A Systematic Review of Technology-Based Dietary Intake Assessment Validation Studies That Include Carotenoid Biomarkers

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Abstract: Technological advances have allowed for the evolution of traditional dietary assessment methods. The aim of this review is to evaluate the accuracy of technology-based dietary assessment methods to determine carotenoid and/or fruit and vegetable intake when compared with carotenoid biomarkers. An online search strategy was undertaken to identify studies published in the English language up to July 2016. Inclusion criteria were adults ≥ 18 years, a measure of dietary intake that used information and communication technologies that specified fruit and/or vegetable intake or dietary carotenoid, a biomarker of carotenoid status and the association between the two. Sixteen articles from 13 studies were included with the majority cross-sectional in design (n = 9). Some studies used multiple dietary assessment methods with the most common: food records (n = 7), 24-h diet recalls (n = 5), food frequency questionnaires (n = 3) and diet quality assessed by dietary screener (n = 1). Two studies were directly web based, with four studies using technology that could be completed offline and data later transferred. Two studies utilised technology in the collection of dietary data, while the majority (n = 11) automated the collection in combination with nutrient analysis of the dietary data. Four studies provided correlation values between dietary carotenoids with biomarkers, ranging from r = 0.13 to 0.62 with the remaining studies comparing a measure of fruit and vegetable intake with biomarkers (r = 0.09 to 0.25). This review provides an overview of technology-based dietary assessment methods that have been used in validation studies with objectively measured carotenoids. Findings were positive with these dietary assessment measures showing mostly moderate associations with carotenoid biomarkers.

Keywords: carotenoids; fruit vegetables; validation; biomarker

1. Introduction

Technological advances in methods of collecting dietary intake data have been achieved in recent years with increased use and access of the internet and smartphones. These advances have allowed for an expansion and adaptation of traditional methods, allowing the collection of detailed dietary intake with lower costs and burden for researchers, clinicians and patients/participants by allowing more timely approaches to data analysis [1]. There has been an expansion into image-based methods.
using mobile devices and development of standardised images to assist in the estimation of portion sizes [2]. These advances in technology have an increasing tendency to allow for self-administered methods rather than interviewer administered or paper-based surveys [3]. With the rapid evolution of technology-based methods there is a need to ensure that these methods are both valid and reliable.

One important aspect of dietary intake is fruits and vegetables. Regular consumption of fruits and vegetables is associated with reduced risk of chronic disease such as specific cancers including breast, oesophageal and lung [4–8], reduced risk of coronary heart disease [9,10], stroke [11,12] and type 2 diabetes mellitus [13,14] and decreased risk of asthma incidence and exacerbation in adults and children [15,16]. Plant components such as fiber, phytochemicals and a range of vitamins and minerals, also contribute to these protective effects [17]. Carotenoids are powerful antioxidants and are obtained primarily from fruit and vegetables. Various carotenoids, including lycopene and β-carotene, have been heavily studied due to their documented associations with decreased risk of disease [18]. Carotenoids are obtained solely from the diet and can also provide useful biomarkers that can be objectively measured in plasma and used to validate dietary assessment tools [19,20].

Our previous review of traditional paper-based dietary assessment methods identified 142 studies demonstrated the popularity of plasma carotenoids as a dietary validation measure [18]. This review summarised the dietary intakes and plasma concentrations and their expected associations by dietary assessment method and provided a benchmark for dietary studies. It was highlighted that the most commonly assessed carotenoids from the diet and biochemically were β-carotene found in high concentrations. The associations between dietary measures and plasma concentrations were strongest for cryptoxanthin (r = 0.38, n = 35 studies) and lowest for α-carotene (r = 0.27, n = 73 studies). Food records had a tendency to have stronger correlations with plasma concentrations than other types of dietary assessment methods. To date, no reviews have synthesized information specifically on technology-based assessments.

The aim of this review was to evaluate the prominent characteristics of studies that compared carotenoid intake assessed by a technology-based dietary assessment method when compared with objective biomarkers of carotenoids.

2. Materials and Methods

An online search strategy was undertaken to identify studies published in the English language up from 1975 to July 2016. The review methodology was registered with PROSPERO (ID number CRD42016047276).

As the initial step, six online databases were searched: CINAHL, Embase, Cochrane, MEDLINE, ProQuest, PubMed and Excerpta Medica. Key words used individually and in combination were dietary assessment OR food frequency questionnaire OR diet/dietary recall OR diet record OR weighed food record OR validity/validation AND carotene OR carotenoids OR fruit OR vegetable. Electronic searches were supplemented by manual cross-checking of the reference lists of relevant publications. All study designs were included with limits placed on searches for adults and English language.

After the removal of duplicates, stage 2 involved the assessment of titles and abstracts of identified studies by two independent reviewers with discrepancies decided by consensus using a third reviewer. A priori inclusion/exclusion criteria were applied to determine the eligibility of each publication for inclusion in the review, as per the following inclusion criteria: adult populations (≥18 years or “adults” depending on the database searched), a measure of dietary intake that specified fruit and/or vegetable, a measure of plasma or skin carotenoids as a biomarker of carotenoid intake, reported the association between diet and biomarker assessments. For the purpose of this review, dietary assessment methods which used information and communication technologies such as interactive programs based on the Internet or a computer [3] primarily to facilitate the collection of dietary intake data were included. This review focuses on carotenoids, individually or in combination, including α- and β-carotene, cryptoxanthin, lycopene, zeaxanthin, and lutein. Papers that met the inclusion criteria, or where eligibility was unclear, were retrieved. Studies were then evaluated for inclusion by
two independent reviewers with discrepancies discussed with a third person. Excluded articles were classified in a systematized way and are summarized in Figure 1. i.e., “not an outcome” refers to a study not reporting information required for the review such as no correlation values.

**Figure 1.** Flow diagram of article identification retrieval and inclusion for the systematic review.

Risk of bias was assessed using a standardized tool from the American Academy of Nutrition and Dietetics [21]. Ten quality criteria were rated as being absent, present or unclear in each study. This included the assessment of population bias, study blinding, a description of the intervention and assessment tool, statistical methods, and study funding. An overall quality rating was assigned, with each study being rated as positive, neutral or negative. No studies were excluded based on quality ratings.

Data were extracted using standardized tables developed for this review and included study design, population demographics, dietary assessment method, technology components (participant training, device used, self or interviewer administered, portion size tools, whether the method was collection only of diet or analysis only or a combination), carotenoids assessed and study outcomes. In cases of uncertainty regarding quality assessment, or data extraction, a third independent reviewer was consulted until consensus was reached. For studies that cited additional references with more details of the technology-based dietary assessment method, these additional references were retrieved.

### 3. Results

The search strategy identified 4518 articles, as summarised in Figure 1. Following elimination of duplicates, initial assessment of titles and abstracts, and evaluation of retrieved studies against the inclusion criteria, 16 articles from 13 studies were identified for critical appraisal and included in the review. The major reason for study exclusion was the dietary assessment method not being a technology-based method or not reporting associations between the outcome variables of diet and objectively measured carotenoids.

The majority of studies were conducted in the USA (n = 6 studies), France (n = 4), with one study each from the Netherlands, UK and Australia (Table 1). Nine studies were cross-sectional, three were cohort studies and one controlled trial. A total of 62,936 participants were included across the studies (mean 4841, range 91–17,688) with females only in three studies [22–24]. Five studies reported having recruited a diverse sample of participants from a range of ethnicities including African American,
Hispanics and populations identifying as indigenous [24–28]. All studies except one [22,29] were published since the year 2000.

The quality assessment appraisals of included studies deemed that seven studies had a positive rating with six rated as having a neutral overall study quality (Supplementary Materials Table S1). As noted, many of the study designs were cross sectional so several of the quality criteria including ‘were study groups comparable’ were not applicable. Those studies which were rated as neutral did not describe details of participants who may have withdrawn from the study and lacked adequate descriptions of study methods.

3.1. Dietary Assessment Methods

In descending order, the most common technology-based dietary assessment methods used were: food records (n = 7), food recalls (n = 5 studies), food frequency questionnaires (n = 3), and diet quality/screener was assessed in one study using a pre-defined diet quality score [26]. The description of the collection of the dietary intake data using the record methods did not explicitly state if the collections occurred prospective or retrospective. Two studies utilised and employed two dietary methods [25,30] and one study employed three separate methods [22,29]. Only n = 3 studies assessed dietary intake data with a reporting a reporting longer than 24 h. Six studies specifically mentioned the assessment of supplements, one study reported intakes separately and not including supplements, while for the majority of studies (n = 6) it was unclear whether supplements were included or not. The nutrient database to evaluate dietary intakes was described in seven studies, with four studies not reporting any details and a further three studies reporting generic information such as “food tables”. Two studies used the USDA and one study each used AusNut, Minnesota, Ciqual and NutriNet.

Descriptive details of the technology-based dietary methods are detailed in Table 2. Training was provided to participants in three studies and in one study training was provided to interviewers. One study detailed that the inclusion criteria for the study was for participants to have basic computer knowledge [31]. Six methods were self-administered, three studies were interviewer administered, one study was a combination with some recalls collected under supervision with guidance and some self-administered [25], and in the remaining studies it was unclear as to which method was used. The specific technology device used was measured in four studies [29,32–34] with three of these using a console with Minitel and one the Portable Electronic Tape Recorded Automatic (PETRA) scales, which recorded the weight and a verbal description of the foods. Two studies were directly web based [25,31] while four studies stated that they could be completed offline and data later transferred [29,32–34]. Eight studies specifically reported that portion size was estimated using household measures or picture books [25,26,30–35]. Two studies utilised technology in the collection of dietary data, while the majority (n = 11) automated the collection in combination with nutrient analysis of the dietary data. The studies which automated collection and analysis of dietary data were all published from 2002 onwards, while only one study which used technology in the collection of dietary information and not analysis was published in 1995.

3.2. Dietary Carotenoids

Five studies reported dietary intakes as food groups, including fruit and vegetables [26,30,31,35], juices [32], or salad and vegetable consumption [28], however, these were all assessed and reported differently (i.e., grams per day, servings, amount of foods) preventing results to be pooled in a meta-analysis (Table 3). One study [24] reported the relative contribution of fruits and vegetables to carotenoid intakes, with the remaining studies reporting on intakes of individual dietary carotenoids. Of those reporting dietary carotenoids, two studies reported on five dietary carotenoids (α-carotene, β-carotene, lutein/zeaxanthin, lycopene and cryptoxanthin [25,27], three studies reported on β-carotene only [31,33,34] and one study reported the total amount of dietary carotene which was not specified further [29].
3.3. Carotenoid Biomarkers

Blood samples were collected from participants in a fasting state in nine studies, with three studies in a non-fasted state, however one of these was skin carotenoids which does not require fasting. For studies which reported plasma concentrations, high performance liquid chromatography (HPLC), which is considered the gold standard analytical technique for analysis of carotenoids, was used to assess plasma carotenoids in nine studies, absorptiometrics was used in one study, spectrophotometry in one, and the method was not reported in three studies.

Five carotenoids were assessed in six studies (α-carotene, β-carotene, lutein/zeaxanthin, lycopene and cryptoxanthin) [24–27,29,35], three carotenoids (α-, β-carotene and lycopene) were reported in one study [28] and β-carotene only assessed in four studies [31–34] (Table 3). One study also reported on total plasma carotenoids [30]. A study by Pezdirc et al. [23] reported on skin yellowness levels measured using reflectance spectroscopy, these were assessed across a range of sites including those which were sun exposed (i.e., shoulder) and non-exposed sites (i.e., sole of foot).

3.4. Correlations

Technology-based methods were compared to more traditional methods of dietary assessment in three studies [25,29,30]. The results reported by Arab et al. [25] demonstrated that a technology-based 24-h recall was more strongly correlated with plasma β-carotene, lutein + zeaxanthin, lycopene than a traditional diet history questionnaire in white but not African Americans. In another study by Bingham et al. [29] the technology-based PETRA weighed food record showed the strongest correlation ($r = 0.45$) compared to other methods which included a 7-day checklist, structured and unstructured 24-h recalls where correlations were $r = 0.25$, 0.06, and −0.01; respectively. In van Lee et al. [30], the technology-based 24-h recall had stronger correlations than the comparative method of an food frequency questionnaire (FFQ) for vegetables ($r = 0.25$ vs. 0.17) but not fruit ($r = 0.09$ vs. 0.25).

The four studies [22,25,27,34] that compared single dietary carotenoids with the corresponding plasma carotenoid biomarker at one time point demonstrated correlations for β-carotene ranging from 0.25–0.48 ($n = 3$ studies), α-carotene 0.21–0.62 ($n = 4$ studies), lycopene 0.13–0.33 ($n = 3$ studies), cryptoxanthin 0.37–0.51 ($n = 2$ studies) and lutein + zeaxanthin 0.35–0.45 ($n = 2$ studies). Those studies which reported fruit and vegetable intake and determined relationships with carotenoids tended to report on total carotenoids or carotenes so it cannot be ascertained which individual carotenoid biomarker was a predictor of fruit and vegetable intake. Studies that were in females only tended to produce similar correlation values with those in mixed gendered studies.
Table 1. Description of included studies.

| Source           | Country | Study Design | n   | Gender | Age (Year) | Dietary Method + Reporting Period | Supplements Assessed | Dietary Carotenoids Assessed | Nutritional Database Used | Biochemical Carotenoids Assessed | Biochemical Method | Fasting Time Length |
|------------------|---------|--------------|-----|--------|------------|-----------------------------------|----------------------|-------------------------------|---------------------------|-----------------------------------|-------------------|----------------------|
| Arab et al. 2011 | USA     | Cohort       | 262 | 34.8%  | M 21–69   | 8 × 24-h recalls over two visits using web-based multi pass method + 124 item diet history FFQ. Yes | a-carotene, ß-carotene, ß-cryptoxanthin, lycopene, and the combined intakes of lutein and zeaxanthin. USDA food composition database and National Cancer Institute database. | lycopene, a-carotene, ß-carotene, ß-cryptoxanthin and combined lutein + zeaxanthin. | HPLC 10 h fast |
| Bingham et al. 1995 | UK     | Cohort       | 160 | 100% F | 50–65     | 6 × 24-h dietary records UC | β-carotene equivalents | Food tables | a-carotene, ß-carotene, ß-cryptoxanthin, lutein, lycopene, Absorptiometric detection | HPLC Fasted |
| Dauchet et al. 2008 | France | Cross sectional | 321 | 42% M  | 35–60     | 3 × dietary records UC | F&V  | NR | β-carotene | HPLC Fasted |
| Faure et al. 2006 | France | Cross sectional | 12,741 | 39% M  | F 35–60; M 45–60 | 6 × daily 24-h food records (4 week days and 2 weekend days) UC | β-carotene | NR | β-carotene | HPLC Fasted |
| Galan et al. 2003 | France | Cross sectional | 3,220 | 42% M  | F 35–60; M 45–60 | 6 × 24-h recalls over 18 months (4 week days and 2 weekend days UC | β-carotene | French CIQUAL table + McCance and Widdowson | HPLC | 13 h |
| Kant et al. 2002 | USA     | Cross sectional | 13,400 | F 49% M 64%  | ≥90 24-h recall UC | NR specifically; F&V intake (in addition to various quantitative ax) | USDA | a-carotene, ß-carotene, ß-cryptoxanthin, lutein, lutein/zeaxanthin UC | Fasted |
| Kant et al. 2008 | USA     | Cross sectional | 8,719 | 49% M  | ≥20; ≥50; ≥50 | 24-h recall UC | Diet Quality: HEI, RFS and DDS | NR | a-carotene, ß-carotene, ß-cryptoxanthin, lutein, lutein/zeaxanthin NR | Fasted |
| Lassale et al. 2016 | France | Cross sectional | 198 | 40% M  | M 50.5 ± 16.2 | 3 × dietary records Yes | F&V | Nutrient Sante composition table | β-carotene | HPLC Fasting for at least 6 h |
| Van Lee et al. 2013 | The Netherlands | Cross sectional | 121 | 45–65 | 2 × non-consecutive 24-h recall, 180 item semi-quantitative FFQ. Yes | F&V | Dutch Composition table | β-carotene, ß-cryptoxanthin, lutein, lutein/zeaxanthin NR | Non-fasting |
| Perdine et al. 2015 | Australia | Cross sectional | 91 | 100% F  | 18.1–29.1 | Australian Eating Survey 2010 (FFQ) 120 item reporting period 6 months Yes | F&V | Australian AusNut 1997 (all foods) revision 17 + AusFoods (brands) revision 5 (FoodWorks version 5/2.51) | Skin carotenoids: a-carotene, ß-carotene, ß-cryptoxanthin, lutein/zeaxanthin | HPLC CM/SSD, specrophotometer Non-fasting |
| Pierce et al. 2008 | USA     | Randomised trial | 2,002 (participants were from the WHEL-study) | 100% F  | 16–70 | Self-reported dietary intake using a set of four 24-h recalls over a 3 week period Yes | None, whole foods only. Food, juice and supplements | Minnesota Nutritional Data System software (Nutritional Data System version 4.0, 2001 University of Minnesota, Minneapolis, MN) | a-carotene, ß-carotene, ß-cryptoxanthin, lutein, lutein/zeaxanthin, lycopene | HPLC Fasting (measures of time length) |
| Signorillo et al. 2010 | USA     | Cross sectional | 255 (125 AA, 130 non-Hispanic) | 40%  | 89-item FFQ. Nine items are specific to fruits or fruit juices, 13 are specific to vegetables Yes | a-carotene, ß-carotene, ß-cryptoxanthin, lutein/zeaxanthin, lycopene | nutrient databases developed for the Southern Community Cohort study that were based on dietary patterns in the southern US. | a-carotene, ß-carotene, ß-cryptoxanthin, lutein, lutein/zeaxanthin | HPLC Non-fasted |
| Su et al. 2006 | USA     | Cross sectional | 17,688 | 47% M  | 18–45 and 55+ | 24-h recall. Additional questions asked about use of vitamin and mineral supplements collected through verbal examination. Yes | Salad, Vegetable | a-carotene, ß-carotene, lutein, lutein/zeaxanthin, lycopene | HPLC | UC |

FFQ: food frequency questionnaire; UC: unclear; F&V: fruit and vegetable; NR: not reported; ax: assessment.
Table 2. Description of technology components of dietary measures from the included studies.

| Reference | Technology-Based Dietary Assessment Method | Training for Participants | Device Used | Quantification of Portion Size | Record/Stand-Alone Software | Collection/Analysis |
|-----------|---------------------------------------------|---------------------------|-------------|--------------------------------|-----------------------------|-------------------|
| Pierce et al. [24] | 24-h recall; subjects were taught to estimate food portions; Start of data collection: 1995 | The first three recalls were collected under supervision at assessment session, last three self-administered. Patients notified by email when recalls needed completion | NR | System contains 5490 foods. Images of foods (>7000) were displayed in a serving vessels and were used by participants to quantify amounts consumed | Stand-alone software: Diet Day | Collection of previous day’s intake following the multiple-pass method in addition to programmed logic to skip irrelevant questions or branch to additional questions if required. Analysis automated using standard food and nutrient composition database (USDA). A reporting feature is also available comparing intake to national (US) nutrition recommendations |
| Galan et al. [33] | Same as Dauchet et al. | | | | Stand-alone software | Collection only: records then coded by hand for computational calculation of nutrient intakes with food tables. |
| Kant et al. [26] | 24-h recall; Start of data collection: 1988 | Participants were assisted by the conventional features of the software and an instruction manual was used for coding food portions | | | Stand-alone software: Diet Day | |
| Su et al. [18] | 24-h recall, multiple pass; Start of data collection: 2007 [40] | Participants were taught to estimate food portions and to describe specifics of foods | Stand-alone software; software driven protocol, 5 pass including quick list for forgotten foods, time and occasion, details and final probes | | | Collection and analysis: The 89 item FFQ was administered through a computer assisted interview conducted in a community health centre. Nutrient estimations were derived from sex and race specific databases developed for the study [42]. Not clear if automated |
| Collection and analysis: Multi-pass software driven protocol with nutrients estimated. Unclear if automated—in particular back then. It appears that system is linked to a food comp database: http://www.ncc.umn.edu/products/ | |

WFR: weighed food record.
Table 3. Outcomes of Included studies.

| Source                  | Dietary Carotenoid Intake                                                                 | Plasma Carotenoid Concentrations                                                                 | Correlations between Diet and Plasma |
|-------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------|
| Ahlu et al. [23]        | Mean intake (mg/day) of carotenoids in African Americans (AA) and Whites (W) from 24HDR and DHQ | Reported in Bingham 1995: Mean ± SEM (AA): β-carotene 0.12 ± 0.02; lutein 0.03 ± 0.07; α-cryptoxanthin 0.08 ± 0.04; | 24HDR—Whites (AA): lutein + zeaxanthin 0.00 (0.25), β-cryptoxanthin 0.01 (0.40), α-cryptoxanthin 0.05 (0.25), lycopene 0.03 (0.15), lutein + zeaxanthin 0.27 (0.18), β-carotene 0.36 (0.03), NCI-DHQ—Whites (AA): lutein + zeaxanthin 0.07 (0.21), β-cryptoxanthin 0.33 (0.26), lutein 0.02 (0.26), α-carotene 0.28 (0.24), β-carotene 0.31 (0.17) |
| Bingham et al. [22,29,36,37] | Five quintiles from PETRA-based WFR: Mean ± SD (AA) 0.04; 1.04; 0.4; 0.3; 4th 3.7 ± 0.3; 7-day estimated food record 3.2 ± 1.8 | Regression analysis: estimated dietary intake and serum β-carotene b coefficient and SE 0.29 (0.02) | |
| Dauchot et al. [52]     | Mean (SD)                                                                                   | Correlation values with β-carotene only range from 0.04 for fruit juices to 0.25 for | |
| Faute et al. [33]       | β-carotene (mg/day) in 35-year-old men: Mean ± SD (MEN): 5310 ± 1540; 4050 ± 2290; 4150 ± 2150; 35-year-old women: 3810 ± 2150; 4150 ± 2150 | Regression analysis: estimated dietary intake and serum β-carotene b coefficient and SE 0.29 (0.02) | |
| Galan et al. [34]       | β-carotene (mg/day) in 55-year-olds: Mean ± SD (M): 0.47 ± 0.35; 0.17 ± 0.06; 0.17 ± 0.06 | Regression analysis: estimated dietary intake and serum β-carotene b coefficient and SE 0.29 (0.02) | |
| Kant et al. [35]        | β-carotene (mg/day) reported with tertiles of energy intake by BMI category (HW reported here) | Regression analysis: estimated dietary intake and serum β-carotene b coefficient and SE 0.29 (0.02) | |
| Kant et al. [26]        | The mean HEI 63.75, RFS 3.97 and DDS-R 2.44                                          | Regression analysis: estimated dietary intake and serum β-carotene b coefficient and SE 0.29 (0.02) | |

**Note:** All dietary scores were strong positive predictors of all serum carotenoids, except lycopene (see DHQ and DDS-R only p < 0.10)
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| Source | Dietary Carotenoid Intake | Plasma Carotenoid Concentrations | Correlations between Diet and Plasma |
|--------|---------------------------|----------------------------------|-------------------------------------|
| Lassale et al. [31] | | | *β-carotene (µg/dL)* |
| Male: Fruit & Vegetables: | Mean (95% CI) 9 | 140 | *β-carotene: 0.42 (0.39, 0.44), Fruit and β-carotene: 0.35 (0.17, 0.51), Veg and β-carotene: 0.38 (0.22, 0.54) |
| Female: Fruit & Vegetables: | lutein + zeaxanthin 2223.4* (1375.1), lycopene 4050.9 (2979.3). | | F: β-carotene: 0.37 (0.19, 0.54), Fruit and β-carotene: 0.41 (0.22, 0.56), Veg and β-carotene: 0.24 (0.04, 0.42) |
| Male: Fruit & Vegetables: | | | Adjusted Correlations |
| Female: Fruit & Vegetables: | | | F: β-carotene: 0.35 (0.16, 0.53), Fruit and β-carotene: 0.29 (0.10, 0.47), Veg and β-carotene: 0.29 (0.10, 0.47) |
| Female (n = 95): | Geometric unadjusted mean (95% CI) Adjusted mean (95% CI) | | F: β-carotene: 0.41 (0.22, 0.57), Fruit and β-carotene: 0.36 (0.17, 0.53), Veg and β-carotene: 0.37 (0.17, 0.53) |
| White male: | | | | |
| | -cryptoxanthin 298.6* (263.4), lutein + zeaxanthin 5497.4* (5769.8), lycopene 6994.7 (5098.4). | | nutrient reported intake and corresponding plasma biomarkers; Crude correlations |
| White female: | | | β-carotene: M 0.47 (0.33, 0.63), F 0.47 (0.18, 0.55) |
| | | | Adjusted correlations |
| | | | β-carotene: M 0.36 (0.20, 0.54), F 0.47 (0.17, 0.53) |
| Van Lee et al. [30] | Mean (SD) 9 | 140 | Correlation (r) for serum carotenoids and Vegetables (24-h recall): 0.25 (0.07-0.41), Fruits (24-h recall): 0.17 (0.01-0.34) |
| | | | Fruit (F): 0.09 – 0.05, 0.27, Vegetables (V): 0.05 – 0.41, 0.15; 0.5 |
| | | | β coefficient ± SE |
| | | | Relationship between veg intake and skin reflectance (wavelengths 400–540 nm) negatively correlated with absorption spectra of lycopene. |
| | | | F&V intake and skin reflectance—only correlated with absorption spectra of β-carotene, lycopene, and mean carotenoid. |
| | | | Full model β coefficients |
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4. Discussion

This review evaluated the prominent characteristics of studies that compared carotenoid intake assessed by technology-based dietary assessment methods and carotenoid status from biomarkers. A total of 13 unique studies from 16 published papers were reviewed, each of which included a technology-based assessment of dietary intake and reported dietary intakes of fruits and vegetables, or carotenoids, and then compared these with a biomarker of carotenoid intake.

The majority (>90%) of studies were published after 2002, indicating a growth in the use of technology for the assessment of dietary intake. This parallels the changes seen in society generally, with regard to access to and use of technology [43]. The internet has allowed enhancements to traditional approaches, such as shifts in the reliance on interviewer-administration of recalls to self-administration. This trend was evident in this review, with only three interviewer administered studies identified. Further, since the introduction of smartphones in the early 2000s, the development and use of technology-based applications has increased dramatically [2,44]. The original descriptions of dietary assessment methods, as summarised by Bingham (1987) [45], were predominantly paper-based, in-person and manual approaches to the collection and coding of intake data. Advances have seen the processing of collected dietary data via food composition software as standard in the analysis on nutrient intakes [46], attention has now shifted to improving efficiencies related to data collection. The majority of studies in the current review automated both the collection and analysis of dietary data through the use of various technologies. Overall, the included studies had relatively high participant numbers (mean 4841) when compared to other dietary validation studies (i.e., doubly labelled water were used [47]) where commonly fewer individuals (<20 per study) are used due to cost, technical skill and burden when technology was not employed in dietary assessment [18]. This may be attributed to the fact that when the collection of dietary intake data is facilitated by technology-based methods, it allows for substantial savings in time, greater scope in the size of the target population, in addition to reducing both participant and researcher burden. For example, the advent of web-based 24-h recall systems means that it is possible to collect 24-h recalls in large-scale undertakings, such as the ASA24, which previously would not have been possible [48].

The majority of studies used food records with a reporting period of 24 h being the most common, with few studies using methods such as FFQs. It is not clear why more methods that measure usual/habitual dietary intake rather than a short term intake were not used. Factors such as the high variation in the number of food items included in the food lists used in FFQs, in particular the increased number of fruit and vegetable items tend to be more strongly related to carotenoids and also the variability in the length of the reporting period may be attributed. FFQs also have to contain all possible or likely fruit and vegetable options whereas when diet is assessed by 24-h recall most people will have consumed a limited range of fruit and vegetables. In addition, FFQs are often generated for a particular group or population, therefore they cannot be as easily adapted to other settings such as a 24-h recall methodology. The majority of studies in this review compared plasma and dietary carotenoids directly. Four studies in this review compared plasma carotenoids with intakes of fruit, vegetables and/or juices with no study comparing a biomarker to specific types of fruits and vegetables which has been previously undertaken in children [20].

The development of technology-based, research tools for the assessment of intake, such as the web-based, automated, self-administer 24-h recall i.e., the ASA-24 [49] developed by the National Cancer Institute reflects the need, availability and popularity of smartphone applications and the popularity of wearable devices for self-monitoring intake [50]. In order to be confident in the data collected and inferences made by newer measures, one must ensure that any methods to be used for research purposes are valid and reliable [51].

Due to the accessibility of mobile devices and the high rates of use in both developed and developing countries [52], the use of technology-based methods has the potential to reach large populations and reduce language barriers through use of images rather than verbal descriptions. Technology allows for greater scale and efficiencies for researchers and government and
non-government organisations relying on regular dietary intake data for surveillance and monitoring. It is important to note that although the conversion of paper-based methods into web-based methods may have benefits, including faster completion, greater reach, and the ability to maximise the collection of complete data, the methods do not address the limitations in terms of misreporting. Thus, there is a need for continued development of methods, as well as to continue to evolve statistical methods to mitigate error. Training research, clinical staff as well as patients on the use of the technology and the method is still highly warranted and will improve results and compliance to the dietary method. Examples of training might include taking images correctly and consistently to aid comparisons in addition to describing foods and remembering to record using the specified device.

Food records were the most common type of dietary assessment method used across the studies included in this review. However for some studies, the description of the collection of intake data using the record methods does not explicitly state if collection occurred in as they were consumed or in real-time [53]. Initiatives such as the STROBE-nut which is a set of standardised guidelines for Strengthening the Reporting of Observational Studies in Nutritional Epidemiology) [54] may assist in improving the reporting of the methods used for the assessment dietary intake. In a previous review, FFQs were found to be the most common type of dietary assessment method used to comparatively validate with carotenoids FFQs were used in 103 of the 142 included studies [18]. FFQs were only used in three studies in the current review and, overall correlations were considered small to moderate. While much less studies were included in this review (n = 16 studies), the correlations in this review are similar to that previously published on traditional paper-based dietary assessment methods (n = 142 studies). Specifically, in the previous review, the weighted mean correlation synthesised by meta-analysis for α-carotene was 0.34 (n = 41 studies) while the correlations in this review ranged from 0.21 to 0.62. Similarly, previously for β-carotene, the correlation r = 0.27 (n = 73 studies while in this review ranged 0.25 to 0.48; cryptoxanthin r = 0.38 (n = 35 studies) vs. in this review 0.37–0.51; lutein/zeaxanthin r = 0.29 (n = 28 studies) vs. in this review 0.35–0.45; lycopene r = 0.29 (n = 42) vs. in this review 0.13–0.33. The results from this review are promising and suggest that the collection of dietary data using technology provides similar estimates to more traditional methods. The differences in the correlations in this review for the different dietary assessment methods may be attributed to the differences in collection methods, such as FFQs, which provide better estimation of longer term intake, may reflect better dietary estimation of more habitual intakes than compared with single 24-h recalls. The majority of dietary assessments in the current review were food records which may be more sensitive to assessing details of dietary intake such as cooking methods and mode of consumption.

Many of the studies were cross-sectional in design, meaning dietary intake and biomarkers were assessed at a single time point. Those studies which had a cohort design also only reported correlations at one time point. Whilst this was suited to the specific aim of studies examining associations between intake and biomarkers, depending on the dietary intake method, it is likely that the biomarker measurement and assessment of dietary intake may not reflect the same time period, i.e., use of an FFQ assessing intake over previous six months when most carotenoids have a half life of 1–2 months [55]. This may explain why many studies in the review used food records for improved compatibility with the biomarker assessment.

This review was limited to studies published in the English language and articles that were available via electronic databases. The review may be predisposed to a publication bias and an overrepresentation of studies that found positive associations between diet and plasma biomarkers. There were substantial levels of heterogeneity in the included studies. Major sources included variations in dietary assessment methods, the participant populations including sex, age and ethnicity, the range of plasma carotenoids assessed and the differing study protocols. Strengths to the review included the registered review methodology that adheres to the PRISMA guidelines for reporting of systematic reviews and the rigorous methodological process of obtaining the included studies that were extracted by two independent reviewers including quality checks to determine any bias and a standardized data extraction.
5. Conclusions

In conclusion, the current review provides an overview of technology-based dietary assessment methods that have been used in validation studies in comparison with plasma carotenoids as a biomarker of usual intake. Technology-based studies most commonly use retrospective measures of dietary assessment for comparison with carotenoid biomarkers. It was found that a wide variation in correlation values exists in the reviewed studies. The correlations were moderate and demonstrate that some of the technology-based dietary assessments can provide good estimates of carotenoid intake when compared to objective biomarkers of carotenoids. More validation studies that use technology-based dietary assessment methods with comprehensive nutrition reporting are required.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-6643/9/2/140/s1, Table S1: Study Quality.

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Conflicts of Interest: The authors declare no conflict of interest.

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