradicate completely.

Available studies suggest that the validity of individual dietary intake as reported on personal digital assistant technologies may be low to moderate. The validity of mobile phone–based technologies is less well studied. Complete technology validation studies have only been undertaken on the well-known Wellnavi instrument. By contrast, several studies have been done to assess the validity and reproducibility of interactive computer-based and web-based technologies. In particular, technically advanced FFQs and other dietary questionnaires have been compared with more established or traditional dietary assessment methods, for example 24-hour dietary recalls or food records. The correlation between the innovative and traditional approaches for most foods and nutrients is in the range of 0.4 to 0.7. In addition, the comparisons of web-based FFQ and traditional paper-based FFQs to various reference methods yielded similar correlations, indicating that the underlying methodology of innovative and traditional FFQs is unchanged by the technology. So far, a limited number of studies have assessed the relative validity of 24-hour dietary recall developed by the use of interactive computer- and web-based technologies. One recent study assessed the criterion validity of the Automated Self-administered 24-hour Recall (ASA24) through a feeding design and found somewhat better performance relative to true intakes for matches, exclusions, and intrusions in the interviewer-administered Automated Multiple-Pass Method. Furthermore, accurate portion-size estimation appears to depend on the technical presentation on the screen. Most studies on camera- and tape recorder–based technologies have integrated a validation component. Studies on camera-based technologies showed moderate to good relative validity against traditional food records and observation methods.

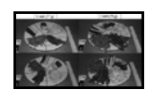
Application of innovative dietary assessment methods and technologies

Innovative technologies are used for dietary assessment in clinical and epidemiological settings as well as in public health settings for nutrition promotion and education. Although there is no rulebook with regard to selecting an innovative dietary assessment technology for a specific context, considerations depend on the study's objectives, its target population and the financial resources available.

In *clinical settings*, innovative technologies are applied for determining a person's dietary adequacy or risk and for purposes of treatment or counselling. In particular, handheld technologies that only capture data on current intake (e.g. personal digital assistant or mobile phone technologies) showed their usefulness in helping patients to self-monitor current diet and/or make good dietary decisions. Much of the published literature focuses on chronic disease management, particularly obesity, type 2 diabetes and chronic kidney dysfunction. In addition, web-based technologies are widely applied for weight loss/management trials.

In *epidemiological settings*, innovative technologies are applied for assessing a person's usual dietary intake. The primary applied advanced methods are interactive computer-based and web-based technologies that aim to address the methodological challenges faced in nutritional epidemiology. In this context, the recent scientific preference for using repeated short-term methods in combination with dietary questionnaires (and biomarkers of intake, discussed later in this chapter) is reflected by the development of several web-based 24-hour dietary recall and dietary questionnaires (see Section 4.6). Web-based technologies are also the method of choice for assessing diet in some newly established large epidemiological

Table 4.2 Description of technologies with potential for improving, complementing or replacing the traditional dietary assessment methodologies. Reproduced from Illner, A.K., Freisling, H., Boeing, H. *et al*. (2012) Review and evaluation of innovative technologies for measuring diet in nutritional epidemiology. *International Journal of Epidemiology*, **41** (4), 1187–1203, by permission of Oxford University Press.

	Description	Common assessment procedure and technology-related strengths and weaknesses	Examples in the literature with variable assessment procedures**
Technologies with potential for improving, complementing and/or replacing traditional food record methodology			
Personal digital assistant technologies*	Hand-held computers that integrate computing and networking features using stylus and/or keyboard for input	The participant is asked to record dietary intake right after consumption, by selecting food items from a drop-down menu of foods and beverages. Amount consumed is estimated by portion size estimation aids. Data is uploaded and matched with food composition databases. • **Strengths:** facilitated real-time data collection, entry and coding; capacity to capture open-ended text; integration of data quality algorithms and easy data transfer to a PC; often good respondent acceptance and possibility for standardised and/or repeated measurements. • **Weaknesses:** substantial initial costs of equipment and software purchases, though cost savings can be achieved with the removal of data-entry costs and data coding; requires respondent training; use of PDA technologies can result in changes in current eating behaviour.	 Beasely *et al*. (2005) Yon *et al*. (2006) Fowles *et al*. (2008) Fukuo *et al*. (2009) McClung *et al*. (2009)
Mobile phone–based technologies*	Portable electronic telecommunication devices connected to wireless communication network	The participant is asked to record dietary intake at eating events, by capturing digital images and/or voice records with a mobile phone. Data are transmitted by SIM card. • **Strengths:** widely available way of data collection, user-friendly and suitable for low-literacy subjects; provision of open-ended dietary data, if they are coupled with digital image-assisted assessment; advanced data-quality control due to real-time and often memory-independent assessment. • **Weaknesses:** high method-development and data-processing effort, e.g. for image analysis and volume estimation; time-consuming training for data managers and respondents (e.g. with regard to power management as the data-storage capacity is limited).	 Six *et al*. (2010) (Mobilephone Food record/mpFR) Weiss *et al*. (2010) (Mobile Food Intake Visualisation and VoiceRecogniser/FIV*R*) Kristal, A. (Dietary Data Recordersystem/DDRS)
Camera- and tape recorder–based technologies	Devices that capture images and/or write voice records onto a tape that are then encoded	Food selection and plate waste are visually or verbally recorded. Trained observers review images on a computer screen by comparing them to reference portions of known food quantities or analysing taped records. Estimates are manually entered into databases. • **Strengths:** fast, cheap, robust and non-repetitive data collection; suitable methods for subjects with memory impairment and for parent-assisted dietary assessment in children. The frequency rate of omitted or forgotten food items can be reduced. • **Weaknesses:** recording can affect food choices and under-reporting and/or result in reduced food consumption. Camera- and tape recorder–based technologies provide only a snapshot of food consumed and multiple measurements are needed.	 Lindquist *et al*. (2000) Williamson *et al*. (2004) Higgins *et al*. (2009) Dahl Lassen *et al*. (2010)

(*Continued*)

Table 4.2 (*Continued*)

	Description	Common assessment procedure and technology-related strengths and weaknesses	Examples in the literature with variable assessment procedures**
Technologies with potential for improving, complementing and/or replacing traditional FFQ and 24-hour dietary recall methodologies			
Interactive computer-based technologies*	Programmable machines with hardware and software components	The participant is asked to report dietary intake during a specified period in the recent and distant past, using computer software with multimedia attributes. Data is directly transferred into electronic databases. • **Strengths:** data consistency and completeness through technical mean, such as skip patterns, plausibility and range checks; reduced organisational study constraints and costs (excluding costs for software development), particularly for larger study populations. • **Weaknesses:** Many interactive computer-based technologies are designed as technically advanced FFQs, diet histories or 24-HDRs, suggesting similar methodology-associated measurement errors (listed in Sections 4.1 and 4.2); literacy, access to a computer and computer skills are required, which can be attributable to selection and response bias.	 Zoellner *et al.* (2005) Heath *et al.* (2005) Wong *et al.* (2008) Murtaugh *et al.* (2010) Baranowski *et al.* (2010) (Food Intake Recording Software System/ FIRSST) Vereeken *et al.* (2005)
Web-based technologies*	Internet-connected tools that shift applications and software from the computer desktop to websites that users access online with their browser	The participant reports short- or long-term dietary intake, using web-based data-collection systems. Data is processed in real time. • **Strengths:** advantageous to reach larger samples and culturally different and geographically dispersed groups; can be completed at any time and location and allow for facilitated repeated measurements; cost- and time-effectiveness due to direct transfer of complete data to the study centre; easily adaptable (e.g. to other languages, to different dietary assessment methodologies). • **Weaknesses:** Similar to computer-based technologies, methodology-associated measurement errors can be introduced; additional reporting and memory bias due to self-completion difficulties of more complex web-based dietary methods, such as 24-HDRs (e.g. resulting from limited nutritional knowledge, difficulties in quantifying portion sizes, reduced level of open-ended food choices); literacy and computer and internet skills are required.	 Boeckner *et al.* (2002) Matthys *et al.* (2007) Subar *et al.* (2007) (ASA24) Beasely *et al.* (2009) Arab *et al.* (2010) Touvier *et al.* (2011)
Other technology groups			
Scan- and sensor-based technologies	Tools that read and digitise data by passing through a scanner or sensor	Subjects scan purchased food item barcodes or wear sensors that automatically record measures of biological movements related to eating activities. • **Strengths:** objective measurements of features related to food consumption (e.g. automatically captured images); low respondent burden. • **Weaknesses:** substantial instrument development costs (for sensor-based technologies); data processing requires specific scan/sensor hardware and processing algorithms (e.g. for images); possible narrow camera field of view and insufficient battery life of devices.	 Lambert *et al.* (2005) Amft *et al.* (2009) Sun *et al.* (2010) (eButton) Jia W, Chen H-C, Yue Y *et al.* (2014)

*May have overlapping technological features.
**From the first to the most recent.

studies, as practical and cost-effective approaches for dietary assessment (e.g. the Oxford WebQ within the framework of the UK Biobank study).

In *public health settings* for nutrition promotion and education, innovative technologies are applied for both changing a person's usual diet towards a healthier diet and transferring nutritional knowledge. Web-based technologies, sometimes supported by social networking sites like Facebook, Twitter and Snapchat as well as interactive computer-based technologies, are prominent research approaches to improving nutritional behaviour and conducting intervention programmes. In addition, the continuing growth of mobile phone–based technology use has offered high potential to transfer nutritional knowledge, particularly in adolescents, but also in middle-aged people.

4.4 Measurement errors in dietary intake

The main goal in dietary assessment is to estimate the usual intake, which is the long-term average intake of food or nutrients of a given individual or population. This long-term average intake or usual intake is a key concept in dietary monitoring and nutritional epidemiology. Depending on the study objectives, the time frame of interest, which should be captured by the usual intake, can be as much as one year or even decades.

The usual intake is not directly observable, but can be estimated from self-reported 'actual' (or acute) intakes. With short-term instruments, repeated measurements on each individual of a given population sample need to be collected to estimate the usual intake. For example, for dietary monitoring, two (non-consecutive) repeated 24-hour dietary recalls per individual are sufficient to estimate the usual population mean and distribution. However, more repeated 24-hour dietary recalls are required to estimate the usual individual mean intake, depending on the food or nutrient of interest. In contrast, a single administration of a long-term instrument, such as a diet history questionnaire or FFQ, may aim to capture individual usual intakes directly, at least to rank individuals according to their intake within a study population for diet–disease evaluations.

However, estimation of the usual intake is challenging, since all methods to measure dietary intake (or any other exposure) are affected by several types of measurement error. Measurement error can be broadly defined as a deviation from the true value – from either the true mean, the true variation or both – and can be assessed by calculating the sample mean and the variation around the mean, expressed by the variance (or standard deviation). Measurement error can be categorised into *random errors* and *systematic errors*. Both types of error can occur at two levels: the *individual level* (within-person) and *group or population level* (between-person).

Random within-person error

An individual's dietary intake varies randomly around his or her usual mean intake, which is referred to as the 'day-to-day-variation' and reflects the true daily variability in a person's eating habits. This daily variability is pronounced in foods that are infrequently consumed (e.g. liver or other offal) or in nutrients that are found in a few food sources only (e.g. vitamin A in high concentration in liver and other offal). In addition, variation around the usual mean intake may result from random measurement errors at the individual level due to instrumental errors. An example is given by errors in portion size estimation, where respondents may randomly under- or overestimate their dietary intake.

The sum of these two sources of variation, day-to-day variation and instrumental errors, is referred to as the *random within-person error* (or random within-person variation); the two sources cannot and usually do not need to be separated in practice (Figure 4.5).

Random between-person error

Between-person variation can be expressed by the difference between an individual's usual intake and the population's usual intake; in Figure 4.5 this is shown as the difference between person A's and person B's usual intakes (solid lines) from the true usual intake of the population (dashed line).

The random within-person error leads to the random between-person error at population level:

$$\sigma^2_{\text{observed}} = \sigma^2_{\text{true}} + \sigma^2_{\text{within}}$$

$\sigma^2_{\text{observed}}$ = observed variation (SD); σ^2_{true} = true variation; σ^2_{within} = random within-person error

Overall, random within-person error or variation will not affect the mean intake of a population, because these types of errors will cancel out provided that the sample size is large enough (large enough sample sizes in national dietary surveys usually comprise ~2000 participants or more); an overestimated or high intake of a given food/nutrient will be balanced by an underestimated or low intake of the same food/nutrient on subsequent measurements/days. However, random within-person error contributes to, and thus inflates, the observed between-person variation (or variation at group level). Therefore, the observed SD of a population is larger than the true SD, which should reflect true differences/variation in intake between individuals only (Figure 4.6).

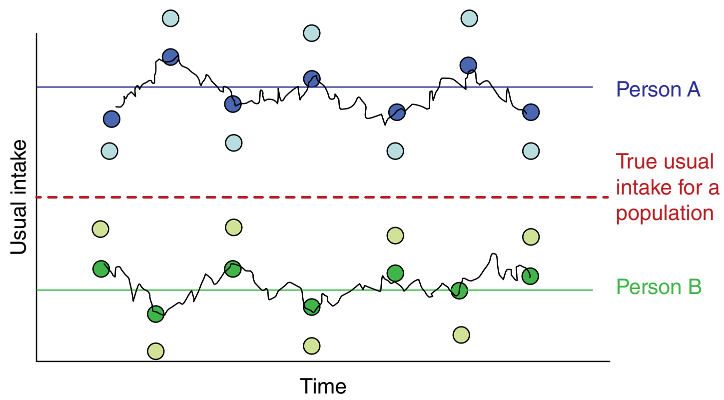


Figure 4.5 Within-person and between-person variation. For persons A and B, the dark-coloured dots represent their day-to-day variation in intake and the light-coloured dots represent their measured intake; taken together these represent within-person variation or random within-person error. Between-person variation is represented by the difference between person A's and person B's usual intake and the population's usual intake. Adapted from NHANES Dietary Web Tutorial (http://www.cdc.gov/nchs/tutorials/Dietary/Advanced/ModelUsualIntake/index.htm).

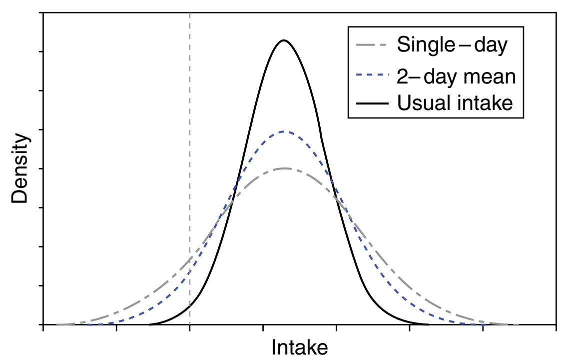


Figure 4.6 Hypothetical distribution of usual intake of a nutrient or a food with no between-person random error (black solid line), contrasted with the estimated distribution from a single or 2-day mean short-term dietary assessment instrument (e.g. 24-hour recall) containing between-person random error (dashed lines). The vertical dashed line represents a hypothetical cut-off of interest (e.g. dietary recommendation). Adapted from NHANES Dietary Web Tutorial (http://www.cdc.gov/nchs/tutorials/Dietary/Advanced/ModelUsualIntake/index.htm).

The main consequences of random between-person errors (i.e. inflated SD) are that the proportion of the population below or above a certain cut-off point (e.g. nutrient recommendation) is over- or underestimated; and, furthermore, the strength of an association between a dietary intake and a health outcome is biased, usually towards no effect (attenuated).

Systematic within-person errors

In addition to the random within-person error, individuals may also systematically under- or overestimate their true food intake (consciously and subconsciously). This is referred to as a *systematic within-person error* and is defined as the difference between observed and true (long-term average) intake.

Systematic within-person errors can take three forms:

- A systematic error that applies to all individuals equally, for example caused by systematic errors in food composition tables or in picture books for portion size estimation; this error is referred to as *systematic additive error/bias*.
- A systematic error that is proportional to the level of individual intake, for example individuals with higher intakes under-report relatively more than individuals with lower intakes; this error is referred to as *intake-related bias* or multiplicative bias.
- A systematic error that differs between individuals according to specific characteristics such as age, sex, education or other unmeasured characteristics; for example obese people tend to underestimate their food intake more than non-obese people, different interviewers conduct interviews (and differ in the way interviews are done); this error is referred to as *person-specific bias.*

Systematic between-person errors

If systematic within-person errors occur non-randomly between individuals, these errors can lead to systematic errors at population level (i.e. systematic between-person errors). As a consequence, the observed mean intake of a given population will be incorrect and either over- or underestimated; this applies to all three forms of systematic error as described above with the exception of person-specific bias. At the group level, these errors can cancel each other out, in which case this error would not contribute to systematic between-person errors. However, this type of error contributes to the observed variation and affects the true intake distribution, so that the observed SD will be further inflated:

$$\sigma^2_{\text{observed}} = \sigma^2_{\text{true}} + \sigma^2_{\text{within}} + \sigma^2_{\text{person-specific}}$$

In practice, all three forms of systematic within-person error tend to be present simultaneously, so that both the population mean intake and its SD are measured with error. This can be summarised by the formula:

$$Q_{ij} = b_0 + b_1 T_i + r_i + e_{ij}$$

where Q = instrument; T = true intake; i = person; j = day; b_0 = additive bias; b_1 = multiplicative bias; r_i = person-specific bias; e_{ij} = random (within-person) error excluding person-specific bias.

In the case of systematic between-person errors, the mean dietary intake of a population is biased (i.e. the observed population mean differs from the true mean). As a consequence, the proportion of the population below or above a certain cut-off point – for example, of a dietary recommendation – is biased. However, diet–health associations are not necessarily biased (i.e. correlation or regression coefficients are unaffected by systematic errors, provided that no person-specific bias is present).

How to reduce measurement errors at the data-collection stage

Random errors

- Repeat measurements for each individual and take the average; the number of repeated measurements depends on the objectives of a given study.
- Standardise measurements, for example through written guidelines (operations manual), training of all people involved in the study, careful selection and standardisation of measurement tools, standardisation of questionnaires, use of computer software. Furthermore, all interviewers should be knowledgeable and trained about foods available in the marketplace and about preparation practices, including prevalent regional or ethnic foods.

Systematic errors

- Apply the same principles as for random errors regarding the standardisation of measurements.
- Use the best available measurement tools or techniques (depending on feasibility).
- Use calibrated measurement tools.
- Perform unobtrusive measurements (e.g. neutral interview techniques).
- Use '*blinding*', where the study objectives are unknown to the participants (although be aware that this may not always be possible; for more information see Chapter 3).

Evaluating measurement errors in dietary intake

After considering all possible and feasible measurement error-reduction techniques, dietary intake measurements (like any measurement) can still contain substantial error. It is thus also important to quantify the overall magnitude of both random and systematic errors in evaluation studies, ideally before a selected dietary assessment instrument/method is applied in the main study. Evaluation includes reproducibility and validation studies.

Reproducibility studies address random errors and investigate the consistency of dietary intake measurements on more than one administration to the same person at different times and under similar conditions. Reproducibility can be quantified in several ways. Often coefficients of variation of differences within individuals are calculated to provide a measure for *precision*. Correlation coefficients can be computed to quantify the consistency of ranking of individuals on two or more occasions (i.e. to distinguish between individuals), which is referred to as *reliability*.

Validation studies address systematic errors and investigate the degree to which a method accurately measures the diet variable that it was designed to measure – that is, the true value over a specified period of time. For example, a valid 24-hour dietary recall would be a complete and accurate record of all food and drink consumed on the day preceding the recall. Depending on a study's objective, validity refers to the accuracy of a population's mean intake, of an individual's usual intake or of ranking of individuals. Validity can be assessed by comparing the main instrument with a superior reference measure. In theory, such a reference measure is free of systematic errors (i.e. unbiased for true intake at population level and no multiplicative error) and random errors are uncorrelated to true intake and to the errors of the main instrument. However, in dietary assessment only a few ideal reference measures are currently available: doubly labelled water for energy intake, 24-hour urinary nitrogen excretion for protein intake, and 24-hour urinary potassium excretion for potassium intake. The lack of a perfect reference method also indicates a continued need to search for better gold standards.

Furthermore, there should be an examination of how the measurement errors affect the results of the study. The outcomes of evaluation studies can subsequently be considered in the interpretation of the study results (e.g. whether the results are under- or overestimating the true value) and used to (partially) correct the observed results of the main study for dietary measurement errors.

Correcting random and systematic measurement errors at the stage of data analysis

Depending on the study objectives, it will often be necessary to correct for measurement errors using statistical approaches.

Linear regression calibration

With a technique referred to as linear regression calibration, random errors, in the form of within-person random error, and systematic errors, in the form of additive and multiplicative bias, can be at least partially corrected for or mitigated. However, *calibration studies* are needed to supply the best predictors of the true usual intake.

In a calibration study, ideally on a subsample of the full cohort or the main study, diet is measured with a superior method – a so-called reference instrument – where the reference instrument should have the same properties as in the validation studies described above. For practical reasons, non-ideal reference measures are often used: 24-hour dietary recalls or food records (see earlier in this chapter). Although it has been shown that 24-hour dietary recalls are less biased than, for example, FFQs, they have been shown to be biased for true intake and to have errors that are correlated with true intake and with the errors of an FFQ. However, it is still preferable to mitigate the effect of measurement errors in a main instrument (e.g. FFQs) with a non-optimal reference measure (e.g. 24-hour dietary recall).

Regression calibration involves two steps (regressions):

- Regress the dietary intake as measured with the reference instrument (superior method) on the main instrument to get the prediction equation (expected values from the superior method) or, alternatively, the so-called attenuation coefficient.
- Regress the health outcome on the prediction equation or divide the risk estimate by the attenuation coefficient; or in other words, recalculate the association between dietary intake and health outcome using the expected values from the reference instrument.

The mean intake of the main instrument can be replaced by the predicted values from the reference instrument and thus the mean intake of the population recalculated – that is, the calibrated mean intake (partially) corrected for measurement error. However, it is important to keep in mind that the measurement error correction is incomplete as long as a non-ideal reference method is used as a reference instrument.

Energy adjustment

Energy adjustment is another way to mitigate the effect of measurement errors. In validation studies, correlation coefficients between dietary intakes of the test instrument (e.g. FFQ) and reference instrument (e.g. biomarker) improve after energy adjustment, which is mostly due to reduced measurement error. A possible explanation is that errors for energy and nutrient intake are correlated and they tend to cancel each other out in the energy-adjusted nutrient intake. The nutrient density method (i.e. nutrient/total energy) is most commonly used, but other methods exist (e.g. nutrient residuals).

Removing within-person variation

Finally, if the interest is in estimating intake distributions of the usual intake at population level, then statistical techniques can be used to remove/reduce the within-person errors (day-to-day variation), leaving only the between-person variation. This is particularly needed in dietary monitoring, where short-term instruments such as 24-hour dietary recalls are the method of choice, in order to estimate the proportion of a population below or above a given dietary recommendation or cut-off point. Basic approaches rely on simple analysis of variance to separate within- from between-person variation and remove the within-person variation. Newer approaches involve additional steps such as normalising transformations, back transformations of varying complexity and the use of empirical distributions. Several methods have been developed in the last few years and there is also a wide range of software solutions available (see Section 4.6).

All approaches require an estimate of the within-person variation for the food group or nutrient of interest in order to separate it from the between-person variation. A prerequisite to calculating the within-person variation is that at least one repeated day of intake data (e.g. repeated 24-hour recalls) has been collected in at least a subsample of the study population. A less favourable approach is to borrow estimates of within-person variation from another study population with similar dietary habits. The magnitude of the within-person variation in relation to the between-person variation not only differs across foods or nutrients, but also across countries, ages, sex and other factors. For example, milk might be consumed on a daily basis among preschool children while not necessarily among adults, leading to higher within-person variability among adults than among children. Differences in the availability of foods by days of the week or season also affect the day-to-day variation (within-person variation) of dietary intake. For example, if citrus fruits (a good source of vitamin C) are mostly consumed during one season, then the within-person variation of vitamin C will be high. Seasonal variation is usually more pronounced for foods than for nutrients and less for total energy intake. For these reasons, it is recommended that a dietary survey covers all seasons at population level, with at least one repeated day of intake data as mentioned above. Generally, the intake of most nutrients varies more within individuals (from day to day) than between individuals. The higher the within-person variation for a given nutrient, the poorer the estimate of an individual's usual intake, for example, if only a single 24-hour dietary recall was available. In contrast, long-term instruments such as an FFQ measure usual intakes over a longer time period (e.g. the previous 12 months), which results in a low within-person variation. Therefore, a separation of within- and between-person variation is usually not needed for long-term instruments. However, it has to be kept in mind that long-term instruments are usually more prone to systematic errors.

4.5 Multivariate analyses of dietary intake

Dietary patterns

Dietary patterns – also referred to as eating patterns or food patterns – were defined in 1982 by Schwerin and co-workers as 'distinct and discrete patterns of consuming foods in different combinations'. The goal of dietary pattern analysis is to summarise a large number of correlated dietary variables, estimated at the food level, but more recently also at the nutrient and/or related biomarker levels, into fewer independent (uncorrelated) components without much loss of information. These patterns are thought to be easier to analyse as compared with a multitude of (individual) foods or food constituents, such as nutrients and other chemicals, and to allow inferences to be drawn to the total diet. In the last three decades, various approaches to derive dietary patterns have evolved and continue to develop. The main methods that have already been frequently applied in nutritional research are described in more detail in this section.

Methods to derive dietary patterns

Dietary patterns are not directly observable or measurable. Statistically, they can be referred to as latent (unobserved) variables. Three main techniques for computing dietary patterns in multivariate analyses can be distinguished (Figure 4.7): hypothesis-oriented (a priori) methods; exploratory (a posteriori) methods; and hybrid methods combining a priori and a posteriori techniques.

Hypothesis-oriented (a priori) methods

Dietary patterns that are defined according to some a priori criteria for a healthy diet (i.e. a hypothesis-oriented approach) are referred to as *diet quality indices* or scores. Such indices can be based on pre-existing dietary recommendations for the general population or specific population subgroups (e.g. food plate, food guide pyramid); guidelines for the prevention of a specific disease (e.g. WCRF [World Cancer Research Fund]/AICR [American Institute for Cancer Research] recommendations for cancer prevention); or dietary habits known to be healthy (e.g. Mediterranean diet). Indices are usually composed of foods, nutrients or a combination of both. Some indices also incorporate measures for dietary diversity or moderation. Diet quality indices that incorporate non-dietary components such as physical activity, body fatness or smoking are usually referred to as *healthy lifestyle indices*. Depending to which degree a given dietary recommendation is met or not, a specific score is assigned and then summed up to the overall index. For example, the Healthy Eating Index (HEI) has ten components consisting of dietary recommendations for five food groups, four nutrients and a component for dietary variety. For each component, individuals receive a score ranging from 0 to 10. If a recommendation is fully met, a score of 10 is given, and this score declines proportionally depending on the degree to which the recommendation is met. The underlying measurement of index items can be quantitative food/nutrient intake, frequency of food intake or a count of reported food groups from short- (e.g. 24-hour dietary recalls) or long-term dietary assessment instruments (e.g. FFQs). However, it is

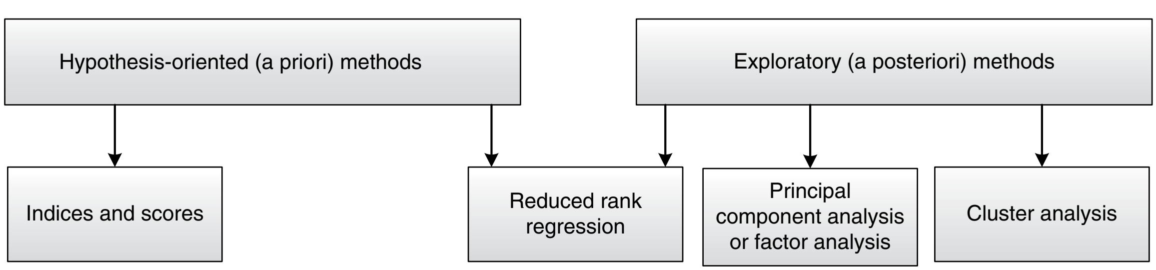


Figure 4.7 Main methods to derive dietary patterns in nutritional research. Adapted from Schulze, M.B. and Hoffmann, K. (2006) Methodological approaches to study dietary patterns in relation to risk of coronary heart disease and stroke. *British Journal of Nutrition*, **95**, 860–869.

important to consider that the dietary data used should be appropriate for the purpose of a given index (e.g. to evaluate the usual diet).

Exploratory (a posteriori) methods

Dietary patterns can also be empirically derived (a posteriori) from the collected dietary data using different statistical techniques. *Factor analysis* (FA) or *principal component analysis* (PCA) aggregates specific foods (groups) or nutrients into a limited number of patterns (factors/components) based on the degree to which these dietary variables are inter-correlated. Individual scores are then computed from each retained component as the sum of products of the observed variables multiplied by weights proportional to the loadings (i.e. linear combinations). The retained patterns or components account for the largest part of the total variation of the underlying dietary variables between individuals. With *cluster analysis*, individuals with similar diets, rather than dietary variables, are aggregated into relatively similar non-overlapping subgroups (clusters). Individuals within a given cluster share similar dietary intakes. The *treelet transform* method is a third empirical approach that produces sparse factors (i.e. foods with zero loadings are ignored to compute patterns) in combination with a cluster tree to visualise related groups of foods or nutrients, and this produces easily interpretable patterns. Input dietary variables for all exploratory methods can be foods, food groups, nutrients or combinations expressed in weight, servings or frequency of consumption as assessed with dietary assessment instruments that provide usual intakes (e.g. FFQs), but also biological markers or (food) metabolites. The patterns are usually labelled according to the highest factor loadings or specific combinations of foods and/or nutrients.

Hybrid methods combining a priori and a posteriori approaches

More recently, methods such as *reduced rank regression* (RRR) or *partial least squares regression* (PLS) have been developed that bridge the gap between a priori and a posteriori approaches. These methods identify dietary patterns by considering a priori information to predict another set of correlated response variables, typically intermediate markers (biomarkers) of disease or nutrient intakes. Biological pathways from the diet to a disease outcome are taken into account by identifying dietary patterns associated with biomarkers of a specific disease. *Decision tree analysis* identifies subgroups of a population whose members share dietary characteristics that influence (intermediate markers of) disease. They can be seen as hybrid methods, because the identified patterns depend on a priori knowledge to select the biomarkers/nutrients and the empirical correlation structure in the dietary data. Similar to exploratory methods, input dietary variables can be foods, food groups, nutrients or combinations expressed in weight, servings or frequency of consumption as assessed with dietary assessment instruments that provide usual intakes (e.g. FFQs). In addition, the hybrid approaches require response variables, which need to be continuous variables, such as biomarker levels. The patterns can be labelled according to characteristic pattern combinations of foods or predicted response variables.

Strengths and limitations of dietary pattern approaches

In general, all of the three methods, a priori, a posteriori and hybrid, have their specific advantages and disadvantages that need to be considered when choosing one or the other. In this respect, it is essential that the derived dietary patterns are evaluated in terms of reproducibility and validity. Comparisons of different methodologies are also recommended. The main strengths and limitations of each of the three methods are shown in Table 4.3.

Dietary patterns (*multivariate analyses*) are considered complementary to the traditional single food or nutrient approach (*univariate analyses*). Since diet is a complex exposure, it calls for multiple approaches to examine the relationship with disease risk.

4.6 An integrated approach for assessing and analysing dietary intake

Considerable advances in concepts of dietary assessment have occurred over time, aiming to prevent or minimise the effects of measurement error in usual dietary intake estimates. This is particularly, but not exclusively, the case for large population-based studies. These approaches are based on the integration and combination of different dietary (self-report) assessment methods and biomarkers, with the ultimate purpose of optimising their strengths while balancing their weaknesses (see Section 4.2). Furthermore, integrated approaches for assessing and analysing dietary intake require the matching of food consumption data to related food composition tables.

Combining different dietary intake assessment methods

In nutritional epidemiology, the use of self-reported dietary questionnaires (e.g. FFQs) on their own has been challenged. New approaches increasingly favour the use of repeated short-term and open-ended dietary assessment methods, such as quantitative 24-hour

Table 4.3 Characteristics of methods of deriving dietary patterns.

Method	Aim	Common principles and method-specific strengths and weaknesses
Hypothesis-oriented (a priori) methods	Evaluating adherence to dietary guidelines, specific diets or guidelines for prevention of a chronic disease	Theoretically defined according to a priori knowledge for a healthy diet; main example: diet quality indices or scores. **Strengths:** Monitoring of overall adherence to dietary guidelines; evaluation of overall effects of dietary interventions, especially where simultaneous changes in the diet can be expected; subgroups in a population at risk of poor dietary quality are more easily identified; diet quality can be assessed even if only limited dietary information is available or obtainable; evaluation of whether current guidelines for a healthy diet have a protective effect against diseases and to estimate the magnitude of overall effect. **Weaknesses:** Overall diet is not necessarily captured since scores usually focus on specific aspects of the diet; correlations between dietary variables are at best not fully considered.
Exploratory (a posteriori) methods	Explaining as much variation in intake of a dietary variable as possible	(1) Dietary variables (e.g., foods, nutrients) are combined into fewer factors based on their linear relationship; main example principal component analysis (PCA). (2) Individuals with similar diets are aggregated into non-overlapping subgroups (clusters); main example cluster analysis. (3) Combination of PCA and factor analysis; main example treelet transform. **Strengths:** Interactive effects of foods eaten in combination on bioavailability and circulating levels of nutrients are more easily captured; alleviates problems of model over-fitting (multicollinearity between individual dietary variables in a single model), of loss of statistical power in detecting diet–disease association, and of confounding of a single dietary variable by dietary patterns. **Weaknesses:** Not necessarily related to health outcomes; lack of reproducibility of patterns over time and/or between different researchers due to many arbitrary and impacting decisions during the process of deriving patterns; outcomes cannot be linked to a single dietary variable.
Hybrid methods	Explaining as much variation in a response variable as possible	Patterns depend on a priori knowledge in selecting a response variable (e.g. biomarker of disease) and the correlation structure of dietary variables; main example reduced rank regression (RRR). **Strengths:** Consideration of a priori knowledge of biological pathways; these methods should be thus more predictive of disease risk. **Weaknesses:** Requires response information (e.g. biomarker), which may not be available in many studies; potential confounding of biomarker by dietary pattern.

dietary recalls or food records. This new design, initially proposed in European and US food surveillance studies, introduced several innovative statistical methods to estimate individual intakes and population means and distributions more effectively when a limited number of repeated dietary measurements (24-hour dietary recalls or food records) are used. The new statistical models assume that usual intake is equal to the probability of consumption on a given day times the average amount consumed on a consumption day. Among those developed in connection with 24-hour dietary recalls are the National Cancer Institute Method (NCI), the Multiple Source Method (MSM) and the Statistical Program to Assess Dietary Exposure (SPADE). All these methods combine quantitative data from repeated 24-hour dietary recalls (at least two) with additional covariate information. For example, non-quantitative FFQs or food propensity questionnaires (FPQs), querying only the frequency of consumption, are employed for identifying habitual users of less frequently consumed foods, hence providing important covariate information aiming to reduce within-person variability (i.e. random errors).

Thus, in contrast to linear regression calibration approaches – which regress 24-hour dietary recall data collected from a representative subsample of the study population on FFQ derived data and apply the derived calibration coefficients to correct for population mean differences and for deattenuation of the relative risk estimates (see Section 4.4) – these newer, combined approaches were designed to use short-term dietary assessment methods for measurement of individual intake in the whole study population.

However, the use of repeated interviewer-administered 24-hour dietary recalls on a large scale is costly and implies high logistical demands. So far, the combined approaches have therefore been applied more frequently in monitoring surveys that often include smaller study populations (several thousands) as compared to epidemiological studies (tens or hundreds of thousands). Although the methodological value of the combined approaches still requires further exploration – for example in terms of precise estimation of the probability of consumption – they seem to be promising approaches for deriving individual usual intake and population mean and distribution. The advent of new technologies fosters both the application of web-based self-reported 24-hour dietary recalls (particularly as the substitute for or complement to traditional FFQs in large study settings), as well as web-based infrastructures to facilitate the conduct and maintenance of traditional interviewer-administered 24-hour dietary recalls.

All self-reported dietary assessment methods are prone to error and none of them alone appears to be suitable for assessing individual usual food intake. The inclusion of recovery or concentration biomarker information (e.g. nutritional biomarkers and increasingly food or other related metabolites) in the estimation of individual usual dietary intake therefore warrants further investigation (see Section 4.4).

In conclusion, the promising direction towards integrated approaches benefiting from advanced technologies to enhance the assessment of usual dietary intake should include, in an optimal study design, short-term repeated dietary assessment methods (i.e. repeated 24-hour dietary recall or food records) for measuring individual dietary intake and population mean and distribution; a complementary food propensity questionnaire (or FFQ) for estimating infrequently consumed foods; biomarkers of diet or its metabolites as independent measurements; and new statistical modelling for integrating the dietary assessment methods and related measurements (Figure 4.8).

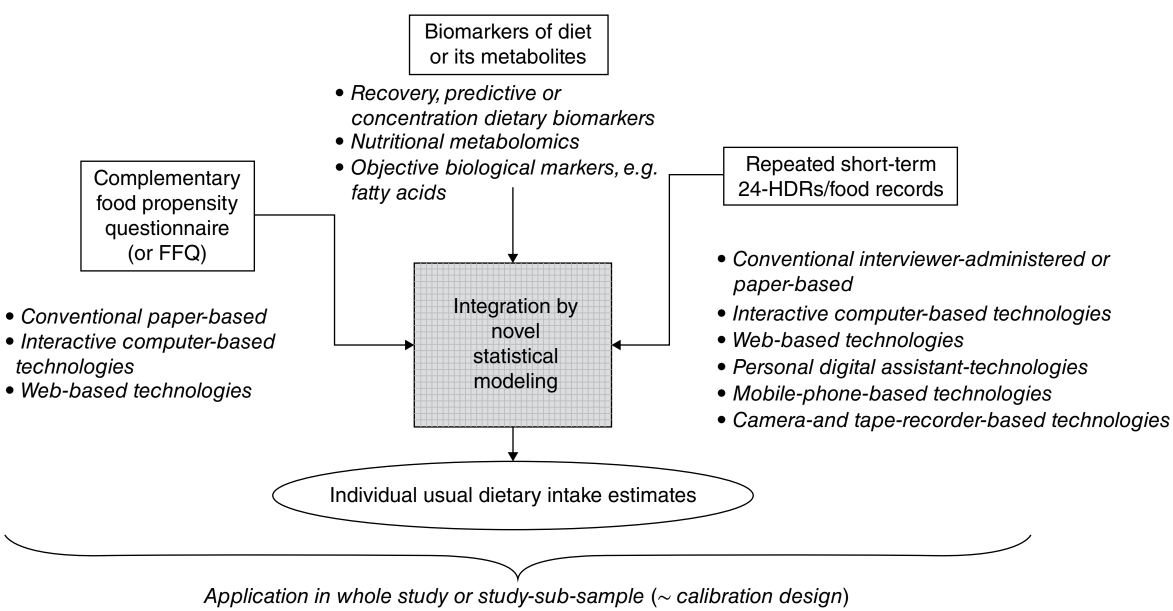


Figure 4.8 Towards an integrated approach to measure diet in international epidemiological studies. From Illner, A.K., Freisling, H., Boeing, H. *et al.* (2012) Review and evaluation of innovative technologies for measuring diet in nutritional epidemiology. *International Journal of Epidemiology*, **41** (4), 1187–1203, by permission of Oxford University Press.

Food composition tables and food matching

Dietary intake is usually assessed at the food intake level, but also at nutrient or other food component levels (e.g. chemicals, additives, contaminants), depending on the research interest. It is therefore necessary to convert collected food consumption data into nutrient intake, through matching to related food composition tables (or databases if in electronic format). In this food-matching process, the best match is sought between food consumption data (e.g. individual food items, ingredients or recipes) and equivalent/similar items in the food composition databases or other occurrence databases. Expert knowledge is required for this process and the related work should not be underestimated. The importance of internationally harmonised food composition databases should also be emphasised, especially in studies aiming at pooling data for analyses at nutrient or food component levels.

These and other requirements and activities related to food composition are detailed in Chapter 5.

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