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METHODS OF MEASUREMENT IN EPIDEMIOLOGY

Review and evaluation of innovative technologies for measuring diet in nutritional epidemiology

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Introduction The use of innovative technologies is deemed to improve dietary assessment in various research settings. However, their relative merits in nutritional epidemiological studies, which require accurate quantitative estimates of the usual intake at individual level, still need to be evaluated.

Objective To report on the inventory of available innovative technologies for dietary assessment and to critically evaluate their strengths and weaknesses as compared with the conventional methodologies (i.e. Food Frequency Questionnaires, food records, 24-hour dietary recalls) used in epidemiological studies.

Methods A list of currently available technologies was identified from English-language journals, using PubMed and Web of Science. The search criteria were principally based on the date of publication (between 1995 and 2011) and pre-defined search keywords.

Results Six main groups of innovative technologies were identified ('Personal Digital Assistant-', 'Mobile-phone-', 'Interactive computer-', 'Web-', 'Camera- and tape-recorder-' and 'Scan- and sensor–based' technologies). Compared with the conventional food records, Personal Digital Assistant and mobile phone devices seem to improve the recording through the possibility for 'real-time' recording at eating events, but their validity to estimate individual dietary intakes was low to moderate. In 24-hour dietary recalls, there is still limited knowledge regarding the accuracy of fully automated approaches; and methodological problems, such as the inaccuracy in self-reported portion sizes might be more critical than in interview-based applications. In contrast, measurement errors in innovative web-based and in conventional paper-based Food Frequency Questionnaires are most likely similar, suggesting that the underlying methodology is unchanged by the technology.

Conclusions Most of the new technologies in dietary assessment were seen to have overlapping methodological features with the conventional methods predominantly used for nutritional epidemiology. Their main potential to enhance dietary assessment is through more cost- and time-effective, less laborious ways of data collection and higher subject acceptance, though their integration in epidemiological studies would need additional considerations, such as the study objectives, the target population and the financial resources available. However, even in innovative technologies, the inherent individual bias related to self-reported dietary intake will not be resolved. More research is therefore crucial to investigate the validity of innovative dietary assessment technologies.

Keywords dietary assessment, technology, epidemiological studies, innovative methodology, nutritional dietary methodologies

Introduction

The first large-scale epidemiological studies to investigate relationships between diet and diseases took place in the 1980s and early 1990s. Then, structured dietary questionnaires, such as the Food Frequency Questionnaire (FFQ), were sent out in paper form to large cohorts (>80 000 subjects) as a cost-effective yet suitable method for self-administered use.[1–3] However, there has been much debate about the accuracy of FFQs in ranking the individuals according to their usual dietary intake[4–8] because methodological limitations of FFQs may lead to bias in dietary exposure measurements and estimated relative risks that ultimately obscure diet-disease associations.[9–11] Some large epidemiological studies have since implemented short-term dietary assessment methods, either as reference calibration method in a sub-sample[12–14] or as main dietary assessment method for the entire population.[15] Indeed, there is cumulated evidence that repeated open-ended quantitative 24-hour dietary recalls (24-HDRs) or food records may outperform the FFQ in assessing accurately individual usual intake.[16–18] The recent development of new technologies tends to reflect preferences for short-term dietary assessment methods.

Technological progress has further prompted the enhancement of dietary assessment,[19–21] resulting in an increased number of articles being published on innovative assessment technologies, such as computer, internet, telecommunication and imaging technologies.[22] Although there are several reviews about the use of specific technologies for dietary assessment in the domain of nutrition promotion and prevention research,[23–26] there are only a few reviews that critically evaluate the whole spectrum of innovative technologies, particularly with regard to their relative merits in nutritional epidemiology. Recently, Ngo and colleagues provided a valuable description and evaluation of the various technology-based dietary assessment tools,[27] but there is still a lack of discussion on their potential for future applications in epidemiological studies, where accurate quantitative estimates of the individual usual intake are required.

Innovative technologies are deemed promising to overcome some of the logistical and financial feasibility constraints that can profoundly affect the design and maintenance of, particularly large-scale, epidemiological studies.[28,29] However, knowledge on the performance of innovative technologies is still limited, in contrast to the well-known strengths and limitations of the conventional dietary assessment methods (e.g. FFQs, food records, 24-HDRs) and on their overall impact on the underlying dietary assessment methodology.[4,30,31] An evaluation of the potential of these innovative technologies to replace, improve or complement these commonly used dietary assessment methods may therefore help to better assess their usability and possible 'added value' in epidemiological studies. It may also help to disentangle the innovative 'methodological' versus 'technological' features of the new technologies. In this context, 'methodological' features refer to methodological principles of collecting individual-level dietary intake data (e.g. for the 24-HDR to collect all foods and beverages consumed the day before the interview/data collection), whereas 'technological' features relate to the way of collecting the data (e.g. by mobile phones, web-based systems). Our limited knowledge about the relative merits of innovative technologies in nutritional epidemiology might also be partially driven by the current misconception in the scientific community that new technologies are also methodologically new, which may not necessarily always be the case.

The objective of this article is to report on the inventory, designed for measuring self-reported diet for critically evaluating the relative merits of innovative technologies in epidemiological studies, particularly in large-scale settings. Thereby, dietary biomarkers, which are increasingly used as complementary or substitutive measurements of dietary intake,[32] will not be appraised and are beyond the scope of this article. The ultimate aim of this review is to inform researchers of technologies available and those under development that show promise for improving, complementing or replacing the conventional dietary assessment methods in ongoing or planned nutritional epidemiological studies.

Methods

Inventory of published studies with innovative dietary assessment technologies

A structured literature search with pre-defined inclusion and exclusion criteria was undertaken. Studies published in English-language journals between 1 January 1995 and 15 September 2011 were included with study designs relevant to nutritional epidemiology. We considered reliability and validity studies when available, and for newer technologies, (e.g. mobile phones and sensor technologies) reviewed tests conducted throughout design of the technology. Studies included populations of all sizes and age-groups, in low-, middle- or high-income countries. Studies applying dietary assessment technologies within randomized controlled trials, clinical studies or other nutritional prevention, promotion and intervention studies were not considered because these study types may have additional objectives beyond dietary data assessment (e.g. to evaluate the acceptability of a pre-defined diet). One exception was one validation study conducted within a behavioural weight-control programme, as the expected altered nutritional behaviour was taken into account in the statistical analyses.[33] Searches were undertaken in PubMed and Web of Science. The Medical Subject Heading database was used to find the appropriate terms that were used separately or in combination. The following search terms were used: 'nutritional assessment, diet, dietary intake, eating, food intake, nutrient, diet records, questionnaires, epidemiological methods, internet, web, digital, Personal Digital Assistant (PDA), computer, electronic technology and technology assessment, biomedical, diffusion of innovation, computers, handheld or cellular phone'. The searches resulted in the identification of 17 520 English citations and abstracts, which were systematically screened according to the eligibility criteria. Potentially relevant articles were retrieved for evaluation, and data were extracted from 74 articles that met the inclusion criteria.

All individual publications were classified into six groups of innovative dietary assessment technologies, according to technological similarities: (i) 'PDA-technologies', (ii) 'Mobile-phone–based technologies', (iii) 'Interactive computer-based technologies', (iv) 'Web-based technologies', (v) 'Camera- and tape-recorder–based technologies' and (vi) 'Scan- and sensor-based technologies'. When several publications were referring to the same technological dietary assessment instrument, it was counted as only one 'technology variant' in our review. To facilitate the understanding and comparison of the six groups identified, their 'common' assessment procedures (i.e. those that were found to be present in all the technology variants within the same technology group) and 'variable' assessment procedures (i.e. those that were found to vary within the same technology group) were highlighted.

Evaluation

A 'relative' instead of an 'absolute' evaluation was applied by comparing innovative dietary assessment technologies with their conventional counterparts regarding their strengths and limitations. For that purpose, relevant criteria and their related attributes for critically reviewing each technology variant and abstracting key information, were defined. The criteria included 'organizational, logistical and financial efforts' (i.e. for the researcher), 'applicability', 'respondent usability', 'potential of standardization', 'accuracy' and the 'likelihood of reporting bias'. More specifically, the related attributes of the 'organizational, logistical and financial efforts' criteria were as follows: instrument development efforts, costs for equipment, for staff and for logistical administration, duration of data collection, data transfer efforts, time for data coding and entry in the database, data cleaning and pooling efforts (i.e. attributes related to the preparation of the assessment instrument, fieldwork and data processing). The 'applicability' implied the applicability to large populations and targeted sub-groups (e.g. children, adolescents, elderly) and for repeated measurements, whereas the 'respondent usability' was explored with respect to training requirements, cognitive efforts and time for completion, required level of literacy and computer skills and subjective acceptance. Furthermore, the attributes of the 'potential of standardization' criteria were as follows: the level of detail, likelihood of error-prone and incomplete data and of food coding errors. The criteria of 'accuracy' encompass the validity and reproducibility for individual- and group-level data (often relative validity), food identification and portion size quantification. The 'likelihood of reporting bias' was reviewed according to the likelihood of recall and social desirability response bias and of reactivity (i.e. conscious or unconscious change of eating behaviour). Structured, self-documenting spreadsheets were used to appraise which of these criteria and attributes are most relevant for each technology variant. An example of the spreadsheet used for appraising the 'potential of standardization', 'accuracy' and 'likelihood of reporting bias' is shown in Supplementary Table 1, available as Supplementary data at *IJE* online. The abstracted information was summarized for each technology group.

Finally, we summarized how innovative alternatives available and those under development may improve, complement or replace the conventional methodologies (i.e. FFQs and other Dietary Questionnaires (DQs), food records and 24-HDRs), help to disentangle the 'methodological' versus 'technological' features of the innovative technologies, and to evaluate their potential for future applications in epidemiological studies.

Results

Availability and use of innovative dietary assessment technologies

Table 1 defines and describes the common and variable assessment procedures and innovative features of the different dietary assessment technologies considered.

In total, 48 technology variants were identified: six for each, the 'PDA-'[33–38] and the 'Mobile-phone–based' technology group,[39–44] eight for 'Interactive computer-based technologies',[45–52] 15 for 'Web-based technologies',[53–67] eight for 'Camera- and tape-recorder–based technologies'[68–75] and five for 'Scan- and sensor-based technologies'[76–80] (details of the studies can be found in Supplementary Table 2, available as Supplementary data at *IJE* online).

PDA-technologies

'PDA-technologies' were first applied in dietary assessment in the mid-1990s,[37] and although there has been progress in software and equipment development in more recent PDAs, the conceptual application procedure still remains the same. After having received some face-to-face training, the participant is instructed to record all foods and beverages consumed by selecting appropriate food items from an integrated and pre-defined drop-down menu. Formerly, participants could choose from about 180 food items,[37] whereas the newer PDAs offer the user a higher number of food items varying from 400[36] to more than 4000 items.[38] Overall, all 'PDA-technologies' provided some type of portion-size measurement aids, which help the subjects quantify the amounts of food eaten. One PDA, for example, displays a colour photograph of each food item together with a default amount (in grams). Subsequently, the respondent adjusts this pre-defined portion size to the consumed amount.[36] In others, subjects are instructed to quantify their amounts using traditional food models and portion-size aids.[35,38] Further variable assessment procedures include the assessment of qualitative information of dietary habits (e.g. meal start time and date),[36] food labels with nutritional information of purchased foods,[34] the provision of personalized feedback and recording alerts and the data transfer mode (i.e. web-based or computerized transfer).

Mobile-phone–based technologies

'Mobile-phone–based technologies' also allow for electronic short-term dietary assessment. However, in contrast to 'PDA-technologies', the possibility for 'real-time' recording at eating events is not based on manual selection from pre-defined food items, but rather on digital photography or voice recording. A well-known variant is the Japanese 'Wellnavi' instrument, which instructs the users to take digital photos of their foods and drinks before and after consumption and subsequently send them via a mobile phone card to the study dietitians.[43] While taking photos, participants would use a fiducial marker (an item of known size, e.g. a pen) to help the dietitian better estimate the portion sizes consumed. A similar recording procedure is used in the recently developed American 'Mobile phone food record'.[42] The food identification and portion-size estimation, however, are based on an automated visualization software and sophisticated digital image and segmentation analysis.[81] Likewise, in the 'Spoken dietary record', the recorded verbal dietary information is automatically extracted, identified and quantified, including the portion sizes and recipe ingredients.[41]

Interactive computer-based technologies

In contrast to possible 'real-time' dietary assessment methodology in 'PDA- and Mobile-phone–based technologies', the 'Interactive computer-based technologies' ask subjects to report food consumption during a specified period in the recent or distant past. They can include comprehensive systems for probing, coding and calculation of intakes by means of multimedia attributes and direct electronic data transfer, which is comparable with 'Web-based technologies', though less programming is involved (see later in the text). One computer system of a calcium-specific FFQ automatically reads aloud the questions, answers and any reminders on each screen. Single foods and dishes are illustrated using standardized portions by digital photographs together with corresponding frequency categories.[52] Also, the Diet History Questionnaire (DHQ) method is available as a computer-assisted self-interviewing tool using headphones, audio- and touch-screen functionalities.[47] A similar interactive multimedia technology was used to develop a 24-HDR for Spanish-speaking low-literacy populations.[51] The dietary recall begins with a 4-minute introductory instruction, and subjects select their answers by listening and touching the appropriate options out of 1125 audio files and 960 graphics. The presented digital pictures of portion sizes can be interactively adapted by the participant.

Web-based technologies

'Web-based technologies' are self-administered instruments for either short- or long-term dietary assessment, involving a lot of programming and characterized by various software components (e.g. interactive help features, adjustable images of portion sizes) that overlap with 'Interactive computer-based technologies'.

They allow for the data to be collected at a time and location that is convenient for the study participants, similar to 'PDA- and 'Mobile-phone–based technologies', and is also processed in 'real-time'. One example

Table 1 Definition and description of common and variable assessment procedures and innovative features of dietary assessment technologies

Technology group	Definition	Common assessment procedures[a]	Variable assessment procedures[b]	*Innovative feature(s)*[c]
Personal digital assistant-technologies ($n=6$)[33–38]	Hand-held computers that integrate computing and networking features, using stylus and/or keyboard for input	Face-to-face instructions by trained personnel are provided The participant is asked to record dietary intake right after consumption, by selecting food items from a finite drop-down menu of foods and beverages. Amount consumed is estimated by portion size estimation aids. Data are uploaded and matched with food composition databases	Food list extensiveness Portion size estimation aids used (i.e. electronic prompts, discrete food photographs, picture books or food models and household measures) Recording of qualitative information (e.g. date and meal starting time) Individual customization of the database Display of nutrient content Data review by dietitians Data upload (electronic or web-based) Direct or staggered database match	Hand-held portable device Self-administered electronic short-term dietary assessment (possibility for real-time assessment)
Mobile phone–based technologies ($n=6$)[39–44]	Portable electronic telecommunication devices connected to a wireless communication network	Face-to-face instructions by trained personnel are provided 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 mobile phone card	Software components (i.e. integrated built-in cameras, speech recognition software or video cameras) Identification of foods (i.e. in self- or automatically-taken digital images and/or verbally recorded text records by dietitians or automatic procedures) Estimation of food volume (i.e. before-after-eating images, or by automatic identification of voice-recorded food quantities by dietitians or automatic procedures) Record of qualitative information (e.g. date and time of recording)	Self-administered or fully automated prospective electronic short-term dietary assessment (possible real-time assessment) Visualization and/or verbalization to identify foods and to estimate portion sizes and digital image/segmentation/analysis Widely used, portable technology
Interactive computer-based technologies ($n=8$)[45–52]	Programmable machines with hardware and software components	Computerized or face-to-face instructions are provided The participant reports short- or long-term dietary intake, using computer software with multimedia attributes. Data are directly transferred into electronic databases	Multimedia attributes (i.e. colours, pictures, animated guides, audio, audio-narration and/or touch-screen or pop-up functionalities) Assessment targeted to total diet or single nutrients or food groups Portion sizes (i.e. single standard or multiple variable) Place of data collection [i.e. in the research centre (with the possibility for supervised completion by an interviewer) or at home]	Self-administered retrospective short- or long-term dietary assessment with multimedia attributes Complete system for probing, coding and calculation of intakes

(continued)

Table 1 Continued

Technology group	Definition	Common assessment procedures[a]	Variable assessment procedures[b]	*Innovative feature(s)*[c]
Web-based technologies ($n = 15$)[53–67]	Internet-connected tools shifting applications and software from the computer desktop to websites by means of programming that users access online with their browser	Web-based instructions are provided The participant reports short- or long-term dietary intake, using web-based data collection systems. Data are processed in real-time	Software components (e.g. interactive help features, flexible images of portion sizes, audio functions, videos, data quality checks) Level of detail in dietary data Methodology of dietary assessment instrument (i.e. Food Frequency Questionnaire/FFQ, 24-Hour Dietary Recall/24-HDR, Food Record/FR)	Self-administered retrospective web-based dietary assessment at a time and location that are convenient for study participants Use of widely accessible technology Real-time data processing
Camera- and tape-recorder–based technologies ($n = 8$)[68–75]	Devices that capture images or/and write voice records onto a tape, which are encoded	Food selection and plate waste are visually or verbally recorded. Trained observers review images on a computer screen by comparing them with reference portions of known food quantities or analyse tape records. Estimates are manually entered in databases	Picture recording mode (self-taken or automatic continuous picture-recording) Place of data collection (i.e. in institutional settings or free-living conditions) Portion size estimation (i.e. fully dietitian-administered or semi-automated computer-imaging)	Direct memory-independent recording of meals Visualization/verbalization of individual portion sizes
Scan- and sensor-based technologies ($n = 5$)[76–80]	Tools that read and digitize 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	Measures of biological movements (i.e. swallowing, chewing) Place of data collection (i.e. in commercial or institutional settings or free-living conditions)	Direct memory-independent recording of snapshots of eating behaviour

[a]The ‘common’ assessment procedures are those that were found to be present in all the technology variants within the same technology group.
[b]The ‘variable’ asssessmentt procedures are those that are found to vary within the same technology group.
[c]The innovative feature(s) summarize the innovative aspect(s) of the within- and between-group characteristics.
Remark: some technology groups may have overlapping functionalities with others.

is the web-based version of the National Cancer Institute's (NCI) 124-item diet history questionnaire (Web-PDHQ) that includes digital photographs to estimate portion sizes.[55] Programming and software development for web-based 24-HDRs appear to be even more sophisticated because the 24-HDR is a more complex open-ended methodology as compared with FFQs/DQs, and the various interview/recording steps require more guidance and quality controls, especially if self-administered.[60,64,82] NCI's web-based, self-administered 24-HDR for use on adults (ASA24), for instance, includes the five steps of the Automated Multiple Pass Method.[63,83]

Camera- and tape-recorder–based technologies

In contrast to the previous technologies described, the dietary assessment in 'Camera- and tape-recorder–based technologies' as well as in 'Scan- and sensor-based technologies' (see later in the text) is instant and intended to be memory-independent. 'Camera- and tape-recorder–based' devices were used to record an image or a verbal account of the food selection and the plate waste, which were subsequently reviewed by trained observers by either comparing the images with reference portions of known food quantities on a computer screen or by analysing the tape records, respectively. In an elementary school setting, for example, digital photos of meals served at lunch were taken before the students left the serving line.[74] After the meal, students were instructed to leave their trays and all waste on the tables to permit monitors to manually capture digital images of the plate waste.

Scan- and sensor-based technologies

With 'Scan- and sensor-based technologies', subjects would scan the barcodes of purchased food items or wear sensors that automatically record their corporal movements related to eating activities (e.g. arm gestures), thus digitizing these data. For example, a recently published study used a wearable electronic device, which contained several sensors and data processing and storage elements, such as a miniature camera and a microphone to recognize food consumption.[79] The device was 62 mm in diameter and worn on a lanyard around the neck.

Strengths and limitations of innovative dietary assessment technologies relative to conventional dietary assessment methodologies

The strengths and limitations of innovative dietary assessment technologies relative to their conventional counterparts are summarized in Table 2. A particular focus is on the methodologies that are predominantly used in nutritional epidemiology.

Innovative alternatives for FFQs and DQs

Several FFQs/DQs have been developed making use of two identified technology variants: self-administered 'Interactive computer-based technologies'[49,52,84] and 'Web-based technologies'.[55,56,58,61,66] Compared with the conventional paper-based FFQs/DQs, even those that are optically scannable, the strengths of these innovative alternatives include data consistency and completeness through technical requisites, such as skip patterns, plausibility and range checks. Furthermore, the innovative variants may help reduce the organizational study constraints and costs (excluding costs for software development), particularly with respect to larger populations. For example, a self-administered interactive computer-based DHQ was applied in 6604 Native Americans and had the advantage of being able to obtain more complete information in a reasonable amount of time (mean completion time 36 minutes) and with minimal staff time for assistance.[84] However, a considerable proportion of older study participants reported more difficulty in using the computer-based DHQ and wanted better completion guidance.[84]

The relative validity of all FFQs/DQs variants of the 'Interactive computer-based technologies'[49,52,85] and the 'Web-based technologies'[55,56,58,61,66] was assessed through comparison with a more established or traditional dietary assessment method, for example 24-HDR. All 'Interactive computer-based' variants were also evaluated for their reproducibility.[48,52,85] In contrast, the reproducibility of only two of the five technology variants in 'Web-based technologies' were assessed.[55,56] For instance, an interactive computer-based FFQ for assessing calcium intake was completed twice, one month apart, by 161 Asian, Hispanic and non-Hispanic adolescents. Reproducibility was better among females as compared with males with correlation coefficients for estimated calcium intake of $r = 0.80$ and $r = 0.61$, respectively.[85] Similarly, moderate-to-a-very good correlation indicating reproducibility was observed between the NCI's Web-PDHQ and its original paper version (Paper-DHQ).[55] Unadjusted correlation coefficients ranged from $r = 0.60$ for Zinc to $r = 0.81$ for Vitamin A. The relative validities for the Web-PDHQ and Paper-DHQ were similar. For energy and nutrient intake, moderate mean correlation between the two administration modes and a 4-day food record (unadjusted coefficient of 0.41 and 0.38 for the Web-PDHQ and Paper-DHQ, respectively), was seen, but only small-to-moderate correlation with a single 24-HDR (unadjusted coefficient of 0.31 and 0.29, respectively).

Innovative alternatives for food records

Food records are used in a variety of application approaches to measure dietary intake over a single period, usually 3 to 7 days. PDA- and mobile-phone–based technologies facilitate the recording through electronic assessment procedures, associated with improved data standardization and consistency between subjects compared with the conventional written format. Furthermore, both innovative approaches

Table 2 Strengths and limitations of innovative dietary assessment technologies relative to conventional dietary assessment methodologies

Dietary assessment methodology	Strengths	Limitations
Food records		
Conventional	Various application approaches (i.e. precoded or open weighed; reviewed or undocumented); often longer time frame than 24-HDR Quantified (if weighed) and detailed intake data; open-ended format; relatively accurate; information on individual meal and eating frequency and cooking practices	Requires literacy; high respondent and researcher burden; multiple days required; possible decreased completion quality over time; recording alters usual eating habits (reactive instrument); underreporting is often reported
Personal digital assistant-based ($n = 6$)	Facilitated real-time data collection, entry and coding (if linked with appropriate databases and direct data transfer); often good respondent acceptance and motivation; possible automatic reminders Possible higher quality control and standardization (e.g. reduced memory bias, data can be recorded consistently from respondent to respondent)	Training required; higher technical development efforts (→ expensive); application restricted to smaller study populations; technical problems in data transfer and storage; digital data transfer requires specific security infrastructure; response problems remain (e.g. reactivity; accurate portion size estimation); lower level of dietary detail because of pre-coded food listings
Mobile-phone–based ($n = 6$)	Widely used technology; suitable for low-literacy subjects; open-ended dietary data; possible higher quality control because of reduced time delay and often independent assessment from memory	Training required; high technical development and data processing efforts; limited data storage capacity; digital data transfer requires specific security infrastructure; unknown accuracy
Camera- and tape-recorder–based ($n = 3$)	Faster data collection; suitable for subjects with memory impairements and for parent-assisted dietary assessment in children; possible reduced frequency rate of omissions	Response problems remain (e.g. underreporting and/or reduction in food intake) poor-to-moderate accuracy
24-hour dietary recall (24-HDR)		
Conventional	Various application approaches (i.e. paper- vs. computer-based administration; in-person vs. telephone; portion size models or measurement aids); literacy not required; relatively low respondent burden; standardization of interviews (if computer-based) Quantified and detailed intake data; information on individual meal and eating frequency and cooking practices; does not affect eating behaviour	Relies on knowledge and memory; multiple days required to estimate usual intake; costly, if interview-administered (training need); likely to omit foods consumed infrequently; requires specific statistical procedures to estimate the usual intake; possible interviewer bias
Interactive computer-based ($n = 3$)	Reduced administrative and data processing costs; good acceptability in children, adolescents and groups with limited computer skills and literacy; increased levels of quality control (e.g. less implausible data, greater standardization of interviews, easier retrospective data collection than web-based)	Requires literacy and computer skills; possible reduced level of data detail; direct coding may hamper later data review and editing; possible increased reporting and memory bias
Web-based ($n = 4$)	Automated data collection systems (→ reduced interviewer workload and costs); completion at any time and location; no supplementary costs to increase the number of measurements; interactive audible and visual aids	Requires literacy, computer skills, internet access, research data security systems; potential non-response bias; possible altered response behaviour because of design issues and technical prerequisites (e.g. browsers used) Currently more data on feasibility available than on validity (→ ~ unknown accuracy); possible increased reporting and memory bias

(continued)

Table 2 Continued

Dietary assessment methodology	Strengths	Limitations
Dietary/ Food Frequency Questionnaires (FFQ)		
Conventional	Low cost of administering/processing (self-administered by pen, machine-readable scanned forms); low respondent burden; not reactive; attempts to estimate individual usual intake with one administration; source of relevant information on true non-consumers	Literacy required; presence of incomplete data; measurement error (i.e. finite food list; often no quantification or imprecise estimation of portion sizes; lacks dietary details); possible bias because of direct food intake; specificity to population of interest
Interactive computer-based ($n = 3$)	Improved data quality; reduction of costs and time from initiation of the study to the receipt of the analysable data; interactive audible and visual aids	Requires computer skills Methodology-associated measurement errors remain
Web-based ($n = 5$)	Improved data quality; cost-effectiveness; suitable for larger, geographically dispersed samples; completion at any time and location; easily adaptable (e.g. to other languages); interactive visual aids and reminders	Requires computer skills, internet access; anonymous recruitment procedures; required research data security systems; potential non-response bias; possible altered response behaviour because of design issues and technical prerequisites Methodology-associated measurement errors remain

may improve subject motivation in maintaining the quality of dietary recording with the passing of days. However, results on PDA-technologies with longer duration of data collection suggest that participant adherence might decrease over time.[33,36] Subjects also experienced continued difficulties in using the search functions and in navigating the databases,[33] whereas in other studies, the PDA-technologies were well accepted.[35,38] In a study involving low-income pregnant women, 70% preferred the PDA-based technology and reported higher ease of use in comparison with an interview-administered 24-HDR.[35] Furthermore, efforts put into instructing the subjects on how to appropriately use the new technology appear to be greater than for the conventional food records. For example, in 'Mobile-phone–based technologies', respondents need to be well trained to take multiple, rotated images to enable the automatic food item recognition and volume estimation.[40,42,86] The overall instrument development efforts of 'Mobile-phone–based technologies' are high. Several challenges need to be overcome (e.g. composite meals, opaque drink containers, the manner in which food is often layered and mixed on a plate and the cultural diversity of foods[81]). Three technology variants of the 'PDA-technologies'[33,34,36–38] and one (the Wellnavi instrument) of the 'Mobile-phone–based technologies'[43,87,88] were validated. Reference methodologies included single interviewer-administered 24-HDR,[34,36,43] 1-day[43,88] or 5-day weighed food records[87] and a FFQ.[37] One PDA variant was validated against doubly labelled water[38] and another study compared the reported energy intake from a PDA with an estimate of the total energy expenditure, based on prediction equations from the literature.[33] The median size of the study populations in 'Mobile-phone–based technologies' and 'PDA-technologies' was $n = 28$ and $n = 44$, respectively. These studies observed both over- and underestimation of nutrient intakes.[33,37,43,87,88] For instance, one study observed an underreporting of energy intake of 41% and highlighted that the bias inherent in self-reported dietary data by individuals (i.e. 'human component') remains a problem that PDA-technology may not eradicate.[33] In another study, there was a positive relationship between energy intake reported by a PDA technology variant and energy expenditure measured using doubly labelled water ($r = 0.60$), and a comparable validity of group means relative to a conventional food record.[38] Similarly, there were no significant differences in the mean daily macronutrient intake, and correlations ranged from $r = 0.51$ for total fat to $r = 0.80$ for carbohydrates between a PDA-technology and an interview-administered 24-HDR.[34]

Innovative alternatives for 24-HDRs

Conventional (i.e. administered by trained interviewer) 24-HDRs have become more favoured as a dietary assessment methodology based on the findings of studies reporting good relative validity and measurement properties.[16–18,89,90] First 24-HDR, completed by paper-and-pencil method,[91] have since been improved and are more and more supported by computerized systems.[92] Comprehensive computer programs, such as the EPIC-Soft® developed to conduct standardized 24-HDRs in large and international epidemiological and monitoring settings (e.g. calibration, validation or dietary surveys), nowadays implement common procedures to identify, describe, quantify and probe reported intake over the day preceding the interview[93–95] in a uniform way.

Despite this, interviewer-based 24-HDRs, are still relatively expensive to be used as the main instrument for the full and large cohort because multiple measurements are required when the aim is to accurately rank individuals' usual intakes.[29,64,89] Facilitated applicability to large populations and cost saving were among the primary reasons for the recent innovations in recall approaches (i.e. 'interactive computer- and web-based technologies'). For example, researchers from the web-based Energetics study reported that their automated self-administered 24-HDR ('DietDay') permitted considerable logistical simplifications and may be highly advantageous for large population-based studies and repeated measurements.[54] The tool was administered to 261 White and African American subjects, with 92% completing eight non-consecutive web-based 24-HDRs.[54] Subjects were asked to complete three 24-HDRs during their study visits and five on their own. Two further studies provided specific information on financial efforts,[51,64] concluding that the innovative alternatives are likely to be more cost-effective with regard to the administration. Furthermore, findings of 'Interactive computer-based technologies' indicate a high applicability to children and adolescents. Studies applying the computerized 24-HDR Young Adolescents Nutrition Assessment on Computer reported that the self-administered tool was well received by most adolescents from 10 different European countries.[96] In addition, Young Adolescents Nutrition Assessment on Computer demonstrated time efficiency, as one researcher or dietitian could guide 15–20 respondents at the same time.[50] However, weaknesses identified include the requirements for computer skills, internet access (for web-based 24-HDRs), possible reporting difficulties because of subjects having limited nutritional knowledge, possible effects on the subjects' actual diet and reduced level of specificity regarding open-ended food choices. In 'web-based', self-administered 24-HDRs, for example, the level of detail varied from 800[97] to more than 1000 different probes to collect more specific information about foods,[64,82] whereas 'Interactive computer-based' 24-HDRs comprised 167[51] to 400 food items.[50] One computer-based 24-HDR for children included artist renderings of 300 foods to prompt recall.[45]

Overall, there were only six studies that assessed the relative validity of 'interactive computer-' and 'web-based' 24-HDRs.[45,51,60,64,96,98] Studies comparing self-administered with interviewer-administered computerized 24-HDRs observed a small but significant under-estimation of energy and fat intake in the self-administered tool,[96] and correlated nutrient intakes with a correlation coefficient of 0.60.[51] One study compared nutrient intakes assessed by a web-based 24-HDR and a conventional 24-HDR and observed a median of energy-adjusted correlation for nutrient intakes of $r = 0.80$.[64] Further, accurate portion-size estimation appears to depend on the technical presentation on the screen.[83,96,99–101] In one study on a computer-based 24-HDR, participants were able to interactively grow and shrink each food to choose among four portion sizes presented.[51] A decrease of correlation coefficients was observed when these reported portion sizes were replaced with standardized portion sizes, as compared with a conventional 24-HDR. Also, the results indicate an improved clarification of foods by means of colour food photographs, particularly racial/ethnic foods. Some preliminary results on a web-based 24-HDR also pointed at increased accuracy when eight instead of four images were presented simultaneously,[83] with no increase or decrease in accuracy when multiple small food pictures were presented on the screen at the same time.[99]

Potential for integration of innovative dietary assessment technologies in epidemiological studies

This inventory shows a large diversity of innovative dietary assessment technologies in published research to date, and the data support their potential to enhance many aspects of dietary intake measurements. However, the results also suggest that a number of considerations have to be observed when innovative technologies are designed and applied for the purpose of dietary assessment in epidemiological studies. Depending on the study's objectives, its target population and the financial resources available, the most appropriate dietary assessment methods have to be chosen for each particular study.[102] A particular challenge appears to be the integration of innovative technologies in large-scale studies, as standardized, cost-efficient and low-burden assessment methods and databases are required to capture the geographical and cultural dietary diversities that exist across countries (Figure 1).

So far, most epidemiological studies have favoured self-administered FFQs/DQs, although their performance to provide accurate estimates of individual usual dietary intake have been seriously questioned.[5,18,103]

Findings from the validation studies published from 1995 onward, support the notion that measurement errors related to the relative validity and reproducibility are most likely, irrespective of the mode of administration, suggesting that the underlying methodology of innovative and conventional FFQs/DQs is unchanged by the technology. More specifically, the cognitively complex completion process, inherent in the FFQ methodology (e.g. averaging a 'usual' frequency and portion size for a series of generic food items or food groups), seems to be similar for paper, 'interactive computer-based' and 'web-based' formats. However, innovative technological alternatives of the

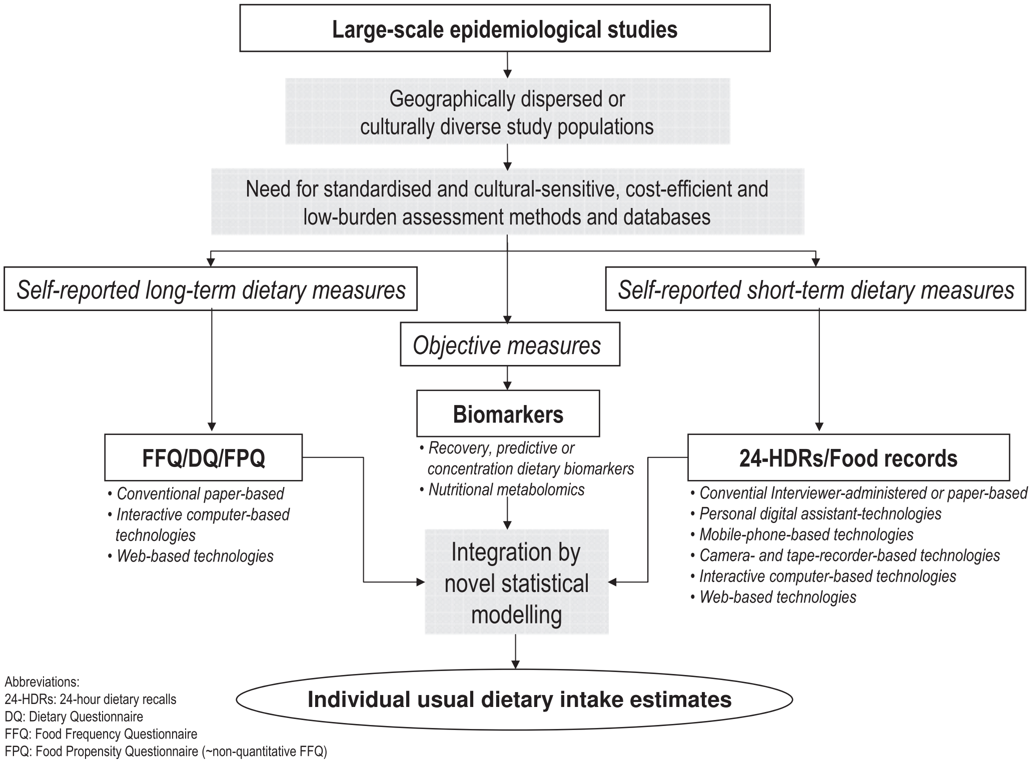

Figure 1 Integrative approaches of measuring diet in large-scale epidemiological studies

FFQs/DQs may have greater potential to overcome some of the completion difficulties that have been reported in the cognitive research about conventional paper-based FFQs.[104,105] Implementing digital pictures, for example, may improve the food identification. Also, certain technical functionalities can facilitate the skipping to more tailored questions at individual level or provide explanations on how to answer questions appropriately. Design issues, however, may differ because of technical prerequisites (e.g. browsers used in 'Web-based technologies') and alter response behaviour.[106] Although the major benefits of 'interactive computer-' and 'web-based' FFQs/DQs appear to be related to higher cost-effectiveness and more complete data sets in larger, geographically dispersed or multi-centric study populations,[106–108] a full replacement of conventional FFQs/DQs by innovative alternatives would not overcome the low validity and high amount of systematic and random measurement errors found in these methodologies.

No self-reported dietary instrument can measure dietary intake totally free of error whether using the conventional formats or innovative technologies.[109] Research to date therefore suggests combining different self-reported and objective measures of dietary intakes to optimize the strengths of each while balancing their weaknesses.[110,111] There is evidence that the complementation of the repeated short-term quantitative measures (i.e. 24-HDR and food record methodologies) with the non-quantitative information on usual consumption (e.g. from non-quantitative FFQs, defined as Food Propensity Questionnaires or FPQs) and/or biomarkers and integrated with statistical modelling, may yield more accurate individual usual dietary intake estimates.[16,110–113] This concept may particularly provide less biased estimates for the intake of infrequently consumed foods that are often missed in the short-term dietary measures, whether obtained through the conventional or innovative methods. However, the use of multiple individual dietary measures in large-scale studies is still greatly restricted by the costs and logistics of data collection. Innovative technological alternatives might overcome some of the feasibility and financial issues, foremost those of the food records and repeated 24-HDRs, but they will also introduce new challenges. For example, reviews in clinical research reported hardware dysfunctions in 'PDA-technologies'[114] and loss of battery capacity that may lead to loss of data.[115] Likewise, 'Mobile-phone–based technologies' appear to have an increased risk of blurred images and limited storage power and space.[39]

Nevertheless, the innovative technological alternatives of food records have several benefits. Because of the portability of the devices, such as the 'PDA-' and 'Mobile-phone–based technologies', the potential for real-time recording and the capability to remind the users to provide intake information, memory bias may be reduced and recording of out-of-home eating occasions facilitated.[38,44] Furthermore, in addition to their applicability in younger study populations, the researcher or dietitian is able to visualize the amount of food consumed, the time and the date of eating occasion, which might be advantageous in terms of accuracy. Although the estimation of the nutrient content is currently problematic and the validity of individual dietary estimates is still low-to-moderate, the automatic digital image and segmentation features in the innovative alternatives open new avenues for the food record methodology. For example, the function to specify the indiscernible details of a picture by directly writing on a display of a device[116] may offer better identification and description of the reported intake than in written food records. Also, complementing conventional formats by the additional use of cameras has been shown to successfully enhance the estimation of food weights.[117] Still, complete replacement of conventional food records with innovative technological alternatives requires careful considerations that go beyond those of labour intensiveness, equipment costs and a specific infrastructure for secure data transfer. The present review showed that training intensity was high even in young and computer-skilled subjects indicating that even with an advanced technology, it may not be possible to conduct the food record approach without extensive training. One main methodological limitation compared with the conventional food records is likely to remain: several diet intervention studies involving 'PDA-based' food records revealed that these technologies also affect study participants' reporting of dietary intake.[118–125] Scientific knowledge about the effects of 'Mobile-phone–based technologies' with respect to this issue is still limited.

Likewise, the integration of innovative alternatives of the 24-HDRs in epidemiological studies needs several considerations. Similar to 'Interactive computer-' and 'Web-based' FFQs/DQs, innovative 24-HDR technologies have practical advantages when conducting dietary assessment in large-scale multi-centric studies. The possibility of a more flexible completion of a recall with respect to the time and place may improve reporting compliance and is promising when repeated 24-HDR-measurements[16,54] are to be conducted. However, in contrast to interviewer-administered 24-HDRs, the self-administered 24-HDR application alternative needs to be fully automated and self-explanatory,[29,96] even those of 'Interactive computer-based' 24-HDRs completed under supervision. Methodological problems, such as memory lapses, individual's difficulty in reporting portion sizes, and limited knowledge of foods, food preparation and quantification might be therefore more critical than in conventional 24-HDRs, where each respondent receives constant and personalized assistance during the assessment. Furthermore, there may be a tendency to alter food intake when the respondents know beforehand the randomly selected dates[64] or times[54] for recall completion. Although this methodological limitation associated with misreporting can also not be fully overcome with interview-administered 24-HDRs, it may be minimized by the conventional retrospective assessment. Thus, a major area of concern related to the measurement error in innovative alternatives of 24-HDRs is the 'human' component of the respondent.

A full replacement of interviewer-administered 24-HDRs is therefore methodologically challenging as there is still limited knowledge on the accuracy of fully automated 24-HDRs. In addition, current results of their relative validity need to be interpreted carefully because tests and conventional reference instruments were consecutive to one another, and their sources of errors are likely to be highly correlated.

Conclusions and future research directions

This inventory and evaluation show a large diversity of innovative dietary assessment technologies in published research to date and emphasize that a rough classification of different innovative technologies is possible. Furthermore, findings support the potential of several groups of innovative technologies to enhance dietary assessment through lower costs related to data collection and data management and less laborious, time-efficient and more acceptable ways of data collection.

However, these advantages should not outweigh the appropriate quality of the collected dietary data for epidemiological purposes. As any conventional dietary instruments, innovative technologies are imperfect, and their integration in epidemiological studies will not provide unbiased measurements of dietary intake.[126]

The new integrative methodological concepts in nutritional epidemiology, which combine dietary information from multiple measures by advanced statistical modelling,[67,112,127] promise to improve the accuracy of the estimates of individual usual dietary intake,[110,113] although the underlying statistical concepts need more exploration. Therefore, further study of the relative merits of the innovative technologies in that specific context is needed. In particular, scientific knowledge on the operational feasibility and performance of the innovative alternatives of food records and 24-HDRs is required with regard to their application in larger and culturally different study populations. This requires testing under a variety of circumstances (e.g. in different age groups or populations having varying experience in computer/web-based technologies). Specifically for 'Web-based technologies', it would be important to examine response rates and drop-out rates of subjects with lower computer skills and technical experience. Given that computer literacy may probably not increase, or at least not equally across study populations in the short run, it may be necessary to collect part of the dietary information obtained by 'web-based technologies' while still assisted by interviewers either by telephone or directly in a local computer lab in each study centre in the case of 'computer-based technologies'.

Future research should also explore the error measurement structure in innovative technologies and its implications for proper disease risk evaluation, particularly in innovative alternatives of food records and 24-HDRs. Well-designed validation studies against biomarker measures are therefore needed to investigate misreporting of dietary intakes, also by race, age, educational level, BMI, gender and appropriate adjustment. Finally, beside new data collection technologies, web-based infrastructures and building capacities are promising to support the set-up, management, dissemination and maintenance of dietary assessment methodologies in epidemiological studies, particularly in the context of international multi-centre studies, where currently it appears too premature to implement innovative alternatives of 24-HDRs or food records on a large scale. For example, it is yet unkown whether web-based 24-HDRs or 'PDA- or Mobile-phone–based technologies' can be equally applied in all population groups to standardize the dietary measurement within and between countries, and/or to ensure representativeness of the entire study population, if they would be applied as reference method within a calibration design. Examples for web-based platforms are the standardized Methodology Platform currently under development by IARC intended to implement and support the EPIC-Soft-methodology[93] or the interactive web-based 'Energetics System' that automates all levels of the dietary assessment management in US clinical trials.[128]

Overall, a promising perspective for integrating innovative dietary technologies in epidemiological studies is given. Disentangling first the 'methodological' and 'technological' features of an innovative technology can then help the researcher to appreciate the different existing methodologies and select an appropriate dietary assessment method to meet their particular study needs.

Supplementary Data

Supplementary Data are available at *IJE* online.

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KEY MESSAGES

- Scientific knowledge about the relative merits of innovative dietary assessment technologies in epidemiological studies is still scarce, which may be partially driven by current misconception that the new technologies are always methodologically new.
- This article reports on the inventory of innovative dietary assessment technologies available and those under development in order to critically evaluate their strengths and weaknesses as compared with the conventional methodologies used in epidemiological studies.
- Six main groups of innovative technologies were identified ('Personal Digital Assistant-', 'Mobile-phone-', 'Interactive computer-', 'Web-', 'Camera- and tape-recorder-' and 'Scan- and sensor-based technologies') and evaluated regarding their potential to improve, complement or replace Food Frequency and other Dietary Questionnaires, food records and 24 hour dietary recalls.
- Most of the innovative dietary assessment technologies were seen to have overlapping methodological features with the conventional methodologies and a potential to enhance the dietary assessment in epidemiological studies through more cost-effective, less laborious and more acceptable ways of data collection.
- The findings emphasize the need to further investigate the validity of innovative dietary assessment technologies, as even in innovative technologies the inherent individual bias related to self-reported dietary intake will not be resolved.

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