REVIEW

Scaling up Dietary Data for Decision-Making in Low-Income Countries: New Technological Frontiers

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ABSTRACT

Dietary surveys in low-income countries (LICs) are hindered by low investment in the necessary research infrastructure, including a lack of basic technology for data collection, links to food composition information, and data processing. The result has been a dearth of dietary data in many LICs because of the high cost and time burden associated with dietary surveys, which are typically carried out by interviewers using pencil and paper. This study reviewed innovative dietary assessment technologies and gauged their suitability to improve the quality and time required to collect dietary data in LICs. Predefined search terms were used to identify technologies from peer-reviewed and gray literature. A total of 78 technologies were identified and grouped into 6 categories: *1*) computer- and tablet-based, *2*) mobile-based, *3*) camera-enabled, *4*) scale-based, *5*) wearable, and *6*) handheld spectrometers. For each technology, information was extracted on a number of overarching factors, including the primary purpose, mode of administration, and data processing capabilities. Each technology was then assessed against predetermined criteria, including requirements for respondent literacy, battery life, requirements for connectivity, ability to measure macro- and micronutrients, and overall appropriateness for use in LICs. Few technologies reviewed met all the criteria, exhibiting both practical constraints and a lack of demonstrated feasibility for use in LICs, particularly for large-scale, population-based surveys. To increase collection of dietary data in LICs, development of a contextually adaptable, interviewer-administered dietary assessment platform is recommended. Additional investments in the research infrastructure are equally important to ensure time and cost savings for the user. *Adv Nutr* 2017;8:916–32.

Keywords: individual-level dietary assessment, low-income countries, developing countries, dietary assessment, technology, innovation

Introduction

Interventions and policies that seek to improve human health through diet or influence the effects of food systems on dietary outcomes require high-quality data on the food and nutrient intake of individuals. Three principle methods are traditionally used to collect individual dietary data: 24-h dietary recalls (24HDRs), FFQs, and weighed food records, all of which are used worldwide depending on the objective of the study (1). High-income countries increasingly rely on self-administered computer- and web-based surveys to implement these methods, whereas low-income countries (LICs) continue to rely on interviewer-administered, paper-based questionnaires because of low literacy rates and sporadic internet connectivity (2). For the purposes of this article, LICs were defined as any country that was classified by the World Bank as being a low- or lower-middle–income country (3). The time-consuming process in most LICs of collecting, entering, transforming, and analyzing data is exacerbated by the lack of research infrastructure needed to process dietary data (e.g., food composition databases [FCDBs] and portion-size conversion factors). Because of these constraints, the collection of individual dietary data is commonly perceived to be cost- and time-prohibitive, resulting in a dearth of routinely available dietary data in LICs.

There is strong demand from researchers and clinical practitioners, as well as from consumers, for dietary assessment approaches that are quicker, more accurate, less costly,

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Abbreviations used: AIM, Automatic Ingestion Monitor; AMPM, Automated Multiple-Pass Method; CCS, Counts of Chews and Swallows Model; FCDB, Food Composition Database; INDDEX, International Dietary Data Expansion; LIC, low-income country; NINA-DISH, New Interactive Nutrition Assistant–Diet in India Study of Health; 24HDR, 24-h dietary recall.

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and more user friendly. A number of articles have provided in-depth reviews of cutting-edge dietary assessment technologies (4–10). Each of these articles reviewed the landscape of innovative technologies, but none considered the potential constraints associated with their use for population-level dietary assessment in LICs. LICs are a heterogeneous group but often face constraints not typically seen in high-income countries, such as low smartphone penetration, low literacy, lack of connectivity, weak research infrastructure, and relatively few formally trained nutritionists. For this reason, conclusions drawn about the appropriateness of new diet assessment technologies cannot be generalized from high-income countries to the rest of the world. The current review extends the geographic focus of previous literature to consider the suitability of dietary assessment technologies for regions with unique limitations and opportunities.

This study grew out of a landscape assessment conducted by the International Dietary Data Expansion (INDDEX) Project (11) that was intended to inform the direction of project investments in dietary assessment tools and related research infrastructure to improve the availability and use of dietary data in LICs. Interviewer-administered, paper-based questionnaires are still standard in most dietary surveys in LICs (2, 12, 13). As such, the first stage of the landscape assessment examined the relative strengths and weaknesses of a paper-based approach relative to the increasingly standard technology for national surveys in most high-income countries: computer- and tablet-based 24HDR programs (14, 15). The second stage of the landscape assessment sought to determine if any innovative technologies (i.e., beyond a computer-based 24HDR) would be appropriate for scale-up and use in large-scale dietary surveys in LICs. Computer-based programs using 24HDR software (as opposed to FFQs or weighed food records) were the focus of the first stage of the assessment because the 24HDR method is flexible and easily adaptable, it can be used for large and small studies alike, it does not require extensive validation in new contexts, and the data produced can be used for a wide range of purposes (1, 16). Furthermore, computer- and tablet-based 24HDRs have become increasingly standard in high-income countries for large-scale collection of individual-level dietary data. For instance, the Automated Multiple-Pass Method (AMPM) is the computer-based 24HDR program used in What We Eat in America, the dietary module within the United States' annual NHANES. GloboDiet (previously called EPIC-Soft) has been used to collect dietary data in the European Prospective Investigation into Cancer and Nutrition study, among other locations. The European Prospective Investigation into Cancer and Nutrition study is a large cohort study with 521,000 participants sampled from 10 different European countries and followed up for nearly 15 y (17). Newer, cutting-edge technologies that were reviewed as the second part of the assessment often blur the lines between traditional diet assessment methods and can be difficult (and perhaps even unnecessary) to classify according to old methodological typologies (4). These newer technologies were included in the review to assess their potential to positively disrupt dietary assessment approaches in LICs.

Methods

The approach taken to identify individual technologies and relevant literature for this review followed a 3-step process. First, peer-reviewed and gray literature were searched by using key terms to identify the universe of diet assessment technologies, resulting in a list of technologies that were grouped into 6 distinct categories. Second, a deeper review was conducted to identify literature that yielded information on a structured set of questions and criteria pertaining to each technology. Third, information on this structured set of questions and criteria was extracted and then evaluated to assess the appropriateness of the technology for use in LICs. Each step is explained in more detail below.

First, a comprehensive search was conducted to identify technologies for dietary assessment. The literature search was conducted in July and August 2015, with limited, selective additions between the initial review and time of publication based on reviewer feedback. The following predefined search terms were used, building on searches conducted in prior published reviews (4–8, 18): *dietary assessment and mobile devices; dietary assessment and sensor-based devices; mobile health and diet; applications and dietary assessment; sensors and diet; sensor-technology and diet; tracking food intake and technology; portion-size estimation and applications; portion-size estimation and sensors; mobile phone and dietary intake; technologies, dietary intake, and self-monitoring; image recognition; image-based and dietary assessment;* and *image capture and dietary assessment*. PubMed, Google, Google Scholar, and abstracts from the 8th and 9th International Conference on Diet and Activity Methods (19, 20) were searched. All literature and websites reviewed were in English.

A modified search approach was used for the computer- and tablet-based 24HDR section and the application-based technologies. In the case of the former, the data reported were originally compiled for a landscape assessment of computer-based and tablet-based dietary platforms conducted by the INDDEX Project (15). The landscape assessment included a structured search for peer-reviewed and gray literature on computer- and tablet-based 24HDR programs by using PubMed, Google Scholar, and Google. In addition to the literature search, the authors conducted key informant interviews with individuals who had experience in the development and use of the identified programs.

In the case of the application-based technologies, a review of Android applications was conducted in the Google Play store by using terms similar to those used by Rusin et al. (8): [(food or diet or nutrition) and (self-manage or self-monitor or registration or monitor or record or diary or intake)] and (count). Given that Google Android operating systems held the highest global market share (85%) of the leading smartphone operating systems in 2016 (21), the search was limited to the Google Play store (i.e., it did not include Apple iOS products). Saturation occurred after reviewing 90 applications, meaning that, by this stage, the authors did not observe additional heterogeneity in objectives, features, or functionality and therefore did not continue to assess the remaining applications returned in the Google Play Store search. This review included only applications that contained a direct link to an FCDB in order to calculate users' nutrient intake and returned reports in graphic or tabular format on the number of calories, macronutrients, and/or micronutrients consumed, which narrowed the number of applications retrieved from 90 to 33.

Based on the results of the review, the technologies were grouped into the following 6 categories: *1*) computer- and tablet-based, *2*) mobile-based, *3*) camera-enabled, *4*) scale-based, *5*) wearable, and *6*) handheld spectrometers.

Second, PubMed, Google Scholar, and Google were searched by using the technology name in order to identify literature that yielded information on a structured set of questions and criteria pertaining to each technology. Some of the information sought through the search was descriptive, whereas other information was searched to determine the technologies' suitability for use in large-scale 24HDR surveys in LICs. The descriptive information was intended to provide a broad overview of the following key features of the technology: *1*) primary purpose; *2*) terminal type; *3*) type of dietary assessment method; *4*) data input type; *5*) the extent of automated data processing in terms of food identification, portion-size estimation, and nutrient intake calculation; *6*) data output type and content; *7*) mode of administration; *8*) availability on the market; and *9*) development in a commercial or academic setting. The criteria pertaining to the technologies' suitability for LICs were *1*) required literacy and numeracy, *2*) battery lasting >8 h, *3*) ability to function without internet connectivity, *4*) collection of sufficient information to quantify macro- and micronutrient intake, and *5*) proven feasibility for use in LICs (**Figure 1**). The battery-life criterion was not considered applicable for the technologies in the computer- and tablet-based and application-based categories given the extensive variety in commercial brands of laptops, tablets, and smartphones where battery life is a function of many factors and not just the device itself.

Third, this extracted information was compiled to provide an overview of key features of each type of technology and rate each one against the predefined criteria for its potential suitability in LICs.

Results

A total of 78 distinct technologies (including applications) were identified and grouped into 6 categories. These categories cover a spectrum of innovation, ranging from computer- and tablet-based dietary assessment programs that are in widespread use in high-income countries to highly innovative technologies that are still under development, such as handheld spectrometers (**Figure 2**). Each section below presents a general description of the technology category followed by an evaluation of each technology against the 5 predefined criteria for use in LICs (Figure 1).

Computer- and tablet-based

Twenty computer- and tablet-based 24HDR programs were identified in the review, each of which collected information on dietary intake via the internet (i.e., referred to as "web-based programs") or offline (referred to as "computer-based programs") by using a laptop or tablet (**Supplemental Table 1**) (16, 22–76). The 2016 version of the Automated Self-Administered 24-Hour Dietary Assessment Tool and Measure Your Food on One Day, which could also be used as a food record (62, 77) of the computer- and tablet-based programs reviewed, were developed for population-level research purposes. Nine of the programs reviewed were on the market. There was insufficient publicly available information to determine the market status of eleven programs.

Unlike some of the other technologies covered in this review, the computer- and tablet-based programs did not contain features that automatically identified or quantified foods that were reportedly consumed (Supplemental Table 1). For food identification, either respondents (in programs with self-administered formats) or interviewers were required to manually select the food consumed from a food list embedded within the program. Likewise, the estimated quantity consumed needed to be manually entered. The programs included a range of techniques to aid the respondent in estimating portion size, including graduated digital images of foods or shapes displayed on the laptop or tablet screen, household measures, standard units (e.g., small, medium, or large), and directly reported gram or volume amounts.

Fourteen of the 20 programs contained features that automated the calculation of individual nutrient intakes. AMPM, Food Intake and Physical Activity of School Children (Portuguese), Web-based Dietary Assessment Software, and the Zambia 24HDR were among those that did not provide fully automated calculation of nutrient intakes: some manual data processing was required to obtain these estimates from the data collected. Dietary data collected via the AMPM were processed and coded by using 2 separate programs (the Post Interview Processing System and Survey-Net) (24). The literature reviewed did not stipulate whether the Synchronized Nutrition and Activity Program and Young Adolescents' Nutrition Assessment on a Computer provided automated calculation of nutrient intakes. Overall, the prime advantage of these programs, compared with paper-based 24HDRs, is that they standardized the 24HDR process, circumvented the need for postsurvey data entry, and, in many cases streamlined data processing.

The first 3 criteria used to judge the suitability of the technology for use in LICs were respondent literacy not required, ability to be used offline, and battery life of >8 h (the last criterion was deemed not applicable for this group of technologies). Because much of the innovation in 24HDR assessment technology has occurred in high-income countries, where high levels of literacy and internet connectivity are the norm, the majority of the programs failed to meet these first 2 criteria (**Table 1**). Eleven of the programs required literacy because they used a self-administration format (the remainder were interviewer administered, and therefore respondent literacy was not necessary). Twelve of the 20 programs required internet connectivity, whereas 8 had the capacity to collect data offline. Five of the 20

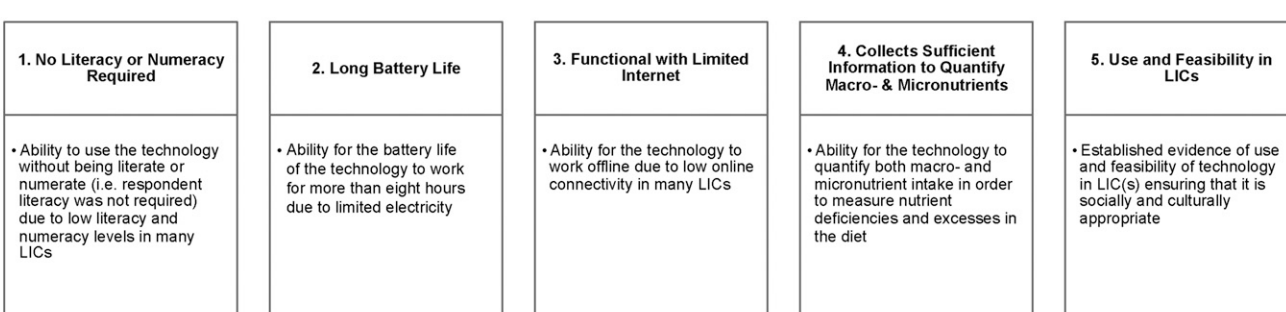

FIGURE 1 Criteria for suitability in LICs. LIC, low-income country.

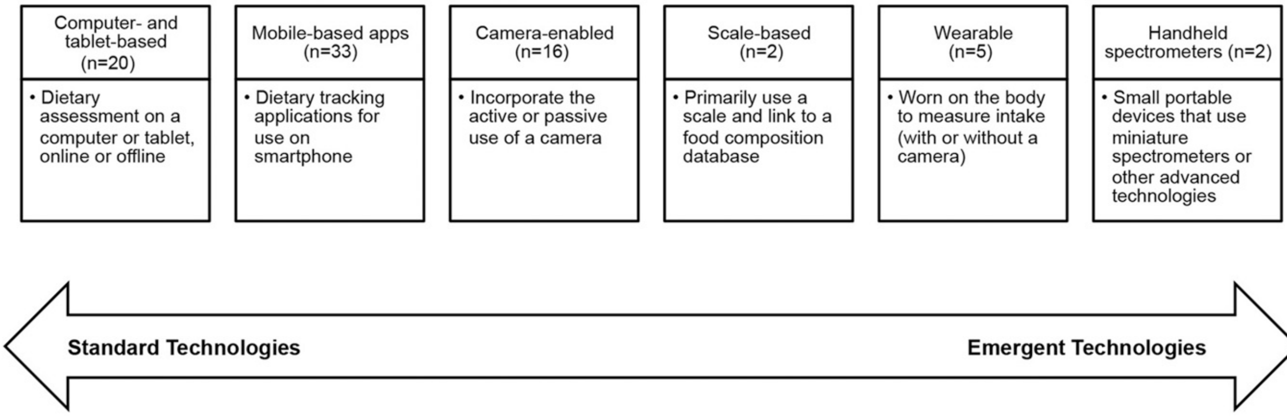

FIGURE 2 Spectrum of innovative technologies reviewed. app, application.

programs met both criteria of enabling offline data collection and not requiring respondent literacy (23, 66, 76, 82–84). The fourth criterion was "collects sufficient information to quantify macronutrients and micronutrients." Because all 20 programs collected sufficiently detailed information to calculate macro- and micronutrient intake of respondents, this criterion was met by all programs.

The final criterion used to assess the appropriateness of computer-based 24HDRs for LICs was prior demonstration of feasibility and use in an LIC. The New Interactive Nutrition Assistant–Diet in India Study of Health (NINA-DISH), which was developed for use in India (83), and the Zambia 24HDR are the only computer- and tablet-based programs known to have been used in an LIC setting (76). Daniel et al. (83) reported that NINA-DISH was used to measure dietary intake in 3 economically and ethnically diverse regions of India (New Delhi, Mumbai, and Trivandum). The researchers did not explicitly assess the feasibility of NINA-DISH in the population surveyed; however, the authors suggest its feasibility through their conclusion that NINA-DISH is "culturally appropriate and helpful to better understand the dietary habits of an understudied population at a high risk of developing chronic diseases" (83). The Zambia 24HDR was developed to measure dietary intakes of children aged 4–8 y old in Mkushi, a rural district in central Zambia (76). The investigators concluded that "conducting 24-h recall interviews in remote settings using tablets is not only feasible but also will make dietary data easier and more affordable to collect."

Although none of the programs reviewed met all the study criteria, the AMPM and Nutrition Data System for Research met all but the criterion of demonstrated feasibility in an LIC context (Table 1). The AMPM (23) and Nutrition Data System for Research (85) have been validated in high-income settings, but the review found no evidence of their prior use in LICs, perhaps because neither system is designed to link to a range of different country- or region-specific food composition tables. In sum, although many of the technologies in this category were developed for high-income countries, the examples of NINA-DISH and the Zambia 24HDR suggest that computer- and tablet-based 24HDR may be a suitable alternative to paper-based 24HDR surveys in LIC settings.

Mobile-based

Thirty-three applications were reviewed (86–118) that tracked food intake on smartphones. Nearly all the applications reviewed were designed to be self-administered food diaries, which allowed users to track daily food consumption in real time, while also accessing information on their consumption trends. Two applications were designed specifically for use in India, whereas all others were intended for consumers in high-income countries (103, 111).

All applications reviewed contained a direct link to an FCDB in order to calculate users' nutrient intake and return reports in graphic or tabular format on the amount of energy and macro- and/or micronutrients consumed. Although 4 applications referenced their use of the USDA National Nutrient Database (88, 91, 106, 112), the others did not specify the source. Some applications noted that the FCDB used crowd-sourced data, and several others stated that the FCDB was "verified" or "validated" or claimed to have one of the largest databases without providing any source for the data (88, 91, 96, 104, 108). The number of food items and dishes in these FCDBs varied widely, from several thousand to 5 million (86, 88, 93, 95, 95, 99, 106, 107, 112, 115).

The applications used a variety of portion-size estimation approaches. One application included images of different types of household measures, such as pictures of cups, bowls, and spoons (93), whereas another included graduated portion-size images of foods from which the user could select (111). Although several applications allowed the users to upload digital images, none of the applications automatically estimated portion size from users' pictures. For an additional cost, 2 applications allowed users to wirelessly transmit meal images to dietitians, who would manually gauge the portion size and nutrient data (96, 111).

Additional user-oriented features included time-stamped images, global positioning system locators to track where

TABLE 1 Computer- and tablet-based technologies: assessment of criteria for use in LICs[1]

Authors, publication year (reference)	Name of device	Literacy and numeracy not required	Battery life >8 h	Able to work offline	Collects sufficient information to quantify macro- and micronutrients	Evidence of use and feasibility in LICs
McDowell et al., 1997 (22); Moshfegh et al., 2008 (23); Raper et al., 2004 (24)	AMPM	Y	NA	Y	Y	N
Kirkpatrick et al., 2014 (25); National Cancer Institute, 2014 (26–28); Subar et al., 2010 (29); Subar, 2015 (78); Subar et al., 2015 (30); Subar et al., 2007 (31); Thompson et al., 2015 (16); Zimmerman et al., 2009 (32); Zimmerman et al., 2006 (33); Zimmerman et al., 2015 (34)	ASA24	Y	NA	N	Y	N
CAAFE, 2013 (35, 36); da Costa et al., 2013 (37); Davies et al., 2015 (38); Davies et al., 2015 (39); Universidade Federal de Santa Catarina, 2013 (40)	CAAFE	N	NA	N	Y	N
Vereecken et al., 2014 (41)	CANAA-W	N	NA	N	Y	N
Shin et al., 2014 (42)	CAPIS	N	NA	N	Y	N
Arab, 2013 (43); Arab et al., 2011 (44); Arab et al., 2010 (45)	DietDay	Y	NA	N	Y	N
Noah et al., 2004 (79); Visual Informatics, 2009 (80)	DietPal	N	NA	N	Y	N
Crispim et al., 2014 (46); de Boer et al., 2011 (47); Diethelm et al., 2014 (48); González-Gross et al., 2013 (49); Huybrechts et al., 2011 (50); Huybrechts et al., 2011 (51); Ocké et al., 2011 (52); Park et al., 2015 (75); Pisa et al., 2014 (2); Slimani et al., 1999 (53); Vereecken et al., 2008 (54); WHO, 2014 (81)	GloboDiet	Y	NA	Y	Y	N
Diethelm et al., 2014 (48); González-Gross et al., 2013 (49); Vereecken et al., 2008 (54)	HELENA-DIAT	N	NA	Y	Y	N
Zoellner et al., 2005 (56); Zoellner et al., 2006 (57)	IMM	N	NA	Y	Y	N
Food Standards Agency Scotland, 2014 (58); Food Standards Agency/Newcastle University, 2013 (59); Foster et al., 2014 (60); Mauerhoefer et al., 2014 (61)	Intake24	N	NA	N	Y	N
Carter et al., 2015 (62)	myfood24	Y	NA	N	Y	N
Nutrition Coordinating Center, 2014 (82); Nutrition Data System for Research, 2014 (66)	NDSR	Y	NA	Y	Y	N
Daniel et al., 2014 (83)	NINA-DISH	Y	NA	Y	Y	Y
Carvalho et al., 2015 (63); Carvalho et al., 2014 (64)	PAC24	N	NA	N	Y	N
Moore et al., 2008 (67); Moore et al., 2014 (68)	SNAP	N	NA	N	Y	N
Hillier, 2010 (69)	SNAPA	N	NA	N	Y	N
Biltoft-Jensen et al., 2013 (70); Biltoft-Jensen et al., 2013 (71); Biltoft-Jensen et al., 2014 (72)	Web-DAS	Y	NA	N	Y	N
Vereecken et al., 2010 (73); Vereecken et al., 2005 (74)	YANA-C	N	NA	Y	Y	N
Caswell et al., 2015 (76)	Zambian 24HDR application	Y	NA	Y	Y	Y

[1] AMPM, Automated Multiple-Pass Method; ASA24, Automated Self-Administered Multiple-Pass Method; CAAFE, Food Intake and Physical Activity of School Children (Portuguese); CANAA-W, Children's and Adolescents' Nutrition Assessment and Advice on the Web; CAPIS, Computer-Assisted Personal Interview System for Open-ended Dietary Assessments among Koreans; HELENA-DIAT, Healthy Lifestyle in Europe by Nutrition in Adolescence Project - Dietary Assessment Tool; IMM, Interactive Multimedia dietary recall; LIC, low-income country; myfood24, Measure Your Food on One Day; N, does not meet the criterion; NA, not applicable; NDSR, Nutrition Data System for Research; NINA-DISH, New Interactive Nutrition Assistant–Diet in India Study of Health; PAC24, Portuguese self-administered computerized 24-hour dietary recall; SNAP, Synchronized Nutrition and Activity Program; SNAPA, Synchronized Nutrition and Activity Program for Adults; Web-DAS, Web-based Dietary Assessment Software; Y, meets the criterion; YANA-C, Young Adolescents' Nutrition Assessment on a Computer; 24HDR, 24-h dietary recall.

foods were consumed, integration with other applications to track additional health-related behaviors, multiple languages, data visualization options, categorization of foods, and on-screen reminders to enter meal information. Although many of the applications could be linked with social media and cloud-based data repositories that allowed users to see other individual users' intake, none of the application descriptions indicated whether individual respondent data could be aggregated into a larger dataset for population-level estimates or whether such data are publicly available.

No application met all, or even most, of the criteria for use in large-scale surveys in LICs (**Table 2**). All applications reviewed required user literacy. The battery life of the applications was dependent on the smartphone being used, and thus battery life varied depending on the capacity of the user's phone. The applications were able to work offline; however, they required internet connectivity for the initial download and intermittent connectivity for updates. To be appropriate for use in LICs, many features of the applications would need to be adapted, such as images of foods and household measures, food items, FCDBs, prompts, units of measurement, and language.

Camera-enabled

Sixteen camera-enabled technologies designed for self-management of dietary intake or dietary assessment research were identified (120–125), including digital cameras (126–128), mobile and smartphones (129–132), wearable cameras (133–139), and other miscellaneous technology that incorporated image capture (138, 139). Image-based dietary assessment technologies were further categorized according to whether the device captured images actively or passively (133). Active image capture required users to manually take images of foods before and after eating (to record any leftovers). Passive image capture allowed the technology to automatically take pictures; usually at timed intervals, which required no intervention by the user beyond turning the technology on and off. Twelve of the 15 technologies used active image capture (121–127, 129–132, 136, 138, 140–145), whereas 4 relied on passive image capture (9, 133–135, 137, 146). The Microcamera Food Record required users to turn the technology on during eating occasions; however, the investigators reported that they planned to advance the technology to enable automatic initiation of image capture triggered by the sound of eating (136). Most of the technologies (9 of 16) were designed exclusively for research purposes, whereas 2 were intended for self-management, and 5 had dual research and self-management applicability. Seven of the technologies were on the market (**Supplemental Table 2**). There was insufficient detail in the search results to determine market availability for 9 of the technologies.

The degree of automated processing varied significantly across these camera-enabled technologies (Supplemental Table 2). Seven of the technologies relied on manual image analysis (128, 128–131, 134–137). In these circumstances, a human (either a dietitian or the respondent) was required to manually identify foods present in images, estimate portion sizes, and calculate nutrient intakes using an FCDB.

Eight of the camera-enabled technologies automated ≥1 of the data processing steps. Six of the technologies contained an automatic food-identification component (121, 122, 125, 132, 140–144). Systems that automatically identified foods first segmented the food within the image. Image segmentation is defined as the automatic determination of the regions in the image where a particular food is located (140). After image segmentation, algorithms are run on the image's key data points, such as color and texture, to identify the food in the image. In 2 cases, machine learning algorithms were used to improve the accuracy of food identification over time (139, 147). The Food Intake Visual and Voice Recognizer required users to identify foods via a voice recording and relied on voice-to-text technology to assign a descriptive label to the food. Another approach to food identification was the use of Amazon Mechanical Turks to identify images of foods (148). Amazon Mechanical Turks were used by the smartphone applications MealSnap (139) and Platemate; however, these technologies were not included in this article because they were defunct at the time of the review.

Nine of the camera-enabled technologies included automated portion-size estimation (121–125, 132, 134, 135, 138–144). Most of these technologies used complex image analysis algorithms to estimate portion size; however, the Dietary Intake Monitoring System and SmartPlate relied on a built-in scale instead. Six technologies intended to develop automated processes for calculating the nutrient content of foods (121, 122, 125, 134, 135, 140–142), although only the SmartPlate was commercially available at the time of this review. In the case of SmartPlate, some level of human intervention was required to calculate nutrient intakes: users needed to verify the accuracy of data generated by the automatic system before the computation of food and nutrient intakes occurred.

Overall, the technologies in the camera-enabled category met many of the 5 criteria for use in population-based research in LICs, although only one of the 15 technologies met all criteria (**Table 3**). First, most of the camera-enabled technologies reviewed (10 of 16) did not require respondent literacy. When respondent literacy was required, it was needed in order to read automated, text-based reminders to take pictures or record food details (e.g., Remote Food Photography Method, and Image DietDay). The original version of the mobile food record, developed for use in adult populations, required that users verify that the automated system had accurately identified the food. The method was later adapted for use in a study that included a sample of children, aged 3–10 y, in which the verification requirement was not included (142). The mobile food record was therefore classified by the authors as not requiring respondent literacy.

Second, the majority of camera-enabled technologies met the criterion of having a battery life of >8 h (11 of 16). Some of the newer technologies, such as eButton, a wearable

TABLE 2 Mobile applications: assessment of criteria for use in LICs[1]

Developer, year updated (reference)	Name of device	Literacy and numeracy not required	Battery life >8 h	Able to work offline	Collects sufficient information to quantify macro- and micronutrients	Evidence of use and feasibility in LICs
MedHelp, Inc., 2015 (86)	My Diet Diary Calorie Counter	N	NA	U/Kn	Y	N
InspiredApps (A.L) Ltd., 2015 (87)	My Diet Coach - Pro	N	NA	U/Kn	N	N
My Fitness Pal Inc., 2015 (88)	Calorie Counter	N	NA	U/Kn	Y	N
FatSecret, 2015 (89)	Calorie Counter	N	NA	U/Kn	N	N
Fenlander Software Solutions Ltd., 2015 (90)	Ultimate Food Value Diary Pro	N	NA	U/Kn	N	N
FitNow, Inc., 2015 (91)	Loseit!	N	NA	U/Kn	N	N
TrackMyFast.com, 2015 (92)	TrackMyFast 5:2 Diet	N	NA	U/Kn	N	N
Chello Publishing Limited, 2014 (119)	Carbs & Cals - Diabetes & Diet	N	NA	U/Kn	N	N
Fooducate, Ltd., 2015 (94)	Lose Weight with Fooducate	N	NA	U/Kn	Y	N
Stefan Diener Software-Entwicklung, 2015 (95)	Calorie Counter Life Balance	N	NA	U/Kn	N	N
MyNetDiary.com, 2015 (96)	MyNetDiary Calorie Counter PRO	N	NA	U/Kn	Y	N
My Daily Bits, 2015 (97)	Food Journal	N	NA	U/Kn	N	N
Noom Inc., 2015 (98)	Noom Coach: Weight Loss Coach	N	NA	U/Kn	N	N
MyNetDiary.com, 2015 (99)	Diabetes & Diet Tracker	N	NA	U/Kn	N	N
Easyfoodplan.com, 2015 (100)	Calorie Counter	N	NA	U/Kn	Y	N
Harmonic Soft, 2015 (101)	Lose weight without dieting	N	NA	U/Kn	N	N
Atkins Nutritionals, 2015 (102)	Atkins Carb Tracker	N	NA	U/Kn	N	N
Obino, 2015 (103)	Obino Weight Loss Coach	N	NA	U/Kn	N	Y
Virtuagym, 2015 (104)	Calorie, Carb & Fat Counter	N	NA	U/Kn	N	N
Everyday Health, 2014 (105)	Calorie Counter	N	NA	U/Kn	N	N
softsysdroid, 2012 (106)	Nutrition Diary	N	NA	U/Kn	Y	N
Meuuha Apps, 2015 (107)	Nutrition Tracker	N	NA	U/Kn	N	N
Outlier, 2015 (108)	Nutritionist+	N	NA	U/Kn	N	N
YAZIO, 2015 (109)	Calorie Counter	N	NA	U/Kn	N	N
Byoni Lifestyle, 2014 (110)	Diet Tracker 2 Go	N	NA	U/Kn	N	N
HealthifyMe, 2015 (111)	HealthifyMe Weight Loss Coach	N	NA	U/Kn	N	Y
Internet Brands, Inc., 2014 (112)	FitDay	N	NA	U/Kn	N	N
Genesant Technologies, Inc., 2015 (113)	FitClick Talk-to-Track Diet	N	NA	U/Kn	N	N
LifeSum, 2015 (114)	Lifesum - The Health Movement	N	NA	U/Kn	N	N
Stefan Diener Software-Entwicklung, 2015 (115)	Calories Carb Prot Fat Counter	N	NA	U/Kn	N	N
SparkPeople, 2015 (116)	Calorie Counter & Diet Tracker	N	NA	U/Kn	N	N
GB HealthWatch, 2015 (117)	Healthwatch 360	N	NA	U/Kn	Y	N
Fooducate, Ltd., 2015 (118)	Amerifit Nutrition Tracker	N	NA	U/Kn	Y	N

[1] LIC, low-income country; N, does not meet the criterion; NA, not applicable; U/Kn, rating is unknown (i.e., not clear based on publicly available information); Y, meets the criterion.

TABLE 3 Camera-enabled technologies: assessment of criteria for use in LICs[1]

Developer, year cited (reference)	Name of device	Literacy and numeracy not required	Battery life >8 h	Able to work offline	Collects sufficient information to quantify macro- and micronutrients	Evidence of use and feasibility in LICs
Lazarte et al., 2012 (126)	FP-24HR	Y	Y	Y	Y	Y
Lassen et al., 2010 (127)	DPM	N	Y	Y	Y	N
Khanna et al., 2010 (140); Schap, 2012 (141); Aflague et al., 2015 (142)	mFR	Y	Y	N	Y	N
Pettitt et al., 2016 (136)	Microcamera food record	Y	U/Kn	Y	Y	N
Ptomey et al., 2012 (130)	DP+R	Y	Y	Y	Y	N
Martin et al., 2009 (143); Martin et al., 2009 (144); Martin et al., 2014 (132)	RFPM	N	Y	N	Y	N
Rollo et al., 2011 (129); Rollo, 2012 (130), Rollo et al., 2015 (131)	NuDAM	Y	Y	Y	Y	N
Weiss et al., 2010 (122); Weiss, 2011 (121)	FIVR	N	Y	Y	Y	N
Shang et al., 2011 (123), Shang et al., 2012 (124)	DDRS	N	Y	N	Y	N
Ofei et al., 2014 (138)	DIMS	Y	Y	Y	Y	N
SRI International, 2015 (125)	Food Recognition Technology	Y	Y	N	Y	N
Gemming et al., 2013 (133), Gemming et al., 2015 (9)	Sensecam	Y	Y	Y	Y	N
Sun et al., 2010 (135); Sun et al., 2015 (134)	eButton	Y	N	N	Y	N
Arab et al., 2011 (137)	Image DietDay	N	U/Kn	N	Y	N
Connor, 2013 (146)	Willpower watch	Y	U/Kn	Y	Y	N
SmartPlate, 2017 (139)	SmartPlate	Y	U/Kn	N	Y	N

[1] DDRS, Diet Data Recorder System; DIMS, Dietary Intake Monitoring System; DPM, digital photography method; DP+R, digital photography plus recall; FIVR, Food Intake Visual and voice Recognizer; FP-24H, food photography 24-hour recall; LIC, low-income country; mFR, mobile food record; N, does not meet the criterion; NuDAM, Nutricam Dietary Assessment Method; RFPM, Remote Food Photography Method; U/Kn, rating is unknown (i.e., not clear based on publicly available information); Y, meets the criterion.

camera, cannot be operated for >8 h; however, battery life may improve as the technology evolves. There is a tradeoff between the rate of passive image capture and battery life: the increased frequency of image capture tends to decrease battery life more quickly (137). Third, 9 of 16 of the technologies were able to work offline. The camera in mobile phones and simpler camera-enabled technologies, such as digital cameras, all functioned without connectivity. When internet connectivity was required, it was usually needed to house the data in an online repository and access web-based FCDBs required for data processing.

Fourth, all camera-enabled technologies met the criterion regarding collecting sufficient information to quantify macronutrients and micronutrients. Because images theoretically can capture all foods consumed, all technologies collected sufficiently detailed data to enable the calculation of both macro- and micronutrient intakes of respondents, although the technologies varied in terms of the extent in which macro- and micronutrient intakes were quantified automatically compared with manually. Fifth, the only example of a camera-enabled technology that met the criterion regarding demonstrated feasibility in an LIC context was the food photography 24-hour recall. Low-literacy respondents who participated in the food photography 24-hour recall study in rural Bolivia reported that using a digital camera was feasible and even “enjoyable” because of the novelty factor presented by the camera in their rural, low-income areas (126).

Scale-based

Another innovative approach to dietary assessment that addressed issues of portion-size estimation is the use of high-tech scales that are designed to measure food intake. Two scale-based technologies were identified for this review: the SITU Scale and Smart Diet Scale (149, 150). These scale-based technologies were targeted primarily to individual users as self-management tools and were available for purchase. The SITU Scale and Smart Diet Scale enable automated portion-size estimation but required users to manually identify foods on an application that is linked with an FCDB, thereby allowing the calculation of nutrient intakes. Both technologies were designed for dietary self-management purposes, produced in a commercial lab, and available for purchase (**Supplemental Table 3**). The Dietary Intake Monitoring System and SmartPlate, discussed in the image-based section because both utilize images for dietary assessment, also relied on scales to quantify the amount of food consumed.

Scale-based technologies failed to meet 3 of the 5 criteria used to judge suitability for use in large-scale dietary surveys in LICs (**Table 4**). Regarding the first criterion, both scales required literacy in order to select the foods being weighed from a list on the application (the SITU Scale presented images of foods from which the user could select, but a minimal level of literacy was required to identify the correct food group). Both the SITU Scale and the Smart Diet Scale had a battery life of >8 h and thus met the second criterion, although they failed to meet the third criterion, as they required an online (Bluetooth) connection to function,

TABLE 4 Scale-based, wearables, and handheld spectrometers: assessment criteria for use in LICs[1]

Developer, year cited (reference)	Name of device	Literacy and numeracy not required	Battery life >8 h	Able to work offline	Collects sufficient information to quantify macro- and micronutrients	Evidence of use and feasibility in LICs
Scale-based						
Michael Grothaus Limited, 2015 (149)	SITU Scale	N	Y	N	Y	N
Smart Diet Scale, 2014 (150)	Smart Diet Scale	N	Y	N	Y	N
Wearable						
HealBe Corporation, 2015 (151)	GoBe by HealBe	Y	Y	N	N	N
Jawbone, 2015 (152)	UP by Jawbone	N	Y	N	N	N
Bite Technologies, n.d. (153)	Bite Counter	Y	Y	Y	N	N
Fontana et al., 2014 (154)	Automatic Ingestion Monitor	Y	Y	N	N	N
Fontana et al., 2015 (155)	Counts of Chews & Swallows	Y	U/Kn	N	N	N
Handheld spectrometer						
Consumer Physics Inc., 2015 (156)	SCiO	Y	Y	N	N	N
TellSpec Inc., 2015 (157)	TellSpec	Y	U/Kn	N	N	N

[1] LIC, low-income country; N, does not meet the criterion; U/Kn, rating is unknown (i.e., not clear based on publicly available information); Y, meets the criterion.

which would be a limitation in LIC environments with poor wireless connectivity. The SITU Scale and the Smart Diet Scale met the fourth criterion related to quantifying information on macro- and micronutrient intakes because each was designed to estimate the energy and nutrient content of all foods (individual foods and mixed-ingredient dishes). The corresponding FCDB for the SITU Scale came from the National Nutrient Database of the USDA (149). The Smart Diet Scale drew on nutritional information from >550,000 food, grocery, and restaurant items from an unspecified source (150). The final criterion was not met, because no evidence was identified documenting feasibility and use in LICs.

Wearable technologies

Wearable technologies were designed to objectively measure diet without relying on user-reported food intake (155), thereby minimizing the types of bias and errors commonly associated with self-reported dietary data. These technologies were designed to be affixed to the user's wrist, neck, ear, or clothing to assess the timing and quantity of food intake. Five unique wearable technologies were identified in the review: the GoBe by Healbe (151), UP by Jawbone (152), the Bite Counter (153, 158, 159), the Automatic Ingestion Monitor (AIM), and Counts of Chews and Swallows Model (CCS) (154, 155). All 5 of the technologies were designed primarily for self-monitoring purposes, but the AIM and CCS were also designed for research purposes. The GoBe and the UP were produced in a commercial lab and are available for purchase. The Bite Counter is also available for purchase (Supplemental Table 3). Two additional technologies identified—the WearSens (160) and the BitBite (161)—were ultimately not included in this review given limited publicly available information.

The GoBe and the UP were intended to be worn as wristbands, and the UP could also be clipped to the users' clothing. The GoBe wristband, which needed to be tapped before eating to activate it, used an impedance sensor, an accelerometer, and a pressure sensor. This technology attempted to automatically estimate energy and macronutrient intake by applying an algorithm to calculate the amount of glucose in the cells. All information (numbers and graphic results) was sent via Bluetooth to the user's application on a smartphone (151). The UP tracked activity and sleep, and the user had to input consumption information by scanning barcodes or logging meals through the corresponding application. Dietary-related advice was generated by the application, taking account of physical activity and sleep patterns (152).

The Bite Counter was another wrist-worn technology that purported to measure energy consumption. The Bite Counter worked by tracking wrist motion by using a small gyroscope to determine the number of bites the wearer takes in the course of a meal; its premise was that a simple multiplication of bites and kilocalories per bite may provide a more accurate estimate of consumption than reliance on respondent memory (158). For a more accurate assessment, the calorie-bite relation could be calibrated to individual users based on a 1-d or 1-wk observation period (153). Although this technology seemed relatively unobtrusive and objective and used passive data collection methods, it could be sensitive to non–eating-related arm movements (158). As with the other technologies, the Bite Counter required the user to turn it on and off at the beginning and end of each eating occasion; however, it could not be kept on throughout the day because of false positives (mistaking arm movements for eating occasions) (159). The Bite Counter provided immediate feedback to the user, including the number of bites and estimated energy intake, which could be downloaded with a USB onto a computer.

The AIM (154) and CCS (155) were under development at the time of this review. Earlier experimental studies confirmed the ability of sensor-based approaches to differentiate between eating-related and non–eating-related jaw movement (e.g., yawning, talking, or chewing gum) (154, 162–164). The AIM worked via an Android smartphone that interfaced with a jaw motion sensor, a hand gesture sensor, and an accelerometer to monitor body motion. This combination of technologies worked together by using sensor fusion and a pattern-recognition method that was developed for food-intake recognition (154). Fontana et al. (155) also attempted to estimate energy intake based on the CCS model by using a throat microphone to detect swallowing sounds, a piezoelectric strain sensor to monitor chewing, and a digital eye camera to videotape the participants throughout the experiment (not worn) (155).

The wearable technologies reviewed met some of the specified criteria for use in large-scale surveys in LICs, although none met all 5 (Table 4). On the positive side, 4 of the 5 technologies reviewed did not require user literacy and had a battery life that lasted >8 h.

On the other hand, almost all technologies required an internet connection (either wireless or Bluetooth and cellular), none of the technologies in this category measured micronutrient intake, and only 2 of the 5 technologies attempted to report macronutrient content of food consumed (the GoBe and the UP). The main objective of these wearable technologies was to measure the quantity and timing of food consumption in order to estimate energy intake, which limited their usefulness for comprehensive population-level dietary surveys. Finally, none of the wearable technologies met the criterion for evidence of feasibility for use in LIC contexts. Overall the wearable technologies reviewed fell short in terms of their overall appropriateness for use in LICs, given certain limiting characteristics plus the lack of evidence of feasibility for use in such contexts.

Handheld spectrometers

For decades, analysis of nutrients in foods has been carried out in laboratories by using a combination of methods including near-infrared spectroscopy (165). Until recently this technology was available only as a large piece of laboratory equipment, but the review identified efforts by 2 different groups to develop a small, handheld spectrometer that would serve much the same purpose. The SCiO and TellSpec were purported to work by focusing the light in the handheld miniature spectrometer on an object—food, in this case. Some of the photons in the light are absorbed, in turn raising the energy state of the molecules in the object and reflecting lower-energy photons (157, 166). The technology was designed to sort the photons by wavelengths and count them, resulting in a "spectrum" that characterized the chemical compounds of the food. This information was linked to a cloud-based server where machine learning algorithms used a database to analyze and identify the foods. In turn the nutrient composition results of the specific food were to be transmitted back to the user via smartphone technology (157, 166).

These handheld spectrometers aimed to identify the food items' energy and macronutrient content, specific ingredients, and potentially, toxins or allergens. Although these technologies have been marketed as tools for individual use, the SCiO was also being promoted as "the world's first database of matter," and researchers are invited to contribute to its development (156), suggesting wider research potential. The company DietSensor was using the SCiO technology as part of its platform for individual diet monitoring (167). The TellSpec was being marketed as a tool for self-management, health, and food safety (Supplemental Table 3). Neither of these technologies was able to measure portion size.

These technologies have limited functionality for quantifying diet intakes in population-based surveys. The first 2 criteria were met: literacy and numeracy are not required to operate the handheld spectrometers, and the battery life lasts >8 h. However, neither the SCiO nor the TellSpec satisfied the final 3 criteria. Neither device can work offline, nor are they able to assess micronutrient content of foods. Evidence is needed regarding the accuracy of nutrient estimates produced, as well as advancements to allow these technologies to measure micronutrients, in addition to energy and macronutrients. The final criterion regarding feasibility and use in LICs was not met (Table 4).

Discussion

This review of innovative technologies for population-based dietary assessment surveys in LICs is, to our knowledge, one of the most comprehensive surveys of this dynamic landscape. In addition it is the first to consider the conditions of many LIC contexts, which are often constrained by illiteracy, innumeracy, limited internet connectivity, and intermittent electricity, among other factors.

Each of the technologies reviewed had certain strengths, yet none was immediately fit for "prime time" application in large-scale LIC dietary surveys. Based on the criteria defined by this study to gauge suitability for use in LICs, the computer- and tablet-based technologies came closest to fulfilling the requirements. High-income countries have developed several 24HDR platforms already, and preliminary evidence suggested that such tools could be successfully and feasibly used in LICs (75, 83). These technologies, although not on the high end of the innovation spectrum, would nonetheless facilitate a large leap forward in the ease and efficiency of dietary data collection and processing in LICs. Furthermore, because the multiple-pass 24HDR method has been validated in some LICs (168–171), it is anticipated that shifting the method from pen-and-paper–based surveys to a computer- or tablet-based platform would not affect the quality or validity of the dietary recall.

Although the concept of a computer- and tablet-based 24HDR for LICs is promising, very few such programs have been developed for use in LIC settings. The 2 programs identified in this review that were applied in LICs were both designed to be used in one specific country context; in other words, neither was designed to be readily adaptable for use across very different settings. Adoption of computer- and tablet-based 24HDR programs is not likely to increase unless newly developed programs are designed to flexibly link to contextually appropriate inputs, such as country- or region-specific FCDBs. Concurrent investments would also be required to update and complete FCDBs and generate context-specific recipes and portion-size conversion factors.

Smartphone applications were designed primarily for dietary self-management and are not appropriate for populations with low literacy levels and no access to a smartphone. This presents a major challenge, because most of these applications are designed as real-time food records rather than recalls and would be logistically infeasible to use in an interview setting. Most people in LICs do not have access to a smartphone despite steadily increasing market penetration of regular mobile phones (172). Although a few researchers have published reviews of the various functionalities and input methods of existing dietary assessment applications for use on smartphones (6, 8, 173), this review did not identify any research examining how these technologies might be harnessed to improve dietary data collection in an LIC context.

Active imaging approaches, which were used to enhance memory and estimate portion sizes, are technologically feasible and have been shown to produce quite accurate results (9, 126). These approaches also have the added benefit of reducing respondent burden and recall time. However, this approach would likely require ≥4 d/respondent: an initial session to train potential respondents to use disposable cameras, ≥2 d for respondents to monitor their food consumption, and a follow-up day for conducting the interviewer-administered 24HDR. Although possibly feasible for small-scale studies in LICs, the benefits are unlikely to outweigh the costs in surveys with large sample sizes.

Passive image technology skirts the fraught issue of respondent recall by measuring food consumption in real-time and ideally could measure usual intake with minimal participant burden. However, none of the technologies have yet achieved fully automated image processing, a large constraint that would likely result in a longer processing time and higher cost than a traditional pen-and-paper dietary recall survey. Even a fully automated system would still need to contend with several factors that affect accuracy, such as dark, poorly angled, or blurry images or hidden ingredients that are difficult to identify in images. To accurately measure food consumed from a shared plate, a common practice in many LIC cultures, any camera-enabled technology would need to have a sufficiently wide-angle lens to capture the entire dish and all diners eating from the shared plate. The technology would need to quantify volume changes in the dish after each individual bite, and individuals might even be required to take turns eating from a shared plate. Although the challenge of accurately capturing food consumed from a common plate is an issue across all the technologies reviewed, it is particularly salient for passive image capture. Further research is also needed to provide evidence of the feasibility and cultural acceptability of having a novel device constantly affixed to an individual while going about activities of daily living.

The scale-based technologies appeared to be potentially useful tools for facilitating weighed food records, which would need to be performed by an interviewer-observer to skirt the literacy issues in many contexts. Direct weighing could increase accuracy; however, interviewer-administered weighed food records require a large time commitment and would likely be feasible only for small sample surveys. If other constraints were overcome, for example, connectivity issues, the scale-based technologies could be useful in LICs.

The wearable technologies are relatively unobtrusive, eliminate issues with recall, and require little to no effort on the part of the user. However, despite attempts to make these technologies unobtrusive, they may not be acceptable in some LIC contexts and could attract unwanted attention. Furthermore, these technologies are not always designed to quantify both macro- and micronutrient intake, limiting their usefulness. With that said, this type of technology could be used in conjunction with others reviewed in this study to overcome the thorny challenge of capturing individual consumption of food consumed from a shared plate. In theory, the individual markers of ingestion (e.g., chewing and swallowing) could be combined with data on the total amount of food served to the meal partakers to estimate the proportion of a shared plate consumed by a single individual. Overall, more evidence of feasibility and accuracy would be required to justify the use of wearable technologies for this purpose.

The handheld spectrometers, although not currently useful for collection of dietary data in a survey, offer the potential to facilitate the process of developing or updating FCDBs, the lack of which is currently a major impediment to effective and accurate dietary data analysis in LICs. If these technologies can deliver on their promised functionality, they could be very useful for quickening the process of food-composition estimation and potentially broadening the scope of up-to-date FCDBs.

A few limitations to this review should be noted. First, because this field is very dynamic and rapidly advancing, some technologies may have undergone name changes or may no longer be relevant since this review was performed, whereas additional technologies may have emerged on the market or in the literature. Second, it is possible that recent developments of some technologies are not reflected here because of the delay in the publication of results in peer-reviewed journals. To try to mitigate this issue, the present study relied on gray literature and commercial websites to identify details of technologies that were discussed in working papers and conference abstracts. Third, an assessment of the established validity of these technologies would have been useful but was outside the scope of this review because of space limitations.

In summary, although none of the technologies reviewed was immediately fit for "prime time" application in large-scale 24HDR surveys in LICs, the assessment criteria suggested that the computer- and tablet-based programs came closest to fulfilling the criteria set forth by this study. In addition to meeting these criteria, any program developed for use in LICs should be user friendly, scalable, open access, and adaptable to use in multiple contexts.

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