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Innovative approaches to estimate individual usual dietary intake in large-scale epidemiological studies

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Valid estimation of usual dietary intake in epidemiological studies is a topic of present interest. The aim of the present paper is to review recent literature on innovative approaches focussing on: (1) the requirements to assess usual intake and (2) the application in large-scale settings. Recently, a number of technology-based self-administered tools have been developed, including short-term instruments such as web-based 24-h recalls, mobile food records or simple closed-ended questionnaires that assess the food intake of the previous 24 h. Due to their advantages in terms of feasibility and cost-effectiveness these tools may be superior to conventional assessment methods in large-scale settings. New statistical methods have been developed to combine dietary information from repeated 24-h dietary recalls and FFQ. Conceptually, these statistical methods presume that the usual food intake of a subject equals the probability of consuming a food on a given day, multiplied by the average amount of intake of that food on a typical consumption day. Repeated 24-h recalls from the same individual provide information on consumption probability and amount. In addition, the FFQ can add information on intake frequency of rarely consumed foods. It has been suggested that this combined approach may provide high-quality dietary information. A promising direction for estimation of usual intake in large-scale settings is the integration of both statistical methods and new technologies. Studies are warranted to assess the validity of estimated usual intake in comparison with biomarkers.

Dietary assessment: Usual dietary intake: Technology: Statistical modelling

Valid estimation of usual dietary intake, i.e. the long-term average intake of a subject, in epidemiological studies is a topic of present interest. As diet–health estimations are based on dietary intakes over the long-term[1], the usual intake of a subject is the relevant exposure in large-scale epidemiological studies[2]. Ideally, a subject's usual intake would be measured on each day of the period under study or at least on a large number of days[3]. However, this is rarely achieved[4]. As such, there are two principles to assess individual usual intake. Firstly, to apply dietary assessment instruments such as an FFQ that is designed to assess the long-term average intake directly by the study participant. Secondly, to apply repeated short-term instruments such as a 24-h dietary recall and to extrapolate this information to usual food intake[5].

The selection of the appropriate instrument for the assessment of usual food intake in large-scale epidemiological studies depends on the research question. In most epidemiological studies, relative ranking of food and nutrient intake is adequate for determination of correlation or relative risks[6]. However, to evaluate the dietary intake of a population in relation to specific dietary recommendations, quantified estimates of the dietary intakes may be required[1].

For a long time, cost and logistic issues have led to favour FFQ for large-scale prospective studies, whereas 24-h recalls have mainly been used in surveys[1,7]. Both

Abbreviations: MSM, Multiple Source Method; NCI, National Cancer Institute.

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Table 1. Web-based 24-h dietary recall tools for dietary assessment

Author	Tool	Country	Features
Albar *et al.*[30], Carter *et al.*[18,29]	myfood24	UK Australia (under development) Germany (under development)	Extensive database with generic and branded food items; meal-based approach; simplified AMPM approach; photographs to aid portion size estimation
Bradley *et al.*[69]	INTAKE24	UK	Meal-based approach; based on AMPM approach; photographs to aid portion size estimation
Lassale *et al.*[70], Touvier *et al.*[71]	NutriNet Santé	France	Meal-based approach; photographs to aid portion size estimation
Thompson *et al.*[32], Diep *et al.*[72], Kirkpatrick *et al.*[73], Subar *et al.*[19]	ASA24	USA Canada Australia (under development)	Meal-based approach; based on the five steps of the state-of-the-art AMPM; photographs to aid portion size estimation; questions about food preparation; available in English and Spanish; optional supplement module
Arab *et al.*[34]	DietDay	USA	Multiple steps similar to the AMPM approach; photographs to aid portion size estimation; questions about food preparation; recording of supplements; provides dietary feedback

AMPM, Automated Multiple-Pass Method; ASA24, automated self-administered 24-h recall.

systematic and random errors have been recognised as problems when FFQ are used alone[8]. Pooled results from recent validation studies using recovery biomarkers such as doubly labelled water and urinary nitrogen suggested that the impact of FFQ measurement error on total energy and protein intakes was severe[9]. This large measurement error may have led to considerable misclassification of participants, and thus may have affected diet–disease estimates. The utility of the FFQ has been questioned and the need for improved dietary assessment techniques has emerged[10–14].

The objective of the present paper is to review recent literature on innovative approaches for the improvement of the assessment of usual dietary intake focussing on: (1) the requirements to assess usual intake and (2) the application of innovative approaches in large-scale settings.

Requirements to assess usual intake

With respect to the assessment of usual food intake in large-scale epidemiological studies, new methodologies and innovative technologies depict promising approaches for a more valid estimation of usual intake[15]. New methodologies relate to the principle of collecting dietary intake data such as combining different assessment instruments[16], while new technologies refer to the collection procedure itself such as the use of mobile phones[17] or web-based applications[18,19].

Innovative technologies for the assessment of usual intake

Technological progress and a significant increase in internet usage in the past years has resulted in the development of a number of innovative technologies for dietary assessment. Different technological strategies are followed to address the challenges in dietary assessment including web-based 24-h recalls, mobile food records or simple closed-ended online questionnaires that assess the food intake of the previous 24 h. To date, a number of literature reviews, each focussing on different new technologies, have been published[15,20–28]. The most comprehensive systematic literature review was conducted by Illner *et al.* in 2012[15]. They classified available tools into six categories: mobile phone-based technologies; personal digital-assistant technologies; interactive computer-based technologies; web-based technologies; camera- and tape-recorder-based technologies; scan- and sensor-based technologies. In the present review, the focus is on web-based instruments and mobile technologies as promising assessment tools in large-scale study settings.

A number of self-administered, web-based 24-h recalls have been developed as illustrated in Table 1. The instruments differ with respect to the number of foods available in the database and the way of collecting information on dietary intake. The myfood24 is an online 24-h dietary assessment tool developed for the application among British adults and adolescents[18]. So far, it is available for application in the UK with respective national databases. An Australian and a German version are under development[29]. The tool can be used for multiple recalls or as a food record. To reduce completion time the myfood24 does not follow the detailed Automated Multiple-Pass Method; however, some aspects are included such as an optional quicklist function, a detailed food search, prompts for commonly forgotten foods and a final review before submission. The UK version of the tool is linked to an extensive database that contains about 40 000 generic and branded food items[29]. Food portion images help in choosing the appropriate portion size. The relative validity of the myfood24 against a traditional interviewer-administered recall was tested among British adolescents with strong correlations for energy and most nutrients[30]. The automated self-administered 24-h recall, developed by the US National Cancer Institute (NCI), represents a detailed 24-h recall for use in adults and children. It collects and automatically codes dietary intake data, and includes detailed questions about portion sizes and food preparation methods based on the five steps of the state-of-the-art Automated Multiple-Pass Method.

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The database includes approximately 8000 food items[19,31]. The automated self-administered 24-h recall was compared with traditional interviewer-administered 24-h recalls in a diverse sample of adults aged between 20 and 70 years from three different geographical areas. Equivalent energy intake estimates between the two recall methods were found for men and women[32]. The web-based recall DietDay, which contains 9349 food items assesses information on portion sizes and preparation methods, and was designed for repeated administration[33]. The DietDay also applies multiple steps similar to the Automated Multiple-Pass Method approach. The validity of six administrations of DietDay was tested using the doubly labelled water method. The rate of underreporting for energy was on average about 30 %, which is comparable with conventional 24-h recalls[34].

To further reduce demands on time for dietary assessment, the development of abbreviated, web-based, self-administered instruments has been initiated that recall the diet of the previous 24 h, but with a finite list of food items[35,36]. The Oxford WebQ, for instance, has been especially designed for the use in several large-scale prospective studies in the UK[35,37]. The instrument is closed-ended like an FFQ, but is intended to be administered at multiple time points in a study similar to a 24-h recall. It obtains information on consumption amounts of twenty-one food groups. Median time for self-completion is 12·5 min. Nutrient intakes are calculated automatically and stored in a secure database. Compared with an interviewer-administered 24-h recall, the Oxford WebQ provided similar mean estimates of energy and nutrient intakes and study participants were reasonably well ranked[35]. Recently, it was shown that 66 % of UK Biobank participants completed the questionnaire more than once[37]. The 24-h food list has been developed for use in the German National Cohort[36,38]. It is by definition intended to be used in a combined approach with an FFQ and not as stand-alone instrument. The tool includes a total of 246 food items. Consumption of food items during the previous day is assessed dichotomously (yes/no). In a feasibility study with 505 participants, median completion time was 9 min and the majority of study participants completed the tool three times.

Mobile phones have a variety of technological features that are promising to facilitate dietary assessment[22]. This technology is mainly used for real-time recording of food intake due to the advantage of portability[15,39]. Smartphone applications (app) have been developed allowing self-monitoring of food and beverage intake[28,39,40]. Intake data can be directly transferred to nutrient output for subsequent analysis. The electronic Dietary Intake Assessment app was developed for use in Australia as a weighed or estimated food record[40,41]. Its relative validity to measure nutrient and food group intakes was tested against repeated 24-h recalls. While a good agreement was found on the group level, large variability of reported intakes at the individual level was observed. Similar results have been observed for the My Meal Mate app, an electronic food record app that was developed to facilitate weight loss[39].

Another promising feature of smartphone-based dietary assessment is the possibility to take pictures of food and beverages[25]. Here, collected data can either be analysed afterwards by trained dietitians or automatically[22]. Using for example the remote food photography method, study participants sent images to a server, which were then analysed to estimate food intake[42]. Further features of this technology include a semi-automated procedure to estimate portion sizes and an automatic identification of foods via bar code scanning. Compared with doubly labelled water, the remote food photography method did not significantly over- or underestimate energy intake[43]. The mobile device food record is a fully automated food photograph analysis tool that analyses type and amount of foods[44]. Users capture images of their foods and beverages before and after eating. A fiducial marker has to be included in the picture to estimate the amount consumed. However, the method overestimated energy intake when compared with laboratory weighed foods in adolescents[45].

Innovation in statistical methods for the estimation of usual intake

Various statistical methods for the estimation of usual dietary intake with focus on intake distributions have been proposed[46–58]. The majority of these methods have been developed for the use in dietary surveys or risk analysis. Following a similar general approach, the methods use data that assess dietary intake on at least two independent days for each subject (e.g. repeated 24-h recalls). Statistical modelling considers the naturally occurring day-to-day variability by removing the so called within-person variation from the total variation[5,59].

To consider a statistical method suitable for the estimation of diet–health relationships, it must enable the estimation of individual usual dietary intake and not only intake distributions. Moreover, the method has to be able to estimate individual intake from both daily and episodically or rarely consumed foods. In this regard, two more recently developed methods are of particular interest, also with respect to large-scale prospective studies: the NCI Method[54–56], and the Multiple Source Method (MSM)[57,60]. The NCI Method has been implemented with SAS macros (SAS Institute, Inc., Cary, NC, USA). The MSM was developed for use in Europe and is available through an online interface.

Both methods follow a two-step approach[54,57,59,61]. In the first part, the probability of consumption is estimated using a logistic regression model. The second part includes an estimation of the amount consumed and is restricted to observed positive intakes on the 24-h recalls. Firstly, a transformation step is used to obtain normally distributed data. Next, mean usual intake and between- and within-person variance on the transformed scale are estimated. The last step eliminates the within-person variance and the results are back-transformed to the original scale. Finally, the two model parts are combined to obtain the individual usual intake by multiplying the probability of consumption and the average consumption-day amount. For daily

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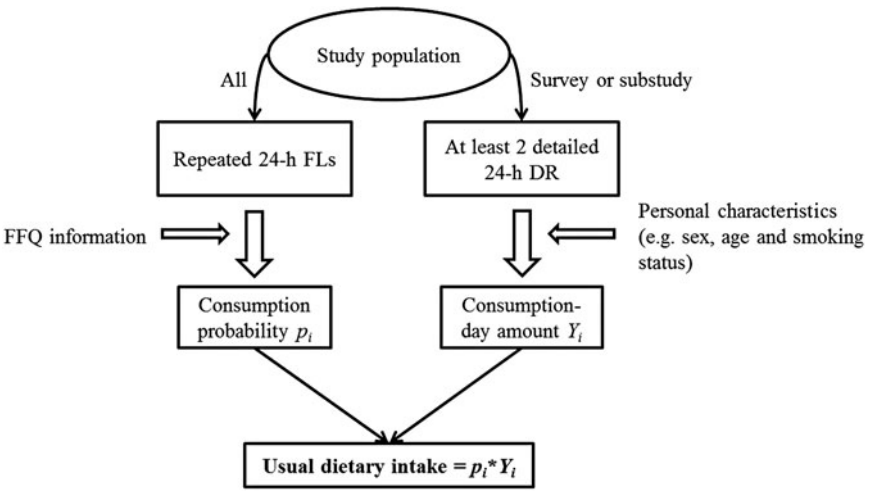

Fig. 1. Proposed dietary assessment and statistical method to derive individual usual dietary intake in the German National Cohort[36,65]. 24-h DR, 24-h dietary recall; 24-h FL, 24-h food list.

consumed foods, only the second part of the model is of relevance.

The statistical methods allow the inclusion of covariates such as age, sex or BMI in both parts of the model to represent the effect of personal characteristics. This is important as studies showed that sociodemographic factors such as education[62], family status[63] and income[64] are associated with food consumption. More recently, the combined impact of eight different determinants of the consumption-day amount was analysed using state-of-the-art variable selection procedures. It was shown that sex, age and smoking status were the most relevant determinants of food intake in a representative German population[65].

The 24-h dietary recall is limited in adequately measuring usual intake of foods or nutrients that are not consumed daily[66]. Even with two administrations of 24-h recalls, the probability of consumption for most foods and nutrients is poorly captured at the individual level. This has led to the extension of the statistical procedures by implementing a combined use of both repeated 24-h recalls and FFQ[54,57,66]. The FFQ assesses the probability of consumption, queried as frequency of usual intake over a specified period of time, and thus, levels out the weakness of the 24-h recall method. These reported FFQ frequencies can be used as a covariate in both parts of the statistical model to enhance the estimation of usual intakes from 24-h recall data. For the MSM, FFQ information can further be used to identify true non-consumers. In this approach, study participants who reported non-consumption of a certain food item or food group within the FFQ and did not report consumption of this food in the 24-h recall are defined as true non-consumers. Here, the probability of consumption as well as the consumption-day amount is set to zero. It has been suggested that this approach of combining instruments may provide high-quality dietary information, especially for the assessment of foods that are not consumed every day[16,55,57,66].

Simulation studies were conducted to compare the performance of different statistical methods, including the MSM and NCI Method[59,61]. These studies concluded that the overall performance of methods was similar. However, a small sample size or large within- and between-person variances might lead to inaccurate estimates. Ultimately, practical reasons such as availability of statistical programs or user-friendliness play a major role in choosing one method over the other.

For Germany, it was recently proposed to use a short 24-h food list to assess the probability of consumption complemented by person-specific standard consumption-day amounts derived from national nutrition survey data instead of individual amounts[36,65]. Thus, the two parts of the statistical model (i.e. (1) estimation of consumption probability and (2) consumption-day amount) are separated as illustrated in Fig. 1. This approach is backed by the insight that the consumption frequency contributes more to the between-person variation than does variation in portion size[67]. Information from an FFQ is added to provide information on true non-consumption and on frequency of consumption of rarely consumed foods. The 24-h food list was designed to have a simple structure and a rapid completion time to facilitate multiple administrations in large-scale settings.

Application of innovative approaches in large-scale settings

New technologies offer several potential advantages in large-scale dietary assessments, and therefore, innovative tools may be superior to conventional detailed assessment methods for data collection[11,15,68]. Firstly, time for data coding can be reduced as data are immediately stored. Moreover, most tools have the capacity to directly compute nutrient and food group intakes. Secondly, new technologies allow self-administered application, which is promising in terms of cost

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reduction. Thirdly, data can be collected at a time and location that is convenient for the study participant. Thus, compliance may be increased and multiple administrations may be more feasible compared with conventional instruments. This is even more important knowing that multiple administrations of 24-h dietary recalls in combination with an FFQ would be ideal for the assessment of individual usual intake. With traditional instruments, this has been impractical in large-scale settings[11].

Thus, a promising direction for the valid estimation of individual usual dietary intake in large-scale settings is the integration of innovative statistical methods and new technologies. A number of tools are available as previously described. Web-based dietary recalls can easily be used instead of traditional methods as suggested by Carroll *et al.*[16]. Mobile food records might also substitute 24-h recalls as dietary assessment instrument. However, smartphone applications for self-monitored dietary intake are limited in accurately measuring food intake on the individual level[39–41], and further research is needed to achieve better validity. Image-based food records are also promising in terms of reducing participant's burden. To be implemented in large-scale settings, automated methods would be superior to methods that need input from a human observer. Clearly, more research is needed to improve the accuracy and reliability of available methods[22]. Also, adaptations of statistical methods seem to be feasible when using simplified assessment tools such as the 24-h food list. However, further research is needed with respect to data analysis.

To be integrated into statistical methods, technologies need to qualify for repeated administration. To date, it is unclear how many administrations of a dietary recall or record can be reasonably expected to be completed without impairment of data quality[16]. One study found a high compliance (92 %) for completion of eight non-consecutive automated 24-h recalls[33]. With each additional recall, however, a decline in mean energy estimates was observed. There appears to be a point in time at which the gain in accuracy due to multiple administrations is offset by loss of participants due to the high burden[16]. Available statistical methods require at least two independent consumption days to estimate individual usual intake.

Conclusion

New statistical methodologies and innovative technologies are promising approaches to improve the estimation of usual dietary intake in large-scale epidemiological studies. Innovative statistical methods such as the MSM or NCI Method are available and can be applied in analyses of diet–health relationships. A combination of different dietary assessment instruments such as repeated 24-h recalls and FFQ is recommended. New technologies offer several advantages compared with traditional instruments and qualify for integration into available statistical methods. Although the performance of new technologies has been investigated extensively, more research is needed in regard to the validity of those instruments. Implications of self-administration (e.g. regarding food lists, search algorithms or reporting accuracy) and related problems need to be evaluated. Another issue that needs to be addressed is the availability of population specific assessment instruments as not all countries have own tools and statistical methods available. With respect to combined assessment strategies integrated into statistical modelling, more evidence from biomarker validation studies is needed.

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Conflicts of Interest

None.

Authorship

J. C. drafted the manuscript. U. N. critically evaluated the manuscript. Both the authors approved the final version.

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