Développement et validation d'outils méthodologiques de mesure de l'adhésion aux recommandations nutritionnelles

Thèse

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Résumé

Les recommandations nutritionnelles visent l'amélioration de la qualité alimentaire par la promotion de saines habitudes. Les enquêtes de santé nous confirment toutefois que ces recommandations sont mal comprises et que le concept de qualité alimentaire crée de la confusion chez plusieurs personnes. L'objectif de ce projet était de développer et de valider deux outils visant à mesurer la qualité de l'alimentation. Le premier est un rappel de 24 heures sur plateforme web totalement automatisé qui vise à faciliter la collecte d'information des chercheurs en nutrition. Les stratégies de validation déployées impliquent l'observation directe de la prise alimentaire chez une soixantaine de sujets, la comparaison des aliments rapportés avec une autre technique bien établie et l'analyse de marqueurs sanguins reflétant certains apports alimentaires chez 150 sujets ainsi que la comparaison des apports avec des marqueurs reconnus de la santé métabolique chez un troisième groupe de près de 1000 sujets. Les travaux réalisés tendent à démontrer un bon niveau de validité pour la mesure des apports en énergie et en nutriments ainsi que pour décrire la qualité de l'alimentation. Le deuxième outil est un outil de dépistage qui a été développé en identifiant les choix alimentaires prédicteurs d'une bonne qualité alimentaire. Une séquence de quatre à six questions est dictée par un algorithme et chacune d'elles demande oui ou non comme réponse. Nos analyses ont mis en lumière que ce nouvel outil avait la spécificité et la sensibilité nécessaire pour servir à identifier les individus ayant des habitudes alimentaires sous-optimales. Il sera mis à la disposition des médecins de famille et des autres intervenants en première ligne afin de faciliter l'identification des individus dont la qualité alimentaire pourrait être optimisée et le référencement vers des nutritionnistes. Enfin, plusieurs réflexions plus larges sur la validité de la mesure des apports alimentaires ainsi que sur la définition de la qualité de l'alimentation ponctuent cet ouvrage.

Abstract

Dietary recommendations are aimed at improving food quality by promoting healthy habits. However, health surveys confirm that these recommendations are poorly understood and that the concept of food quality creates confusion for many people. The objective of this project was to develop and validate two tools aimed at measuring food quality. The first one is a fully automatic web-based 24-hour dietary recall that aims to facilitate data collection for researchers in the field of nutrition. The validation strategies deployed involve direct observation of food intake in around sixty subjects, comparison of reported intakes with another well-established technique and analysis of blood markers reflecting specific dietary intakes in 150 subjects as well as comparison of food intakes with recognized markers of metabolic health in a third group of nearly 1000 subjects. The work carried out tends to demonstrate a good level of validity for measuring energy and nutrient intakes as well as for describing diet quality. The second tool is a screening tool that has been developed by identifying food choices predicting good nutritional quality. A sequence of four to six questions is dictated by an algorithm and each of them can be answered by yes or no. Our analyzes revealed that this new tool had the adequate specificity and sensitivity to be used to identify individuals with suboptimal eating habits. It will be made available to family physicians and other primary care workers to facilitate the identification of individuals whose food quality could be improved and the referral to nutritionists. Finally, broader reflections on the validity of the measurement of food intake and on the definitions of diet quality are found throughout this thesis.

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Liste des abréviations

AHEI: Alternative healthy eating index
AMPM: Automated multiple pass method
ASA24: Automated self-administered 24-hour dietary assessment tool
BMI: Body Mass Index
BMR: Basal metabolic rate
BW: Body weight
CART: Classification and regression tree
CFG: Canada's food guide
C-HEI 2007: Canadian Healthy Eating Index 2007
DEE: Daily energy expenditure
DLW: Doubly labelled water
DP: Dietary pattern
EAR: Estimated average requirement
FFQ: Food frequency questionnaire
FM: Fat mass
FR: Food record
GAC: Guide alimentaire canadien
HEI: Healthy eating index
HOMA-IR: Homeostasis model for insulin resistance
HPLC: High performance liquid chromatography
INAF: Institute of nutrition and functional food
IQR: Interquartile range
Kcal: Kilocalorie
MetS: Metabolic syndrome
Modified C-HEI: Modified Canadian Healthy eating index 2007
NHANES: National health and nutrition examination survey
NPV: Negative predictive value
PCA: Principal component analysis
PPV: Positive predictive value
R24W : Automated web-based 24-hours dietary recall
rEI: Reported energy intake
ROC: Receiving Operating Characteristic
RRR: Reduced rank regression
SD: Standard deviation
STROBE-nut: Strengthening Reporting of Observational Studies in Epidemiology – Nutritional epidemiology
TG: Triglycerides
USDA: United States Department of Agriculture
VF: Vegetables and fruit
WC: Waist circumference
webFFQ: web-based food frequency questionnaire

À mon papa qui a toujours été tellement fier de moi et qui m'a donné le droit de croire que je pouvais réussir n'importe quoi.

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« La vie, c'est comme une bicyclette, il faut avancer pour ne pas perdre l'équilibre. »

Albert Einstein

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Avant-propos

Cette thèse de doctorat s'inscrit dans une programmation de recherche dirigée par ma superviseure Dre Simone Lemieux qui s'intitule : Adhésion aux recommandations visant la saine alimentation: identification des mesures, déterminants et interventions. Plus précisément, les projets que j'ai eu l'opportunité de développer composent le premier axe de cette programmation dont l'objectif est d'optimiser la mesure de l'adhésion à la saine alimentation.

Cette thèse inclut une introduction, un état des connaissances (chapitre 1), les objectifs et hypothèses (chapitre 2), six articles scientifiques (chapitres 3, 4, 5, 6, 7 et 8), une conclusion générale, de même qu'un article professionnel (annexe A).

Je présenterai dans cette section chacun des articles ainsi que ma contribution et celle des différents coauteurs et collaborateurs. Toutefois, je tiens, avant tout, à souligner l'implication exceptionnelle de ma directrice de thèse, **Dre Simone Lemieux**, professeure titulaire à l'École de nutrition de l'Université Laval dans l'élaboration et la révision de chacun des articles. **Dre Lemieux** est à l'origine de la réflexion initiale de la problématique de recherche et a été partie prenante dans l'élaboration et la réalisation de chacune des étapes du projet. Je dois aussi mentionner la contribution importante du **Dr Benoît Lamarche**, mon codirecteur de thèse ainsi que tous les investigateurs impliqués dans la programmation de recherche, notamment **Dre Julie Robitaille, Dre Marie-Claude Vohl** et **Dr Charles Couillard** qui ont participé activement aux discussions entourant la direction et l'évolution du projet. Enfin, il me faut souligner le rôle crucial joué par **Catherine Laramée**, professionnelle de recherche chargée de coordonner le projet de développement et de validation du nouvel outil d'évaluation nutritionnel. Sa maitrise du sujet et son expérience du terrain ont été des facteurs déterminants dans le succès de ce projet. Je tiens aussi à remercier chacun des participants des différents projets de recherche pour le temps et l'énergie investis.

Chapitre 3

Lafrenière J, Lamarche B, Laramée C, Robitaille J, Lemieux S. Validation of a newly automated web-based 24-hour dietary recall using fully controlled feeding studies. *BMC Nutr*. 2017;3:34.

Cet article, ainsi que les quatre suivants détaillent les processus de validation d'un nouvel outil d'évaluation nutritionnelle, le R24W. Il s'agit d'un rappel de 24 heures auto-administré et automatisé sur plateforme web qui permet l'évaluation des apports en énergie, macro et micronutriments tout en permettant le calcul automatique de scores de la qualité alimentaire. L'objectif spécifique de cet article était d'évaluer certaines fonctionnalités de l'outil, notamment les questions servant à guider les répondants dans le rappel de leurs apports et les images servant à préciser l'estimation des tailles des portions consommées. Les données utilisées pour ces analyses ont été récoltées dans le cadre de trois projets de recherche randomisés contrôlés à l'Institut sur la nutrition et les aliments fonctionnels (INAF). Ma contribution a été de développer le plan d'analyses statistiques en me basant sur la littérature scientifique, de faire les analyses et de rédiger l'article. **Catherine Laramée, Dre Julie Robitaille, Dr Benoît Lamarche** et **Dre Simone Lemieux** ont été impliqués dès les premières étapes de la conception du R24W. Ils ont contribué à élaborer le protocole d'analyses et ils ont révisé le manuscrit. Les professionnelles de recherche **Julie Maltais-Giguère, Amélie Charest** et **Iris Gigleux** ont coordonné les projets de recherche desquels sont issues les données analysées. Elles ont été d'un grand soutien pour regrouper les informations essentielles à cet article.

Chapitre 4

Lafrenière J, Laramée C, Robitaille J, Lamarche B, Lemieux S. Assessing the relative validity of a new, web-based, self-administered 24 h dietary recall in a French-Canadian population. *Public Health Nutr*. 2018 Jul;1–9.

Chapitre 5

Lafrenière J, Laramée C, Robitaille J, Lamarche B, Lemieux S. Relative validity of a web-based, self-administered, 24 h dietary recall to evaluate adherence to Canadian dietary guidelines. *Nutrition*. 2019 Jan 1;57:252–6.

Ces deux articles ont été rédigés suite à l'analyse des données de l'étude validation du R24W. Cette étude a été élaborée par **Dre Simone Lemieux, Dre Julie Robitaille et Dr Benoît Lamarche** et a été coordonnée par **Catherine Laramée**. Mon rôle dans ces deux publications a été de développer le plan d'analyses statistiques, de conduire les analyses et de rédiger les articles. Dans ces deux articles, les données nutritionnelles issues du R24W ont été comparées à celles de journaux alimentaires de trois jours. Étant donné que ceux-ci étaient complétés manuellement par les participants, quatre étudiantes au baccalauréat en nutrition se sont vu attribuer le mandat de codifier toutes les entrées dans les logiciels d'analyse nutritionnelle. Je tiens donc à remercier **Pascale Bélanger, Myriam Landry, Amélie Bergeron** et **Caroline Trahan** pour leur implication dans la réalisation de ce projet.

Chapitre 6

Lafrenière J, Couillard C, Lamarche B, Laramée C, Vohl MC, Lemieux S. Associations between self-reported vegetable and fruit intake assessed with a new web-based 24-hour dietary recall and serum carotenoids in free living adults: A validation study. *J Nutr Sci.* 2019 Aug 5;8:e26

Cet article est aussi issu de l'étude de validation du R24W. Cependant, cette fois, les données d'apports nutritionnels fournis par le R24W ont été comparées aux dosages sanguins de caroténoïdes. **Dr Charles Couillard** et **Dre Marie-Claude Vohl**, professeurs titulaires à l'École de Nutrition ont grandement contribué aux réflexions entourant l'inclusion de l'analyse des caroténoïdes sériques en tant que biomarqueurs de l'apport en légumes et fruits. Je tiens aussi à souligner le travail réalisé par **Tatiana Allore** dans le cadre de son projet de maitrise sous la supervision du Dr Couillard. Ce dernier a permis de jeter les bases des analyses réalisées dans le cadre de cet article. **Catherine Laramée, Dr Benoît Lamarche** et **Dre Simone Lemieux** ont, une fois de plus, contribué grandement à la genèse du projet de validation du R24W et ont été partie prenante des discussions entourant les différentes analyses. Mon travail fut d'élaborer le plan d'analyses statistiques, de faire les analyses et d'écrire l'article. Je dois aussi souligner la contribution de **Véronique Richard**, technicienne de laboratoire à l'INAF pour son travail minutieux dans la mesure des échantillons de caroténoïdes sériques.

<u>Chapitre 7</u>

Lafrenière J, Carbonneau É, Laramée C, Corneau L, Robitaille J, Labonté MÈ, Lamarche B, Lemieux S. Is the Canadian Healthy Eating Index 2007 an Appropriate Diet Indicator of Metabolic Health? Insights from Dietary Pattern Analysis in the PREDISE Study. *Nutrients*. 2019 Jul 14;11(7)

L'article présenté au **chapitre 7** illustre une démarche de réflexion visant à créer un nouveau score permettant à la fois d'évaluer l'adhésion aux recommandations nutritionnelles tout en prévoyant le risque de maladies chroniques liées à l'alimentation. Les données utilisées pour les analyses présentées dans cet article sont issues du projet PREDISE (Prédicteurs individuels, sociaux et environnementaux) coordonnée par **Louise Corneau**, professionnelle de recherche à l'INAF, **Élise Carbonneau**, étudiante au doctorat sous la supervision de la Dre Simone Lemieux et de la **Dre Lemieux**. Ces dernières ont été d'un grand soutien pour l'obtention des données et leur interprétation. **Dre Julie Robitaille** et **Dr Benoît Lamarche** ont été impliqués dans les réflexions entourant la validation du R24W et la portée de ses analyses dès le début. Leurs idées ont guidé l'orientation du projet. **Catherine Laramée** a grandement contribué à implanter le calcul automatique du score Healthy Eating Index Canadien 2007 dans le R24W. Elle a été en contact avec les spécialistes derrière le développement des recommandations nutritionnelles à Santé Canada. Son apport dans l'élaboration du projet est manifeste. **Dre Marie-Ève Labonté** a développé une expertise dans l'analyse de patrons alimentaires au cours de ses études doctorales et s'est beaucoup intéressée aux questions de mesure de la qualité alimentaire lors son stage postdoctoral. Sa révision critique du manuscrit a été grandement pertinente. Au fil des discussions avec ma directrice, Dre Lemieux, j'ai développé l'idée originale de ce projet de recherche. J'ai utilisé les données issues de la cohorte PREDISE pour faire les analyses et j'ai rédigé l'article.

Chapitre 8

Lafrenière J, Harrison S, Laurin D, Brisson C, Talbot D, Couture P, Lemieux S, Lamarche B: Development and validation of a screener assessing diet quality in the French-speaking adults from Quebec. *Int J Behav Nutr Phys Act*. 2019 Aug 6;16(1):61

L'article présenté au **chapitre 8** est le résultat du développement et de la validation d'un outil de dépistage visant à identifier les individus présentant une qualité alimentaire sous-optimale en vue de les référer vers des services personnalisés en nutrition. Cet outil a vu le jour grâce une technique de prédiction statistique au sein d'une cohorte composée d'adultes ayant pris part à différents projets de recherches conduits par **Dr Benoît Lamarche, Dre Simone Lemieux** et **Dr Patrick Couture** professeur titulaire à la Faculté de médecine. L'outil a ensuite été validé dans une autre cohorte composée d'adultes plus âgés participant à une étude longitudinale sur la santé cardiovasculaire dirigée par **Dre Danielle Laurin** et **Dre Chantal Brisson**, toutes deux professeures titulaires à la Faculté de pharmacie et chercheures au Centre de recherche du CHU de Québec. Tous ces chercheurs ont donc contribué grandement à l'obtention des données et ont révisé scientifiquement l'article. L'idée originale du projet appartient au **Dr Lamarche**. **Stéphanie Harrison**, étudiante au doctorat sous la supervision du Dr Lamarche s'est beaucoup impliquée dans la classification et l'analyse des données dans le cadre de son projet de maitrise pour lequel une technique statistique similaire a été employée dans la même cohorte de développement, mais pour répondre à une autre question de recherche. **Dr Denis Talbot**, statisticien et professeur à la Faculté de médecine a été d'un soutien indéfectible dans l'analyse des données. Il a développé la programmation nécessaire au moyen du logiciel statistique R et a été disponible pour me guider à plusieurs étapes des analyses. Avec l'aide de Stéphanie et du Dr Talbot, j'ai réalisé les analyses statistiques nécessaires au développement et à la validation de l'outil et j'ai rédigé l'article.

Annexe 1

Lafrenière J, Couillard C, Lamarche B, Lemieux S. Les caroténoïdes sériques comme biomarqueurs : une stratégie pour améliorer la validité de l'évaluation alimentaire. *Can J Diet Pract Res.* 2017 Oct 3;79(1):23–7**.**

Cet article est une revue de la littérature portant sur l'utilisation des caroténoïdes sériques dans l'évaluation nutritionnelle. Il a été publié en français dans la Revue canadienne de la Recherche et de la pratique en nutrition. J'ai réalisé la lecture et la synthèse de la littérature scientifique et la rédaction de cet article. **Dre Simone Lemieux** et **Dr Benoît Lamarche** ont contribué à révision scientifique en s'appuyant sur leur expertise en évaluation nutritionnelle alors que **Dr Charles Couillard** a contribué à la révision sur la base de son expertise concernant les caroténoïdes.

Introduction

L'évaluation nutritionnelle est la pierre d'assise de la recherche en nutrition. C'est grâce à elle que nous pouvons mettre en association l'alimentation et la santé et proposer des recommandations basées sur des données probantes. Contrairement à plusieurs autres objets d'étude, il existe cependant peu de techniques robustes pour évaluer la prise alimentaire. Les chercheurs doivent se baser, depuis des décennies, sur les apports auto-rapportés des individus et établir des ajustements mathématiques pour en tirer des estimations réalistes de l'alimentation globale d'une personne ou d'un groupe. Il ne va pas sans dire que cette approche a reçu son lot de critiques avec les années (1). Les techniques d'évaluation ont toutefois évolué au gré des technologies et il est maintenant établi qu'elles doivent démontrer une validité adéquate avant d'être utilisées comme outil de recherche (2).

Bien que les données précises sur les apports alimentaires soient difficiles à obtenir, les autorités de santé publique se doivent de fournir aux citoyens des recommandations assez détaillées pour leur permettre de faire des choix alimentaires judicieux. Étant donné que la recherche, tout comme l'offre alimentaire évolue, il est indispensable de réviser les recommandations nutritionnelles régulièrement. Cette révision permet à la fois de réévaluer la pertinence scientifique des recommandations, mais aussi de contester les méthodes de diffusion et déterminer qui sont les individus qui adhèrent aux recommandations et qui sont ceux qui n'y adhèrent pas complètement.

Les prochains chapitres constituent le cœur de cette thèse. Le premier chapitre offrira un tour d'horizon de la littérature scientifique portant sur les méthodes d'évaluation alimentaire et leurs techniques de validation. De plus, la définition de la qualité alimentaire ainsi que l'élaboration des recommandations nutritionnelles seront abordées. Le second chapitre présentera les objectifs ainsi que les hypothèses testées. Enfin, les articles scientifiques se retrouvent aux chapitres 3 à 8 et une conclusion globale clôturera le tout.

Chapitre 1 – État des connaissances

1.1 Mesurer les apports alimentaires : contester les fondements et perfectionner les techniques

La science de la nutrition est à un moment décisif. En effet, un nombre grandissant d'articles scientifiques est publié à son sujet, tel que démontré par les statistiques de la plateforme de recherche Pubmed qui dénombrait 15 000 articles associés au terme « diet » en 2010 et près de 25 000 en 2019.

Pourtant, des voix s'élèvent dans la communauté scientifique pour critiquer les résultats des recherches nutritionnelles des dernières décennies (3). Les fondements de la collecte de données nutritionnelles, soit les outils de mesure de l'alimentation, sont au cœur du litige. En effet, les chercheurs utilisent le plus souvent des entrevues ou des questionnaires dont les données sont auto-rapportées pour mesurer la prise alimentaire (4). Bien que ces outils soient généralement validés avant de servir en recherche, ils demeurent sensibles à plusieurs biais, notamment des biais associés à la mémoire, à la désirabilité sociale (ou l'envie de se conformer à une norme en vigueur), à la réactivité (ou la modification d'un comportement sachant qu'il est analysé), à l'entrée de données ou à la variabilité des apports d'un jour à l'autre (5,6). De plus, pour être utilisées en recherche, les données recueillies avec les outils d'évaluation alimentaire doivent être converties en énergie et en nutriments selon les données présentes dans des tables de valeurs nutritives. Ces dernières sont parfois incomplètes ou représentent des aliments différents de ceux consommés par les répondants (7). Au Canada, la base de données utilisée comme référence est le Fichier canadien sur les éléments nutritifs (8). Les valeurs nutritives qui y sont présentées sont souvent tirées du fichier américain (*United States Department of Agriculture*) et sont mises à jour de manière ponctuelle. Dans une étude récente, Parpia et al. ont observé que 60% des valeurs nutritives présentées dans le Fichier canadien sur les éléments nutritifs dataient d'avant l'an 2000 et que l'information sur certains aliments n'avait pas été mise à jour depuis 1983 (9). Les chercheurs ont aussi noté que la teneur en minéraux dosée chimiquement de 20% à 40% des échantillons de viandes, volailles et poissons testés présentait des écarts notables par rapport aux valeurs présentées dans le Fichier canadien sur les éléments nutritifs (9). Ces éléments contribuent à entretenir un doute sur la validité des informations obtenues dans des projets de recherche en nutrition.

Les chercheurs en nutrition ont longtemps utilisé les données issues d'outils de mesure de l'alimentation sans trop contester leur fiabilité. Cependant, certains outils biochimiques permettent maintenant d'envisager l'ampleur de l'écart entre les apports auto-rapportés et les apports réels. En effet, l'utilisation de marqueurs sanguins de la prise alimentaire a permis d'observer que les adultes rapportaient en moyenne 18-23% moins d'énergie que ce qu'ils dépensaient (10). Dans certains cas, l'écart quotidien pouvait atteindre 500 kcal/jour (11). Ces écarts sont attribuables autant à une réduction des apports alimentaires pendant la période à l'étude qu'à une déclaration inadéquate des aliments consommés (12). Les marqueurs sanguins indiquent aussi que les protéines sont sous-rapportées dans une moins grande proportion que l'énergie, ce qui suggère que les glucides et/ ou les lipides sont quant à eux systématiquement sous-rapportées (13,14). L'utilisation de caméras portatives a aussi permis de déceler que les condiments et les collations sont les aliments les plus souvent omis lors du rappel de l'alimentation (15) ce qui entraîne une évaluation inadéquate des nutriments qu'ils contiennent. De plus, des analyses de variance et de régressions ont permis d'identifier les caractéristiques des individus qui sous-déclarent leurs apports dans une plus grande proportion. Ce sont les sujets plus jeunes (16), en surpoids (17), ayant un niveau socio-économique et un degré de scolarité plus faibles (18) qui tendent à rapporter des apports alimentaires inférieurs à leurs apports réels. Chez les femmes, celles ayant un score élevé de désirabilité sociale sont aussi celles qui sous-déclarent davantage leurs apports (19). Les individus qui tendent à sous-rapporter leurs apports négligent plus souvent certains groupes alimentaires tels que les frites, les sucreries, les gâteaux et les pâtisseries ce qui contribue à surévaluer leurs apports en protéines par rapport à leur apport en glucides et/ ou en lipides (20). Mieux connaitre les limites méthodologiques des différents outils de mesure de l'alimentation nous permet de contester leurs fondements, mais aussi d'envisager d'en optimiser le fonctionnement afin de les rendre plus fiables.

Loin de croire que la recherche en nutrition est une quête vaine, de nombreux chercheurs ont vu en cette prise de conscience, l'opportunité de revoir et de moderniser leurs techniques d'évaluation alimentaire (7). C'est ainsi qu'une panoplie de nouveaux outils ont été développés. Ceux-ci utilisent les avantages de la technologie pour atténuer les biais connus (21) et permettent de représenter des profils de participants plus variés que les outils traditionnels (22). Les plateformes web permettent aussi une analyse en temps réel des réponses enregistrées ce qui accélère grandement le traitement des données en plus d'uniformiser les méthodes et de limiter les oublis ou les réponses incohérentes (23). Une attention plus grande est désormais portée sur le processus de validation. Ces nouveaux outils doivent démontrer que leurs observations sont robustes par une analyse comparative avec un autre outil ne partageant pas les mêmes biais, mais aussi avec des biomarqueurs de la prise alimentaire (24–26).

1.2 Valider les outils de mesure de l'alimentation : une démarche à standardiser

Les résultats de recherche en nutrition devraient systématiquement impliquer le descriptif des outils d'évaluation alimentaire utilisés ainsi que leur méthode de validation.

La validité est la caractéristique d'un outil qui mesure ce qu'il est conçu pour mesurer (27). La validité peut être évaluée de différentes manières. Il est toutefois difficile d'évaluer la validité absolue d'un outil de mesure de la prise alimentaire étant donné que le contexte de recherche peut rarement permettre une mesure exacte de l'alimentation dans un contexte représentatif de la vraie vie. On s'intéresse le plus souvent à la validité relative qui se fait par comparaison avec l'outil connu qui dispose de la meilleure validité démontrée. Cet outil est alors considéré comme la mesure étalon (*Gold Standard* en anglais). Considérant les nombreux biais présents en évaluation alimentaire, on cherche souvent à établir une preuve de validité convergente qui s'exprime lorsque plusieurs tests différents tendent à démontrer le même concept (28). On distingue aussi la validité interne de la validité externe. La première représente l'absence de biais ou d'erreur systématique dans une mesure. Celle-ci est généralement préalable à la validité externe qui démontre dans quelle mesure les résultats peuvent être généralisés à une population ou un groupe n'ayant pas participé à l'étude (29,30).

La validité est souvent définie comme la combinaison de l'exactitude (correspondance avec la réalité) et de la précision. La précision (ou fiabilité, reproductibilité) est la caractéristique d'un outil qui permet d'obtenir des mesures suffisamment similaires lorsqu'il est utilisé à plus d'une reprise chez les mêmes individus dans les mêmes conditions. Il s'agit d'une mesure de la cohérence. On peut s'attarder à la cohérence dans le temps (test-retest), à la cohérence intra-évaluateur (lorsque le même évaluateur prend les mesures de façon répétée) et la cohérence inter-évaluateurs (lorsque différents évaluateurs prennent les mesures à une occasion ou de manière répétée). Plus un outil est précis, plus la variabilité entre les mesures répétées d'un même concept sera petite (26,28,30).

L'objectif d'une étude validation d'un outil de mesure de l'alimentation ne devrait pas être de déterminer simplement si ce dernier est valide et précis. Il devrait également permettre d'identifier les erreurs potentielles afin que les chercheurs en tiennent compte dans l'interprétation de leurs données. Il existe deux types d'erreurs. L'erreur aléatoire (*random error* en anglais) ne suit pas un patron précis. Plusieurs facteurs peuvent y contribuer, notamment la variation dans les apports d'un jour à l'autre. Cependant, la loi des grands nombres détermine que plus l'échantillon analysé est grand, plus les erreurs aléatoires tendent à s'atténuer ramenant la moyenne près de sa vraie valeur. Les erreurs aléatoires peuvent être relevées en testant la cohérence de l'outil dans le temps. L'objectif de ces études est d'évaluer l'envergure des erreurs aléatoires et de déterminer le nombre de mesures nécessaires pour en limiter l'impact sur la qualité de la mesure (26). L'erreur systématique, quant à elle, est une anomalie dans le fonctionnement d'un outil de mesure qui entraîne une erreur de la même force et dans la même direction à chaque utilisation. Ainsi, l'erreur persiste même avec un très grand nombre d'observations. Les erreurs systématiques sont plus difficiles à détecter puisqu'elles n'apparaissent pas dans une étude de reproductibilité. Il faut alors valider l'outil au moyen d'un autre outil dont la précision a déjà été prouvée (une mesure étalon). Les erreurs systématiques n'affectent pas les coefficients de corrélation, mais peuvent avoir un impact majeur sur les valeurs absolues mesurées, comme lorsqu'on s'intéresse à la proportion d'individus dont les apports en nutriments correspondent aux recommandations au terme d'une enquête nationale de santé (30).

Il n'existe pas, à l'heure actuelle, de méthode universelle de validation d'outil de mesure de la prise alimentaire. Les tests effectués et leur interprétation varient considérablement d'une étude à l'autre. Dans une revue portant sur 60 études de validation de questionnaires de fréquence alimentaire, Lombard et al. (2) ont dénombré un total de six tests statistiques différents permettant de déterminer la validité d'un outil. Dans la majorité des études, un à trois tests à la fois étaient utilisés. Toutes les études concluaient en une bonne validité de l'outil sans que des barèmes précis aient été établis au préalable. Lombard et al. ont donc choisi de proposer une stratégie standardisée pour représenter différentes facettes de la validité soit la cohérence, l'association et les biais au niveau individuel et au niveau d'un groupe. Les six tests relevés sont le coefficient de corrélation, le test-T pairé, le pourcentage d'écart, la classification-croisée (par tertiles, quartiles ou quintiles), le coefficient de Kappa pondéré et l'analyse du graphique Bland Altman. Pour chacun des tests, un critère de validité est proposé, basé sur la littérature disponible. Deux critères sont proposés pour la classification croisée (soit la proportion d'individus classés dans le même tertile, quartile ou quintile et la proportion d'individus classés dans des tertiles, quartiles ou quintiles opposés) ce qui donne un total de sept critères d'interprétation de la validité. Selon le résultat obtenu en fonction de chaque critère, les différentes facettes de la validité peuvent être catégorisées comme faibles, acceptables ou bonnes et la combinaison de tous les résultats peut ensuite être interprétée dans le contexte de la recherche (2).

Les biomarqueurs de la prise alimentaire

L'une des avancées notables dans le domaine de la validation d'outils de mesure de l'alimentation dans les dernières années est l'utilisation de biomarqueurs de la prise alimentaire. Bien que cette technique ne soit pas encore perfectionnée, plusieurs chercheurs défendent qu'elle représente la seule façon de valider un outil de mesure de la prise alimentaire puisqu'il s'agit d'une observation indépendante de l'apport réel. Cette science est encore jeune et tendra à se préciser avec le temps, mais elle apportera certainement un soutien important à la validation des outils de mesure de la prise alimentaire. Les biomarqueurs permettent de contourner les biais reliés aux participants (biais de mémoire ou de désirabilité sociale) et ils sont indépendants de l'interprétation culturelle et du niveau de littératie. Les écarts entre les dosages et les apports alimentaires réels sont donc dus à la variabilité génétique et physiologique qui influence l'absorption et le métabolisme des nutriments ainsi qu'à l'analyse en laboratoire des biomarqueurs (26,27).

Il existe trois types de biomarqueurs. Les premiers sont des biomarqueurs de récupération qui sont associés directement à la consommation d'un nutriment. Par exemple, la dépense énergétique totale peut être estimée avec une grande précision chez des individus vivant librement grâce à la technique de l'eau doublement marquée. Elle consiste à administrer une dose connue d'eau (H_2O) marquée des isotopes stables ^{18}O et ^{2}H. Sachant que le ^{18}O sera éliminé du corps sous forme d'eau et de dioxyde de carbone alors que le ^{2}H ne sera éliminé que sous forme d'eau, la différence entre les taux d'élimination des deux atomes permet de déterminer avec précision la quantité de dioxyde de carbone (CO_2) produite par les cellules du corps. Celle-ci peut ensuite être convertie en kilocalories (kcal) dépensées grâce au coefficient respiratoire (34,35). L'excrétion urinaire quotidienne d'azote est quant à elle un biomarqueur reconnu de l'apport en protéines (36). Enfin, les taux urinaires de sodium et de potassium sont les indicateurs de leur consommation. On appelle le deuxième type de biomarqueur, biomarqueurs prédictifs. Ce sont des composés dérivés de produits alimentaires qui peuvent être dosés en quantité proportionnelle à leur consommation dans le sang ou l'urine, par exemple, le fructose ou le sucrose urinaire (6). Enfin, le troisième type de biomarqueurs est appelé biomarqueurs de concentration. Ceux-ci peuvent aussi être dosés dans le sang ou l'urine ou encore être prélevés dans certains compartiments du corps tels que le tissu adipeux et les cheveux, puis corrèlent avec les apports alimentaires sans les prédire directement (6). Selon leur métabolisme, ils peuvent être des indicateurs des apports nutritionnels à court, moyen ou long terme. Les caroténoïdes, des pigments d'origine végétale présents dans plusieurs légumes et fruits sont des biomarqueurs alimentaires de concentration fortement étudiés. Les six plus fréquemment observés sont le lycopène, le β-carotène, l'α-carotène, le β-crypthoxanthine, la lutéine et la zéaxanthine (37). De nombreuses études ont démontré l'association entre les taux sériques de caroténoïdes et les apports en légumes et fruits (38–41). Entre autres, dans une récente étude réalisée dans nos laboratoires, les mesures plasmatiques de caroténoïdes de 350 adultes ayant pris part à des études où l'alimentation était totalement contrôlée ont été analysées et comparées à leur apport en légumes et fruits (32). Les diètes à l'étude fournissaient de 7 à 21 portions de légumes et fruits par jour en moyenne. Les taux sanguins de β-crypthoxanthine, de lutéine et de zéaxanthine ont démontré une association significative avec le contenu en légumes et fruits des différentes diètes consommées par les participants (32). Burrows et al. ont conduit deux revues systématiques de la littérature portant sur l'utilisation des caroténoïdes sériques dans la validation d'outils traditionnels de mesure de l'alimentation (42) et des outils utilisant des supports technologiques (43). Au total, près de 160 articles ont été répertoriés. En somme, l'association entre les caroténoïdes sériques et l'apport en légumes et fruits est généralement modeste, mais significative avec des coefficients de corrélation se situant le plus souvent entre 0.20 et 0.30. Prenant en compte la grande variabilité dans les contenus en caroténoïdes de différents légumes et fruits, il est généralement suggéré d'additionner les dosages de différents caroténoïdes et de certains autres composés tels que la vitamine C et les phénols afin d'obtenir un indicateur de la consommation de légumes et de fruits (44–46).

1.3 Tour d'horizon des outils utilisés pour la mesure de l'alimentation

L'observation directe

Dans le cadre de projets de recherche, l'alimentation peut être directement analysée en demandant aux sujets de rapporter un duplicata de tous leurs repas au laboratoire. Cette technique nécessite un certain investissement de la part des sujets, mais permet d'éliminer le biais de mémoire. Elle est très utile pour évaluer l'impact de contaminants environnementaux par exemple. Cependant, les coûts engendrés par l'analyse nutritionnelle grimpent rapidement avec le nombre de sujets impliqués ce qui limite grandement son utilisation. Les risques d'erreurs systématiques sont faibles et les erreurs aléatoires sont assez bien contrôlées si les sujets répondent aux consignes données (47).

Le journal alimentaire

Le journal alimentaire est un outil servant à collecter des informations sur tous les aliments et les boissons consommées au cours d'une période d'une journée ou plus. Le nombre de jours de collecte doit être déterminé en fonction des objectifs de l'étude. Cependant, il a été suggéré qu'un minimum de trois jours était nécessaire pour obtenir un portrait fiable des habitudes alimentaires. Un journal de sept jours consécutifs est souvent utilisé, ce qui permet d'inclure des jours de fin de semaine. Par contre, certains chercheurs rapportent que la qualité des informations recueillies est altérée lorsque le journal doit être rempli plus de quatre jours consécutifs (48). Il s'agit d'un outil auto-rapporté où le participant note ce qu'il consomme sans suivre un format préétabli. Habituellement, les répondants sont encouragés à écrire le plus de détails possible pour aider les chercheurs à bien identifier les aliments consommés. Grâce à ce format ouvert, les risques d'erreurs systématiques sont très faibles. Le journal peut être rempli au fur et à mesure ce qui limite le biais de mémoire. Pour obtenir des données de qualité, il est essentiel d'enseigner aux répondants comment bien rapporter ce qu'ils consomment. Il est important de souligner que ce type d'outils demande du temps et des efforts aux répondants et que ces derniers doivent donc être très motivés ce qui peut engendrer un certain biais de sélection des sujets (47). Vu l'étendue des données auxquelles il donne accès, il est souvent considéré comme une mesure étalon (48,49) et par le fait même, il est utilisé comme comparatif pour la validation d'autres outils tels que le rappel de 24 heures et le questionnaire de fréquence alimentaire surtout lorsqu'une balance est remise aux sujets afin qu'ils rapportent le poids exact des aliments consommés (50). La richesse de l'information qu'il procure est aussi liée à son principal désavantage. En effet, cet outil demande beaucoup de temps aux sujets, surtout s'il est utilisé pendant plusieurs jours. Cela peut encourager les répondants à modifier leurs habitudes alimentaires ou à négliger de tout rapporter pour alléger le travail de rédaction. Ce phénomène, appelé biais de réactivité augmente le risque d'erreurs aléatoires. De plus, le journal alimentaire exige aux équipes de recherche beaucoup de temps pour l'analyse et l'entrée des données. Les sources d'erreurs sont aussi attribuables à l'interprétation du journal par le chercheur ou à la précision du logiciel permettant l'analyse (47,51).

Le questionnaire de fréquence alimentaire

Le questionnaire de fréquence alimentaire contient un nombre bien précis de questions fermées servant à quantifier la fréquence et parfois la taille des portions de certains aliments consommés dans les dernières semaines ou les derniers mois ou de la dernière année. Il porte souvent sur certains aspects spécifiques de l'alimentation en fonction des besoins d'un projet de recherche et ne représente pas nécessairement la diète dans son ensemble (52). Le questionnaire est auto-administré le plus souvent et représente la moyenne des apports pour certains groupes alimentaires ou certains nutriments de la période couverte. Il n'a donc pas à être rempli à plusieurs reprises pour améliorer sa validité. Les questions portant sur les apports passés, il s'appuie donc sur la mémoire générique. Les risques d'erreurs systématiques sont assez élevés puisque le format des questions influence directement les réponses obtenues (47). La majorité des questionnaires de fréquence alimentaire sont développés en modifiant un questionnaire existant (52). Ainsi, si certains groupes d'aliments sont absents ou si les options de tailles de portions ou de fréquence de consommation sont incomplètes, l'interprétation des apports nutritionnels sera biaisée. Plusieurs chercheurs ont d'ailleurs remis en question l'utilisation des questionnaires de fréquence alimentaire en observant que certaines associations entre l'alimentation et l'incidence de cancer qui étaient perceptibles dans des études avec cas témoins ne l'étaient pas dans des études de cohortes utilisant des questionnaires de fréquence alimentaire (53). Le questionnaire de fréquence peut être validé en comparant les apports relevés avec ceux d'un journal alimentaire ou de plusieurs rappels de 24 heures administrés pendant la période couverte par le questionnaire (54).

Le rappel de 24 heures

Le rappel de 24 heures est généralement administré par un intervieweur et permet de tracer un portait détaillé de la dernière journée. Cet outil offre la possibilité d'obtenir des détails supplémentaires par rapport au journal alimentaire puisque l'interviewer peut questionner directement le participant. L'outil doit être utilisé à plus d'une reprise et selon un horaire aléatoire pour tenir compte des variations journalières dans la prise alimentaire (55). La fréquence des mesures nécessaires dépend de la variabilité attendue, des nutriments d'intérêt et de l'objectif de l'étude. Certains auteurs suggèrent que trois rappels permettent de tracer un portrait adéquat des apports en énergie (56) alors que d'autres relèvent que pour certains sous-groupes tels que les femmes en surpoids, jusqu'à 15 jours de rappels aléatoires seraient nécessaires (57). Si l'objectif de l'étude est de décrire généralement les habitudes d'une population, un seul rappel peut être suffisant. Pour estimer la distribution des apports, deux rappels sont alors nécessaires pour une partie de la population à l'étude. Lorsque l'association entre l'alimentation et la santé est visée, l'administration de quatre à six rappels permet d'obtenir un meilleur pouvoir statistique (27). Référant aux 24 dernières heures, cet outil fait nécessairement appel à la mémoire à court terme. Le risque d'erreurs aléatoires est plus important que le risque d'erreurs systématiques étant donné que les questions sont générales et laissent au participant la place pour donner plus ou moins d'informations (58).

Bien que de nombreux chercheurs aient priorisé l'utilisation du questionnaire de fréquence alimentaire au fil des ans, surtout dans le contexte d'études épidémiologiques, l'émergence de nouvelles technologies informatiques a permis le développement de rappel de 24 heures auto-administrés et automatisés qui répondent aux besoins d'efficacité et d'efficience des chercheurs (59,60). Ce type de questionnaire a démontré une lecture de la prise alimentaire moins biaisée que le questionnaire de fréquence alimentaire (14,24,61,62) particulièrement si la technique de collecte des informations utilisée a été validée. C'est le cas de l'*Automated Multiple Pass Method* (AMPM) développée par le *United States Department of Agriculture* (USDA). Cette méthode mise sur l'utilisation d'énoncés standardisés et de plusieurs étapes de questionnements qui favorisent les associations entre les aliments rapportés et ceux fréquemment oubliés. L'heure et le lieu du repas sont ainsi demandés afin de le situer dans la journée et des détails descriptifs sont proposés pour préciser les choix (63). Lorsque comparée à un biomarqueur de l'apport énergétique, l'AMPM a démontré un taux de sous-déclaration de 11% (64). Sachant que le coefficient de variation dans les apports quotidiens est estimé à environ 13% sur une période de 7 jours, une erreur d'estimation de cette ampleur peut être considérée comme acceptable (34). De plus, les outils développés sur plateforme web peuvent compter sur l'ajout d'un support visuel améliorant la précision dans l'estimation des portions (65,66). En effet, l'illustration de plusieurs options de tailles présentées en même temps réduit l'erreur d'estimation (67,68).

L'ASA24

L'automated self-administered 24-hour dietary assessment tool (ASA24) est un rappel de 24 heures sur plateforme web développé par l'Institut américain sur le cancer en 2009 et qui est basé sur les travaux du docteur Tom Baranowski. Depuis son lancement, l'ASA24 a été mis à contribution dans plus de 5100 études et plus de 400 000 rappels ont été enregistrés sur la plateforme. L'ASA24 a été développé en utilisant le modèle de l'AMPM. Les répondants doivent d'abord rapporter les aliments consommés par repas pour toute la journée puis ajouter les détails (description des aliments, méthode de cuisson, taille des portions) pour chacun des aliments. Des questions visant à récolter plus de détails et des suggestions d'aliments fréquemment oubliés sont finalement proposées. Le logiciel est disponible sans frais pour les chercheurs et une version canadienne est également disponible depuis peu avec une interface en français et en anglais pour les utilisateurs. Dans cette version, l'offre d'aliments a été modifiée pour refléter le marché canadien, les tailles de portions utilisent le système métrique à la place du système impérial, la valeur nutritive issue du Fichier canadien sur les éléments nutritifs est utilisée à la place de celle provenant de la base de données américaine pour plusieurs aliments et une estimation des portions déterminée par le Guide alimentaire canadien (GAC) 2007 est disponible (69).

Plusieurs études de validation ont été conduites sur l'ASA24 depuis son lancement. D'abord, Thompson et al. (70) ont comparé l'évaluation alimentaire produite avec l'ASA24 à celle d'un rappel de 24 heures administré par un intervieweur en utilisant la méthode de l'AMPM. Ils ont démontré que pour l'énergie ainsi que pour 87% des groupes alimentaires ou nutriments testés, l'apport évalué était comparable entre les deux outils. De plus, 70% des répondants préféraient l'ASA24 et le taux de rétention des participants étaient aussi supérieur avec cette méthode. Kirkpatrick et al. (71) ont aussi comparé l'ASA24 et un rappel de 24 heures administré par un intervieweur, mais dans un contexte particulier où les sujets étaient invités à consommer des aliments issus d'un buffet. Tous les mets étaient pesés avant et après leur consommation permettant aux chercheurs de comptabiliser les apports réels à l'insu des participants. Cette méthode a permis à Kirkpatrick et ses collègues de comparer la proportion d'aliments bien rapportés (consommés et rapportés), d'aliments exclus (consommés et non rapportés) ainsi que d'inclusion (rapportés, mais non consommés) au moyen de l'ASA24 et du rappel administré par un interviewer. Bien que les sujets dont les apports ont été analysés au moyen du rappel de 24 heures administré par un interviewer ont bien rapporté quelques aliments de plus que ceux dont les apports étaient analysés avec l'ASA24 (83% vs 80%), les deux méthodes semblaient se comparer de manière équivalente aux apports réels mesurés par les chercheurs. Enfin, Park et al. (72) ont conduit une étude où les apports en énergie, protéines, sodium et potassium issus de six rappels de 24 heures obtenus via la plateforme ASA24, d'un journal alimentaire de quatre jours et d'un questionnaire de fréquence alimentaire étaient comparés à des marqueurs urinaires de l'alimentation. De manière générale, les apports évalués au moyen des rappels de 24 heures étaient plus près des apports mesurés au moyen des biomarqueurs que les données obtenues avec les autres outils bien qu'ils étaient tous sous-estimés de 4 à 16%.

Une version adaptée de l'ASA24 a aussi fait l'objet de validation dans une cohorte d'enfants de 9 à 11 ans. Alors que l'outil a démontré une moins bonne représentation des apports qu'un rappel de 24 heures administré par un interviewer, il en est surtout ressorti que les apports alimentaires sont difficiles à analyser chez cette clientèle (73).

Le R24W

Le rappel de 24 heures auto-rapporté et automatisé sur plateforme web (R24W) a été développé par notre équipe de recherche (74). Il contient une liste de 2670 aliments répartis en 16 catégories et 98 sous-catégories élaborées par un groupe de nutritionnistes spécialisé en évaluation alimentaire ainsi qu'en consultant le Fichier canadien sur les éléments nutritifs. Un total de 1491 photographies standardisées de différentes tailles de portions a été pris pour faciliter la sélection de la portion consommée. Ainsi, les aliments de forme indéfinie (riz, pâtes, yogourt, etc.) et ceux de forme définie (pizza, gâteau, fromage, etc.) sont représentés par quatre images, les jus et le lait par huit images alors que les items de forme unique avec un seul format (poire fraiche, etc.) sont présentés par un menu déroulant sans image et ceux avec plusieurs formats (muffin, tortillas, etc.) par deux ou trois images (74). À la fin de chaque repas et lorsque toute la journée a été rapportée, une liste d'aliments fréquemment oubliés est proposée. Elle inclut: jus, lait, boissons gazeuses, eau, autres boissons non alcoolisées, vin, bière, autre boissons alcoolisées, chocolat, bonbons, crème glacée, pâtisseries et autres sucreries, croustilles, bretzels, popcorn, noix mélangées et autres grignotines salées, légumes et fruits, fromage, pain et autres produits de boulangeries et autres aliments et boissons. Toutes les étapes de la création du R24W sont décrites dans le mémoire de maitrise de Simon Jacques (75). Le R24W a été développé pour pallier l'absence d'outils d'évaluation alimentaire automatisés en français et adapté à la réalité québécoise. En effet, la version française de l'ASA24 a été rendue disponible quelques années après le lancement du R24W. Le R24W s'inspire principalement de l'ASA24, mais aussi d'autres outils développés dans différentes régions du globe, notamment le Dietday aux États-Unis (76), l'outil Nutrinet-santé en France (77) et le Myfood24 en Grande-Bretagne (78). Bien que la méthode de collecte d'information soit aussi basée sur l'AMPM, le R24W se distingue de l'ASA24 sur plusieurs aspects. D'abord, les répondants sont invités à sélectionner un repas (déjeuner, dîner, souper ou collation) puis à y inscrire les aliments consommés ainsi que le détail de chacun de ces aliments. Des aliments complémentaires sont immédiatement proposés afin de recueillir toute l'information sur ce repas au lieu d'y revenir à une étape subséquente comme c'est le cas avec l'ASA24. Un nombre illimité de repas peut être ainsi ajouté. Ensuite, en plus d'utiliser le Fichier canadien sur les éléments nutritifs comme base de données de référence, 632 nouveaux mets composés ont été inclus en utilisant les valeurs nutritives de recettes populaires au Québec sélectionnées à partir des cinq premiers résultats obtenus lors d'une recherche Google (74). Ces mets sont donc plus représentatifs de ceux consommés par les répondants québécois. De plus, le logiciel a été programmé pour répondre aux besoins précis des chercheurs de notre équipe. Ainsi, lors de son administration, le R24W est envoyé aux participants par courriel automatiquement à des dates aléatoires dans les limites proposées par les chercheurs (par exemple trois jours de semaine et un jour de fin de semaine sur une plage de quatre semaines). Le rappel peut être entièrement complété au moyen d'un ordinateur ou encore d'un téléphone intelligent. Suite à la collecte des données, le R24W permet de produire des rapports comptabilisant les portions issues du GAC 2007, mais aussi des scores de qualité alimentaires validés tels que le *Healthy Eating Index* Canadien 2007 (C-HEI 2007) (79) et le score méditerranéen (80), et ce, sans avoir recours à une formule statistique subséquente. Le R24W est d'ailleurs mis à jour régulièrement pour répondre aux questions émergentes des chercheurs. Par exemple, la teneur en sucres libres et en sucres naturellement présents dans les aliments a récemment été ajoutée à la liste des nutriments produite par l'outil (81).

1.4 Sélectionner l'outil de mesure de l'alimentation le plus approprié

Les chercheurs en nutrition disposent de différents outils pour évaluer la prise alimentaire. La sélection du bon outil n'est pas une mince tâche. Il doit tenir compte des ressources disponibles, du nombre de sujets participant à l'étude et du type d'information recherchée. Afin de tenir compte des différents enjeux, l'Institut national sur le cancer américain propose un guide pour diriger les chercheurs vers l'outil d'évaluation alimentaire le plus approprié à leurs questions de recherche. Il est accessible en ligne à l'adresse : https://dietassessmentprimer.cancer.gov/approach. Toutefois, les données disponibles suggèrent que plusieurs chercheurs négligent le processus de sélection de leur outil de mesure de l'alimentation, ce qui contribue à produire des données nutritionnelles dont la validité est questionnable. Kirkpatrick et al. ont conduit une revue détaillée des outils d'évaluation alimentaire auto-rapportés utilisés dans les études canadiennes (4). Ils rapportent que 64% des études publiées entre 2009 et 2014 soutiraient leurs analyses nutritionnelles d'un questionnaire de fréquence alimentaire ou d'un outil de dépistage alors que le journal alimentaire et le rappel de 24 heures étaient les outils privilégiés dans 18 et 14% des études respectivement. La revue fait principalement état du peu d'informations rapportées par les auteurs sur les raisons entourant le choix de la méthode de mesure de l'alimentation ainsi que de l'impact de ce choix sur l'interprétation de leurs données. De même, ils rapportent que les outils sont parfois inadaptés à la population ciblée, le devis de l'étude et les composés nutritionnels étudiés (4). En somme, les chercheurs semblent utiliser les différents outils d'évaluation nutritionnelle de manière interchangeable sans remettre en question la validité des résultats qu'ils produisent. Cette démarche est sérieusement discutable dans le contexte actuel où les biais associés aux différents outils sont bien connus (82).

Pour faire face à ce type de problèmes, un groupe de plus de cinquante experts en épidémiologie a récemment proposé un ensemble de vingt-quatre recommandations pour optimiser la présentation des données issues de la recherche en nutrition. Le document intitulé "Strengthening Reporting of Observational Studies in Epidemiology – Nutritional epidemiology (STROBE-nut) statement" vise à offrir un guide pour rendre les publications en épidémiologie nutritionnelle plus complètes et plus transparentes. Concernant les méthodes d'évaluation alimentaire, les experts suggèrent que les publications décrivent systématiquement l'outil utilisé (méthode d'évaluation de la taille des portions, nombre de jours et d'items recueillis, méthode d'administration et de contrôle de la qualité, méthode d'intégration de l'apport en suppléments) ainsi que la base de données nutritionnelles de référence et le processus de validation de l'outil. Ensuite, ils proposent que les publications mentionnent les biais associés à l'outil sélectionné et la méthode pour tenir compte de ces biais. Enfin, les experts recommandent que toutes les analyses et tous les ajustements soient décrits et expliqués notamment en ce qui a trait à l'exclusion de sujets pour des données manquantes ou sous-estimées (6). Bien qu'il soit impossible d'éliminer les biais associés aux outils d'évaluation alimentaire, le fait de les présenter et d'en tenir compte dans l'interprétation des données nutritionnelles rendra certainement la recherche plus cohérente et informative.

1.5 Définir et mesurer la qualité de l'alimentation

Bien que les outils d'évaluation alimentaires puissent décrire les apports en énergie et en nutriments, cette lecture de l'alimentation est considérée comme réductionniste par plusieurs chercheurs. En effet, les nutriments peuvent avoir des effets différents sur la santé en fonction des autres nutriments ou composés bioactifs avec lesquels ils sont consommés. Considérant que les nutriments sont véhiculés par des aliments et que les apports en aliments sont modulés par de nombreux facteurs socioculturels (revenus, préférences, croyances, traditions, environnement…) il est très important de pouvoir mesurer la diète dans une perspective globale. De plus, un changement alimentaire n'est jamais isolé. Il se manifeste généralement par une substitution ou une compensation impliquant d'autres aliments (83). Les chercheurs en nutrition s'intéressent ainsi de plus en plus à la caractérisation des patrons alimentaires associés à la santé (84,85). Ceux-ci permettent de tenir compte de l'effet synergique des aliments au lieu de se limiter à l'étude de leurs effets isolés ou de celui de leurs composantes nutritionnelles (86).

Les habitudes alimentaires varient grandement à travers le monde. Toutefois, certaines habitudes alimentaires semblent être associées de manière consensuelle à la santé. De nombreuses revues systématiques et méta-analyses récentes démontrent de façon constante que la consommation importante de légumes et de fruits est associée à une réduction du risque de cancer, de maladies cardiovasculaires et de la mortalité (87–89). L'Organisation mondiale de la santé reconnait aussi l'alimentation comme l'un des principaux facteurs de protection aux maladies chroniques (90). Considérant le poids de ces maladies sur le système de santé, certains chercheurs estiment même l'impact économique de la faible qualité alimentaire des Canadiens à plus de 13 milliards de dollars en 2015 (91). Les études de validation des outils de mesure de l'alimentation se concentrent souvent à évaluer leur habileté à mesurer l'énergie et les nutriments ce qui limite l'interprétation de leur utilisation pour caractériser la qualité de l'alimentation au sens plus large. Il est toutefois essentiel de développer et valider des outils qui permettent de mesurer les concepts-clés de la qualité alimentaire afin d'en suivre l'évolution à travers le temps.

1.5.1 Les recommandations nutritionnelles au Canada

Le GAC est le véhicule des recommandations alimentaires au Canada. Il a été mis à jour en 2019 suite à une revue approfondie de la littérature scientifique sur l'effet de l'alimentation sur la santé. Les données jugées pertinentes issues de publications d'organismes reconnus tels que l'Organisation mondiale de la santé, le World Cancer Research Fund International et le Dietary Guidelines Advisory Committee des États-Unis ont entre autres été consultés. Le fondement de la saine alimentation, tel quel décrit par Santé Canada dans les lignes directrices canadiennes en matière d'alimentation, est la consommation d'aliments de haute valeur nutritive (92). Ainsi, les légumes, les fruits, les grains entiers et les aliments protéinés – en priorisant ceux d'origine végétale – devraient être consommés de manière régulière. La consommation de viande rouge et de viande transformée devrait donc être limitée alors que les légumineuses, les noix et le soya devraient prendre plus de place dans l'assiette des Canadiens. De plus, les aliments contenant des lipides insaturés devraient remplacer progressivement les aliments contenant des lipides saturés et l'eau devrait être la boisson de premier choix. Ces recommandations sont associées à une réduction de la prévalence de maladies cardiovasculaires (93) et de cancer (94). Les lignes directrices canadiennes en matière d'alimentation mentionnent aussi qu'il faudrait réduire la consommation d'aliments transformés ou préparés qui augmentent les apports en sodium, en sucres libres ou de lipides saturés tels que les boissons sucrées et les produits de confiserie. Enfin, une troisième ligne directrice met en valeur l'importance du développement et du maintien des compétences alimentaires en matière de sélection et de préparation des aliments (92).

Étant donné que la version la plus récente du GAC a été publiée en 2019, soit après l'initiation des travaux de la présente thèse, il est pertinent de s'intéresser aussi au guide alimentaire précédent. Certains chapitres subséquents y référeront directement. La différence la plus marquante entre l'édition 2019 du GAC et la version publiée en 2007 est l'accent porté sur la prévention des maladies chroniques. En effet, dans l'édition 2007, la qualité alimentaire était définie tout d’abord comme un apport adéquat en nutriments, puis dans un deuxième temps, par des apports limitant le risque de maladies chroniques (95). Des recommandations précises visaient donc à ce que les Canadiens consomment les aliments leur permettant de combler tous leurs besoins en vitamines et minéraux en fonction de leur âge et de leur sexe (96). Ces recommandations ont été développées suite à un processus en deux étapes. D’abord, des composites nutritionnels ont été créés. Il s’agit d’unités de mesure de chacun des groupes alimentaires basés sur la consommation réelle dans la population canadienne. Ainsi, une unité du composite « fruits » représentait une portion standard de fruits dont la valeur nutritive était calculée en fonction la proportion des fruits les plus consommés par les Canadiens selon le sondage sur les dépenses alimentaires des Canadiens de Statistiques Canada ainsi que certaines bases de données provinciales. Ce composite pouvait avoir, par exemple, la valeur nutritive de 50% d’une portion d’orange, 25% d’une portion de pomme et 25% d’une portion de banane. À partir des composites de tous les groupes alimentaires, des diètes simulées représentatives des apports rapportés des différents groupes d’âge et de sexe au Canada ont été produites. Les recommandations en termes de portions de chacun des groupes alimentaires pour chacun des groupes d’âge et de sexe des Canadiens ont ensuite été déterminées en utilisant la valeur nutritive des différents composites alimentaires dans le but de produire des modèles de diètes où les besoins en nutriments étaient comblés. Le modèle final est donc très élaboré et recommande des apports précis et adaptés aux différents groupes d’âges et de sexe. Enfin, des recommandations additionnelles étaient précisées pour chacun des groupes afin de guider les utilisateurs à faire les meilleurs choix. Par exemple, le guide recommandait que les portions quotidiennes de légumes et de fruits incluent au moins une option verte foncée et une option orangée et que la moitié des portions de produits céréaliers soient faites de grains entiers (95).

Les deux dernières éditions du GAC visent la promotion d’une alimentation riche en légumes, en fruits et en grains entiers, mais se présentent dans des formats très différents. Dans le guide de 2019, on suggère de prioriser une variété d'aliments sains tous les jours pour favoriser des apports adéquats en énergie et en nutriments, mais aucune recommandation précise en termes de portions par jour n'est offerte. Les créateurs du guide ont voulu miser sur un modèle visuel plus simple sachant que les recommandations par portion étaient mal comprises par la population canadienne (97). À cet effet, une analyse publiée par Susan Barr en 2019 a démontré que la consommation d'aliments suggérés dans le modèle d'assiette santé du nouveau GAC 2019 dans les proportions adéquates pour couvrir les besoins en énergie de différents groupes d'âges et de sexe permettrait de combler les besoins de la grande majorité des nutriments importants. Les chercheurs relevaient cependant que la probabilité d'apports inadéquats en calcium et en vitamine D serait de plus de 50% dans la plupart les groupes (98).

Le nouveau GAC 2019 illustre les principaux consensus scientifiques actuels en matière de nutrition. Cependant, vu sa nouveauté, peu d'études se sont encore penchées sur son impact sur les habitudes alimentaires des Canadiens.

1.5.1 Les scores de qualité alimentaire

La qualité alimentaire se définit principalement par l'adhésion à un certain ensemble de recommandations alimentaires, par exemple, celles décrites dans le GAC. Ces dernières, issues de la littérature scientifique, évoluent constamment. Comme elles impliquent plusieurs dimensions, la mesure de l'adhésion à ces recommandations est un réel défi pour les chercheurs. Deux méthodes peuvent être utilisées pour procéder à l'évaluation de la qualité alimentaire. La première, plus théorique, implique le calcul de points associés au degré d'adhésion à certaines recommandations sélectionnées. Cette approche permet la création de scores nommés « a priori ». Il en existe au moins une vingtaine dans la littérature scientifique (99). Étant standardisés, ils peuvent être utilisés dans différentes populations et leurs résultats peuvent être comparés entre les études. Ils donnent aussi une indication du taux d'adhésion aux recommandations nutritionnelles en place (83). Cependant, ces scores fixes ne prennent pas en considération l'interaction entre différents groupes alimentaires ni les spécificités de différents groupes sociaux culturels. De plus, ils deviennent rapidement dépassés lorsque les recommandations changent. Dans une revue des scores de qualité alimentaire prédéfinis, Waijers et al. relatent que les auteurs ont dû prendre plusieurs décisions arbitraires notamment par rapport aux items inclus, aux valeurs de coupures et aux méthodes d'attribution des scores (100). Enfin, ces scores mesurent la qualité globale de l'alimentation. Ainsi, un score de 50% peut être attribué à deux individus ayant des habitudes très différentes. Il est donc essentiel de s'intéresser aussi à chacun des sous-scores afin d'interpréter quels changements spécifiques devraient être suggérés aux répondants (83). La deuxième méthode d'évaluation de la qualité alimentaire est plus intuitive. Elle repose sur la création de patrons alimentaires propres à une population. De ces patrons, on peut dériver des scores « a postériori » qui sont très spécifiques, mais souvent plus adaptés à des sous-groupes de la population. La méthode utilisée permet aussi de s'assurer que les patrons mettent en relief certaines caractéristiques de la diète telles que l'apport en nutriments d'intérêt ou encore l'association entre la consommation de certains aliments et la présence de caractéristiques métaboliques chez les consommateurs (101). Tel que mentionné précédemment, il est essentiel que des outils visant l'évaluation de l'alimentation puissent tracer un portrait valide de la qualité alimentaire qu'elle soit définie par des scores « a priori » ou des scores « a posteriori ». Ces mesures doivent aussi être adaptées aux besoins des chercheurs (surveillance et épidémiologie) ou encore des professionnels de la santé (clinique).

Le Healthy Eating Index

Parmi les scores prédéfinis, l'un des plus étudiés est le *Healthy Eating Index* (HEI). Ce dernier, mis au point en 1995, par Kennedy et al. (102) du USDA, comptabilise les portions consommées des cinq groupes alimentaires du guide alimentaire américain (grains, légumes, fruits, lait et viande), l'apport de quatre nutriments (gras total, gras saturé, cholestérol, sodium) et considère également une mesure de variété. Les points sont attribués en fonction du ratio d'atteinte de chacune des recommandations pour un maximum de 10 points par recommandation. Le score a été mis à jour en 2005, 2010 et 2015. La dernière version inclut des recommandations plus spécifiques quant aux fruits entiers, aux légumes verts, aux légumineuses, aux grains entiers, aux protéines végétales, aux sucres ajoutés et aux gras saturés (103). Plusieurs versions canadiennes du score HEI ont aussi été développées et validées. Glanville et al. (104) et Dubois et al. (105) ont adapté le score de Kennedy aux recommandations du GAC 1992. Woodruff et al. ont quant à eux ajusté le calcul des scores précédents afin qu'ils soient cohérents avec les recommandations du GAC 2007. De plus, Garriguet (79) a développé une version canadienne optimisée inspirée du HEI-2005 américain incluant les sous-catégories associées aux fruits entiers, aux légumes orangés et vert foncé et aux grains entiers (**Tableau 1**). Enfin, Jessri et al. ont proposé une version du score HEI-2010 américain adapté aux recommandations du GAC 2007 (106), mais aucune version du HEI-2015 adapté au GAC 2007 ni au GAC 2019 ne sont disponibles à l'heure actuelle.

Les versions 2005 (107), 2010 (108) et 2015 (103) du HEI américain et la version 2007 (79) du HEI canadien (C-HEI 2007) ont été testées afin d'évaluer leur validité. Pour ce faire, les chercheurs ont démontré que les diètes modèles inspirées des recommandations obtenaient des scores près de la perfection et que les scores discriminaient entre les groupes connus pour avoir un écart dans la qualité de leur alimentation (p. ex. non-fumeurs vs fumeurs ou femmes vs hommes). De plus, une analyse factorielle a démontré que toutes les versions du score sont composées de plusieurs sous-facteurs qui influencent indépendamment le score final. D'autres chercheurs ont établi la validité du score HEI en démontrant son association avec les valeurs plasmatiques de plusieurs biomarqueurs de l'apport en fruits et légumes notamment les caroténoïdes et la vitamine C (109) ainsi que la vitamine E et le folate (110). Des analyses ont démontré qu'un score HEI plus élevé est associé à une réduction de la prévalence de diabète chez les femmes (111) et d'obésité chez les hommes de race blanche (112). Dans une cohorte multiethnique de plus de 200 000 adultes américains, Harmon et al. ont démontré que le score HEI-2010 était inversement associé au risque de mortalité et de maladies cardiovasculaires et de cancers (113). Liese et al. ont obtenu des conclusions similaires dans trois grandes cohortes américaines (63 000 à 420 000 adultes) (114) et Schwingshackl et Hoffmann l'ont aussi démontré dans une méta-analyse regroupant 1 020 642 participants (86). Ces analyses n'ont toutefois pas encore été réalisées au moyen du C-HEI 2007.

Tableau 1 : Composantes du score *Healthy Eating Index* Canadien-2007 tel que décrit par Garriguet (2009)

Composantes	Étendue des scores	Critères de pointage
Adéquation	0 à 60 points	
Légumes et fruits	0 à 10 points	Minimum: 0 Maximum: 4 à 10 portions
Fruits entiers	0 à 5 points	Minimum: 0 Maximum: 0.8 à 2.1 portions (21% des recommandations en légumes et fruits)
Légumes vert foncé et orangés	0 à 5 points	Minimum: 0 Maximum: 0.8 à 2.1 portions (21% des recommandations en légumes et fruits)
Produits céréaliers	0 à 5 points	Minimum: 0 Maximum: 3 à 8 portions
Grains entiers	0 à 5 points	Minimum: 0 Maximum: 1.5 à 4 portions (50% des recommandations en produits céréaliers)
Laits et substituts	0 à 10 points	Minimum: 0 Maximum: 2 à 4 portions
Viandes et substituts	0 à 10 points	Minimum: 0 Maximum: 1 à 3 portions (150 à 225 grammes)
Gras insaturés	0 à 10 points	Minimum: 0 Maximum: 30 à 45 grammes
Modération	0 à 40 points	
Gras saturés	8 à 10 points	Minimum 7% à 10% de l'apport énergétique total
	0 à 8 points	10% jusqu'à un maximum de 15% de l'apport énergétique total
Sodium	8 à 10 points	Apport adéquat jusqu'à l'apport maximal tolérable
	0 à 8 points	Apport maximal tolérable jusqu'à deux fois l'apport maximal tolérable.
« Autres aliments »	0 à 20 points	Minimum: 5% ou moins de l'apport total en énergie Maximum: 40% ou plus de l'apport total en énergie

L'Alternative Healthy Eating Index

Initialement proposé en 2002 puis mis à jour en 2010, *l'Alternative Healthy Eating Index* (AHEI) est aussi un score de qualité alimentaire très étudié. Contrairement au HEI, il n'est pas basé sur l'adhésion aux recommandations nutritionnelles, mais plutôt sur la somme de plusieurs recommandations nutritionnelles issues de la recherche sur la santé cardiovasculaire (115). Il s'agit d'un score total de 110 points attribués selon les apports en légumes, en fruits, en grains entiers, en boissons sucrées, en noix et légumineuses, en viandes rouges et transformées, en gras *trans*, en acides gras oméga-3, en acides gras polyinsaturés, en sodium et en alcool (**Tableau 2**). Il se compare aux versions les plus récentes du score HEI (2010 et 2015) quant aux recommandations sur les légumes, les fruits, les noix, les légumineuses, le sodium et les acides gras. Toutefois, il est caractérisé par des recommandations plus spécifiques sur les viandes rouges et transformées ainsi que sur l'alcool et n'inclut pas le pointage pour les apports en produits laitiers (115). Comme le score HEI américain, il a été associé à une réduction de la mortalité et de l'incidence de maladies cardiovasculaires et de cancer (86,113,114), mais a aussi démontré une meilleure prédiction de la santé cardiovasculaire que le score HEI-2005 américain (115).

Tableau 2 : Composantes du score *Alternative Healthy Eating Index* 2010 tel que décrit par Chiuve et al. (2012)

Composantes	**Critère pour le score minimum (0)**	**Critère pour le score maximum (10)**
Légumes (portions/jour)	0	≥5
Fruits (portions/jour)	0	≥4
Grains entiers (grammes/jour)	0	
Femmes		75 (approximativement 5 portions/jour)

Hommes		90 (approximativement 6 portions/jour)
Boissons sucrées et jus de fruits (portions/jour)	≥1	0
Noix et légumineuses (portions/jour)	0	≥1
Viandes rouges et transformées (portions/jour)	≥1,5	0
Gras *Trans* (% de l'énergie)	≥4	≤0,5
Acides gras à longue chaine (n-3) (EPA+DHA) (mg/jour)	0	250
Acides gras polyinsaturés (% énergie)	≤2	≥10
Sodium (mg/jour)	Plus grand décile	Plus petit décile
Alcool (consommations/jour)		
Femmes	≥2,5	0,5-1,5
Hommes	≥3,5	0,5-2,0
Total	0	110

Les principaux scores de la qualité alimentaires préétablis (HEI et AHEI) font ressortir des consensus scientifiques associés à la saine alimentation et permettent de suivre l'évolution de l'adhésion au concept de saine alimentation au sein d'une cohorte d'individus ainsi que de comparer les apports de différentes cohortes. Considérant l'étendue de la littérature scientifique faisant appel à ces scores, il est primordial qu'un outil de mesure de l'alimentation puisse les mesurer de manière efficace et valide.

Les patrons alimentaires

Bien que les principaux scores « a priori » aient démontré une bonne association avec la santé métabolique et le risque de maladies chroniques, certains critiquent leur rigidité sachant que des groupes alimentaires ont une incidence plus marquée que d'autres sur la santé et que cet effet peut varier d'une population à une autre. Dans une méta-analyse conduite par Schwingshackl et al. l'effet spécifique de 12 groupes alimentaires sur la mortalité toutes causes confondues a été analysé (116). Ces chercheurs ont constaté que la consommation de grains entiers, de légumes, de fruits, de légumineuses, de noix et de poissons était négativement associée à la mortalité alors que la consommation de viande rouge, de viande transformée, d'œuf et de boissons sucrées y était associée positivement. Aucune association significative n'était observable avec les produits laitiers et les grains raffinés. De plus, les courbes décrivant les associations avec les légumes, les fruits, les noix et les produits laitiers n'étaient pas linéaires. Enfin, la qualité des preuves scientifiques variait pour chacun des groupes de très faible pour les œufs à élevée pour les grains entiers en passant par faible et modérée pour chacun des autres groupes (116). Ces données démontrent qu'il est difficile de concevoir qu'un seul score où tous les groupes alimentaires ont le même poids puisse bien mesurer l'association entre l'alimentation et la santé métabolique.

On définit un patron alimentaire comme la quantité, la variété ou la combinaison de différents aliments et boissons dans la diète ainsi que la fréquence à laquelle ils sont habituellement consommés (117). Un patron alimentaire n'est pas simplement l'addition de certains composés alimentaires tels que décrits par les scores prédéfinis, mais bien un portrait de l'alimentation d'un groupe d'individus qui tient compte de l'interaction entre les apports en différents aliments ou groupes d'aliments (118). Les patrons alimentaires ne sont pas basés sur des concepts issus de la littérature scientifique, ils sont orientés par les données de consommations alimentaires (83). Ils sont obtenus grâce à des analyses mathématiques visant à établir les associations ou les différences importantes entre les apports des individus (119). Une technique largement utilisée est celle de l'analyse de composante principale (*principal component analysis* ou PCA en anglais). Celle-ci vise à expliquer la variabilité dans les apports en certains aliments ou groupes d'aliments au moyen de quelques fonctions linéaires (les composantes principales) (101). Les groupes ainsi formés sont, par définition, différents d'une population à l'autre. Ils sont toutefois souvent caractérisés comme « santé » ou « prudent » ou encore comme « traditionnel » ou « western » en fonction du type d'aliments qu'ils contiennent (83). Un score peut ensuite être dérivé d'un patron alimentaire afin de décrire l'adhésion à ce dernier. Le score tient compte des apports rapportés pour chacun des principaux groupes alimentaires inclus ainsi que du poids de chacun des groupes dans le patron alimentaire (118). Par exemple, le nombre de portions de légumes verts pourrait composer 25% du score total alors que le nombre de portions de poisson ne représenterait que 10% du score total.

Cette technique permet de faire ressortir les tendances alimentaires réelles dans un groupe d'individus. Cependant, bien que les patrons de type « santé » ou « prudents » soient généralement associés à un risque réduit de maladies chroniques (120), la méthode du PCA ne permet pas d'évaluer l'incidence de l'alimentation sur la santé de manière plus discriminante que les scores « a priori » tels que les scores HEI et AHEI (83,101). Une approche proposée récemment vise à modifier la PCA en incluant quelques variables réponses d'intérêt qui sont soit des nutriments associés à la santé ou encore des marqueurs intermédiaires de la santé tels que des mesures sériques ou anthropométriques associées à la santé. Cette méthode nommée Régression de rang réduite (*Reduced rank regression* ou RRR en anglais) est donc en quelque sorte une combinaison des méthodes « a priori » et « a postériori ». En effet, elle vise à identifier des patrons au sein d'une cohorte d'individus (a postériori), mais en se basant sur des hypothèses issues de la littérature scientifique (a priori) liant certains nutriments ou biomarqueurs à la santé (83,101). Les scores ainsi développés sont toutefois très spécifiques aux populations dans lesquelles ils ont été élaborés et largement dépendants de la méthode d'évaluation alimentaire ainsi que des groupes alimentaires préalablement identifiés (121). Par exemple, dans des études récentes ayant eu recours au RRR pour identifier des patrons alimentaires associés à la prévalence du syndrome métabolique, les groupes alimentaires mis de l'avant étaient assez différents, voire contradictoires. Dans une étude allemande, un patron alimentaire décrit par des apports élevés en pommes de terre, légumineuses, pain, bœuf, porc, viandes transformées, autres gras (autre que les huiles végétales) et en sauces et bouillons ainsi que par des apports faibles en thé et en pâtes et riz étaient associés à une plus forte prévalence du syndrome métabolique (122). Ensuite, dans une étude suédoise, le patron alimentaire associé à la prévalence du syndrome métabolique était décrit par des apports élevés en boissons sucrées, lait faible en gras, boissons sucrées artificiellement, viande rouge, viande transformée et en sucreries ainsi que par de faibles apports en vin, bière, crème, fromage, thé et légumes (123). Enfin, dans une étude australienne, le patron décrit par des apports élevés en fruits à pépins, carottes, légumes racines, pains de grains entiers, céréales de grains entiers, noix et graines et par des apports faibles en boissons aux fruits, lait entier, crème, chocolat et pains de grains raffinés était associé à une plus faible prévalence de certaines des composantes du syndrome métabolique (124).

En somme, l'analyse de patron alimentaire peut être une approche pertinente pour établir de nouveaux facteurs alimentaires importants associés à la santé dans une population précise. Ces facteurs peuvent ensuite être mis de l'avant dans le cadre de mesures de promotion de la santé (83,125). Il est donc d'une grande importance qu'un outil d'évaluation nutritionnelle visant à mesurer et suivre l'évolution de la qualité alimentaire puisse permettre l'analyse et l'interprétation de patrons alimentaires.

1.5.3 Dépister la qualité alimentaire inadéquate

Les outils de mesure de l'alimentation sont indispensables pour fournir aux chercheurs les données essentielles à leurs travaux. Ces outils pourraient aussi servir aux professionnels de la santé afin d'identifier les individus présentant des facteurs de risques alimentaires à plusieurs maladies chroniques pour lesquels le counseling en nutrition devrait être au cœur de l'intervention (126,127). Cependant, selon une étude canadienne, les médecins proposent des modifications nutritionnelles à seulement 30% de leurs patients diabétiques et à 10% des autres patients (128). Tel que précédemment décrit, les scores prédéfinis comme le HEI et le AHEI issus de l'analyse d'un rappel de 24 heures ou d'un questionnaire de fréquence alimentaire offrent la possibilité de classifier les sujets en fonction de la qualité de leur alimentation et démontrent des associations avec plusieurs indicateurs de santé. Par contre, ces méthodes d'évaluation alimentaire sont peu utilisées à l'extérieur des études scientifiques, principalement parce qu'elles exigent trop de temps ainsi qu'une certaine expertise en évaluation nutritionnelle. De plus, pour calculer des scores prédéfinis, l'utilisation d'un logiciel d'analyse nutritionnel est essentielle puisque l'apport en nutriments (p. ex. lipides, gras saturés et sodium entre autres) est requis. Face à cette contrainte, certains questionnaires courts ont été développés à l'intention des intervenants de première ligne avec un succès mitigé. La plupart des outils sont en fait des versions écourtées de questionnaires de fréquence alimentaire (129). L'outil *Starting the Conversation*, élaboré par Paxton et al. (130), est un résumé en 8 questions d'un questionnaire déjà validé visant l'évaluation alimentaire chez les individus à risque de maladies cardiovasculaires. Le *Starting the Conversation* est simple et rapide à compléter et démontre une certaine corrélation avec le questionnaire de fréquence alimentaire long ainsi que la précision permettant de discerner les changements en lipides dans la diète. Par contre, ce dernier ne permet pas de classer les répondants en fonction de la qualité globale de leur alimentation, ce qui limite son interprétation. Gans et al (131) ont quant à eux développé le *Rapid Eating and Activity Assessment for Patients* visant à évaluer l'adhésion aux recommandations nutritionnelles du USDA en 10 minutes. Ce dernier démontre une corrélation avec le score HEI-1995 et une bonne acceptabilité, mais demeure relativement long à remplir ce qui peut limiter son utilisation à grande échelle et en clinique. En utilisant une version écourtée d'un questionnaire de fréquence alimentaire, van Lee et al. (132), ont mis au point un questionnaire court de 34 items visant à prédire la qualité alimentaire des habitants des Pays-Bas telle que mesurée avec le score Dutch Healthy Diet. Bien que les scores obtenus avec le questionnaire écourté corrélaient assez bien avec celui produit par le questionnaire de fréquence alimentaire de 180 items, le questionnaire court n'a démontré aucune association avec des marqueurs de la santé métabolique. Fung *et al.* (133) ont développé un score à base d'aliments ayant un effet sur la prise de poids à long terme (134) et ont démontré que celui-ci permettait de prédire le risque relatif de maladies cardiovasculaires au sein d'une cohorte étudiée sur une vingtaine d'années. Ce score a été établi en fonction du classement des individus de la cohorte par quintiles de consommation des aliments sélectionnés et n'a pas été adapté pour être utilisé en clinique. Cependant, il démontre qu'il est utile et pertinent de baser le développement d'un outil de dépistage sur une analyse des prédicteurs possibles.

Certaines approches statistiques issues de l'intelligence artificielle pourraient soutenir les chercheurs dans le développement de ce type d'outils. Entre autres, les arbres de classifications et de régression (*Classification and regression tree*, CART en anglais) pourraient être utilisés. Cette méthode d'apprentissage supervisée permet de tracer des patrons alimentaires et d'identifier les meilleurs prédicteurs d'une condition identifiée parmi une liste de variables. Chacune des variables sélectionnées permet de sous-diviser l'échantillon de participants en sous-groupes mutuellement exclusifs (135). Le résultat final prend la forme d'un arbre décisionnel facile à interpréter sans assistance statistique spécialisée (136). Il n'existe pas, à ce jour, d'outil validé permettant de faire du dépistage nutritionnel adapté aux recommandations alimentaires canadiennes et disponible pour les intervenants de première ligne.

Chapitre 2 – Objectifs et hypothèses

Sachant qu'il est primordial que les chercheurs puissent disposer d'outils valides pour évaluer la qualité alimentaire et sachant que des méthodes statistiques éprouvées permettent de préciser le degré de validité des outils ainsi que de cibler les concepts-clés définissant la qualité de l'alimentation, l'objectif général du présent projet de doctorat est de développer et valider un questionnaire long (rappel de 24 heures automatisé et auto-administré, le R24W) et un questionnaire court (questionnaire court de dépistage du risque nutritionnel) visant à caractériser les répondants en fonction de la qualité globale de leur alimentation.

Hypothèse générale : Nous émettons l'hypothèse qu'un rappel de 24 heures automatisé et auto-administré ainsi qu'un questionnaire court de dépistage du risque nutritionnel développé en tenant compte des biais fréquemment associés à ces types d'outils prédisent la qualité alimentaire telle que défini par les recommandations nutritionnelles canadiennes ainsi que par des biomarqueurs de la santé métabolique.

Afin d'atteindre cet objectif général, six objectifs spécifiques ont été identifiés.

Objectif spécifique 1 : Tester les fonctions de recherches et d'entrée de données du R24W chez un groupe d'adultes impliqués dans des études d'alimentation contrôlées où tous les apports alimentaires sont connus de l'équipe de recherche afin de vérifier si des biais systématiques sont présents pour ce qui touche la recherche d'aliments et l'estimation des tailles des portions.

Hypothèse 1 : L'utilisation d'une méthode inspirée de la technique de l'AMPM de l'USDA ainsi que la présentation de deux à huitmages simultanées afin de proposer une étendue réaliste des tailles de portions permettent de limiter la sous-déclaration associée au biais de mémoire ainsi que la marge d'erreur dans l'estimation des portions au moyen du R24W.

Objectif spécifique 2: Tester la validité relative du R24W pour estimer les apports en énergie et nutriments en les comparant aux apports évalués par un outil de référence, le journal alimentaire de trois jours.

Hypothèse 2 : Nous supposons que la démarche utilisée pour développer le R24W ainsi que l'utilisation de la base de données du Fichier canadien sur les éléments nutritifs et l'inclusion de 632 recettes de mets composés permettant d'offrir une bonne représentativité des options alimentaires de notre population cible permettent l'estimation des apports en énergie et en nutriments avec une marge d'erreur de moins de 10% par rapport à l'outil de référence.

Objectif spécifique 3: Tester la validité relative du R24W pour estimer le score de qualité alimentaire C-HEI 2007 en le comparant aux apports mesurés par un outil de référence, le journal alimentaire de trois jours.

Hypothèse 3 : Nous supposons que la démarche utilisée pour développer le R24W permet de fournir un portrait assez détaillé de l'alimentation pour bien estimer le score de qualité alimentaire C-HEI 2007. Nous émettons l'hypothèse que plus de 80% des sujets seront classés de manière équivalente en matière de qualité alimentaire avec le R24W et avec le journal alimentaire de trois jours.

Objectif spécifique 4 : Tester la validité du rappel de 24 heures pour identifier les plus grands consommateurs de légumes et de fruits, un marqueur important de la qualité alimentaire en utilisant le dosage de caroténoïdes sériques comme biomarqueur sanguin.

Hypothèse 4 : Nous posons l'hypothèse que les apports en légumes et en fruits mesurés au moyen du R24W sont corrélés aux taux sériques de caroténoïdes des participants.

Objectif spécifique 5 : Tester la capacité du R24W à décrire adéquatement la qualité alimentaire en définissant cette dernière comme un ensemble de comportements alimentaires favorisant une faible incidence du syndrome métabolique au moyen de scores de la qualité alimentaire prédéfinis (C-HEI 2007 et AHEI) ainsi que de patrons alimentaires élaborés au sein d'une cohorte d'adultes québécois.

Hypothèse 5 : Nous soumettons l'hypothèse que les scores prédéfinis permettent d'identifier adéquatement les répondants ayant une plus faible incidence du syndrome métabolique et que les patrons alimentaires élaborés au moyen des apports rapportés avec le R24W seront cohérents avec les recommandations nutritionnelles actuelles.

Objectif 6 : Développer et valider un outil de dépistage nutritionnel permettant de classifier les sujets quant à leur score AHEI pouvant être complété facilement et rapidement.

Hypothèse 6 : Nous proposons que le questionnaire court de dépistage nutritionnel, développé grâce à la technique d'arbre de classification et de régression permet de catégoriser plus de 70% des répondants en fonction du risque nutritionnel tel que décrit par le score AHEI et permet d'identifier les répondants ayant plus de risque de développer des problèmes liés à la santé métabolique.

Chapitre 3 - Validation of a newly automated web-based 24-hour dietary recall using fully controlled feeding studies.

Résumé

L'objectif de cette étude était de valider un nouveau rappel de 24 heures auto-administré et automatisé sur plateforme web (R24W) dans une population d'adultes prenant part à des études d'alimentation contrôlée. Soixante-deux adultes ont complété le R24W à deux reprises alors que tous leurs repas étaient préparés par notre équipe de recherche. En général, le R24W a démontré une bonne performance étant donné que les participants ont été en mesure de rapporter adéquatement les items offerts et de sélectionner les tailles de portions fortement associées à celles reçues. Cela suggère que les aliments sont faciles à trouver dans le moteur de recherche du R24W et que les images proposées permettent une bonne évaluation des portions consommées.

Title page

Title: Validation of a newly automated web-based 24-hour dietary recall using fully controlled feeding studies.

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Abstract

Background: Assessment of food intake is a cornerstone of nutritional research. However, the use of minimally validated dietary assessment methods is common and can generate misleading results. Thus, there is a need for valid, precise and cost-effective dietary assessment tools to be used in large cohort studies.

Objective: To validate a newly developed automated self-administered web-based 24-hour dietary recall (R24W), within a population of adults taking part in fully controlled feeding studies.

Methods: 62 adults completed the R24W twice while being fed by our research team. Actual intakes were precisely known, thereby allowing the analysis of the proportion of adequately self-reported items. Association between offered and reported portion sizes was assessed with correlation coefficients and agreement with the kappa score while systematics biases were illustrated with Bland-Altman Plot.

Results: Participants received an average of 16 food items per testing day. They reported 89.3% of the items they received. The more frequently omitted food categories were vegetables included in recipes (40.0%) as well as side vegetables (20.0%) and represented less than 5% of the actual daily energy intake. Offered and self-reported portion sizes were significantly correlated (r= 0.80 P<0.001) and demonstrated a strong agreement as assessed by the kappa score of 0.62. Reported portion sizes for individual food items were on average 3.2g over the offered portion sizes. Portions of more than 100g were on average underestimated by 2.4% (r=0.68 P<0.01; kappa score=0.50) while small portions were overestimated by 17.1% (r=0.46 P<0.01; kappa score=0.43). A nonsignificant underestimation (-13.9kcal ± 646.3kcal; P=0.83) of energy intake was noted.

Conclusion: R24W performed well as participants were able to report the great majority of items they ate and selected portion size strongly related to the one they

received. This suggests that food items are easily to find within the R24W and images of portion sizes used in this dietary assessment tool are adequate and can provide valid food intake evaluation.

Background

High quality nutritional research hinges on valid assessment of food intake. However, it remains a real challenge to adequately measure food intake. Because of wide within subject variation, self-reported tools have some degree of random errors (1) often associated with incoherent research results (2). Recent researches demonstrated that those errors may be significantly reduced by improving data collection techniques and by selecting tools adapted to the studied population. Furthermore, it is essential to validate a new dietary assessment tool before its first use (3).

Self-reported food assessment tools are often associated with high rates of misreporting leading to underestimation of energy and nutrient intakes compared to objective measurements (4). Misreporting can be explained in part by undereating and in part by under-recording. Indeed, subjects tend to reduce or change their food intake when they have to report it. This has been referred to as the reactivity bias (5). In addition, studies have shown that subjects frequently fail to remember all the items they ate and they have trouble estimating the exact portion sizes consumed (6–8). These errors could be attributed to memory or social desirability bias (4,9).

Automated self-administered 24-hour recalls received attention lately and are increasingly used because there are convenient and cost-effective (10). For cohort studies, automated 24-hour dietary recall is becoming the tool of choice instead of food frequency questionnaire because of it superior precision and accuracy (11,12). Furthermore, it present characteristics that can help reducing the above-mentioned biases. First, as participants generally filled their recalls on unannounced days, this limits the reactivity bias. Second, those recalls are completed by the respondent, outside of a laboratory setting, thus in a neutral environment (13). This reduces the social desirability bias as compared with a face to face administration of recalls (14,15). Third, the inclusion of memory cues in the recall can attenuate memory bias which can therefore contribute to reduce underreporting. For example, with an approach like the USDA automated multiple pass method, items are reviewed to make sure that nothing has been forgotten, context of the meal is accentuated because it helps to remember details about the food consumed and many questions are asked about frequently forgotten food items (16). In addition, images of portion sizes can improve estimation accuracy by up to 60% (17,18). Finally, presentation of simultaneous different portion size options can reduce error rates compared to presentation of only one option (7).

Some studies have shown that, compared with the traditional interview, web-based 24-hour recall generates equivalent results with a reduced precision for some nutrients (6,19,20). However, the preference for the web-based version was highlighted by many researchers. Indeed, Thompson et al. (19), showed that using a web-based 24-hour recall reduced attrition rate compared to interview administered 24-hour recall. Furthermore, with the web-based approach, the completion time is reduced and the coding step is automated thereby saving a significant amount of time (21). The main concern remaining is the accessibility as internet connexion is not yet equivalently spread causing an underrepresentation of older adults with lower incomes (in 2012, 28% of them had internet access compared with 95% of younger adults with higher incomes (22)).

It has to be emphasized that when a new dietary assessment tool is developed, a rigorous validation process needs to be performed before it can be used in cohort studies. One strategy that can be used when validating dietary assessment tools is to compare self-reported food intake to the actual food intake consumed in the context of fully controlled feeding studies. In these projects intended to evaluate the effects of specific nutritional manipulation, participants receive all their meal for the duration of the study. The specific composition and weight of each food item consumed is therefore known and can be compared to the recall filled by the participants afterwards.

The R24W is a newly developed web-based, self-administered and fully automated 24-hour recall (23). It is the first French-language web-based automated 24-hour recall developed to assess dietary intake in the French-Canadian population. The aim of this study was to validate the R24W in a context of fully controlled feeding studies. More precisely, we wanted to evaluate adequate reporting of food items and portion size evaluation. We hypothesize that the majority of offered food items are adequately reported using the R24W. We also hypothesize that there is a portion size estimation error of less than 10%. Furthermore, as other authors reported that adults tend to underestimate large portion sizes compared with smaller ones (24,25) we decided to test specifically error rate in small and larger portions portion sizes and we hypothesize that, because of the large distribution of portion sizes illustrated in the R24W, the difference between them is not significant.

Methods

Participants

We invited 33 men and 29 women already enrolled in three fully controlled feeding studies currently conducted in our research institute. To be included in these studies, they had to be non-smoking men or women aged between 18 and 75 years old with stable weight. Women should not be pregnant or lactating. Each participant had to be free from cardiovascular or endocrine diseases and should not have a food allergy or aversion to any food item offered in the feeding protocol. These studies received the approval of the Laval University ethics committee and participants provided written informed consent prior to taking part in the study. The analysis performs in this article was directly presented in one of the three consent forms (the latest study) and was proposed to the participants already included in the two other studies in an addendum to their initial consent form. Therefore, all participants gave their informed consent before completing their first 24-hour recall knowing that it was part of a validation process.

These clinical trials were registered at http://www.clinicaltrials.gov as NCT02763930, NCT02106208 & NCT02029833. Participants followed the initial research protocol but in addition to this, we asked them to fill the R24W twice.

The automated web-based automated 24-hour recall (R24W)

Details on how the R24W was developed have been published elsewhere (23). Briefly, R24W was developed in French language and was inspired by the AMPM of the USDA (16). However, as opposed to AMPM, R24W is using a meal-based approach in the first step. An unlimited number of meals or snacks per 24-hour period can be added by the respondent. R24W allows automatic calculation of different diet quality scores in addition to energy and nutrient intakes. The application was programmed in such a way that the days for which the recall has to be completed are randomly generated with the possibility of using specific criteria (e.g., proportion between weekdays and weekend days). For this validation study, the same two days in each study were used for recalls. The application also allows the automatic sending of e-mail messages to participants prompting them to complete their 24 h food recall. The database includes 2865 items linked to the Canadian Nutrient File (2010 version) or the USDA Nutrients Database for the few items that were not available the Canadian Nutrient File. Questions about the context of the meal are asked to help respondents to recall all the items consumed. There is also systematic questions about frequently forgotten food items. Portion sizes are represented by up to eight food pictures representing predetermined portion sizes in a fixed neutral set-up. Portion sizes are expressed in units and/or volume under each picture. Respondents also have the option to select a multiplicative or a fraction of each portion shown. The format has been designed to be intuitive. In a pre-test in a cohort of 29 adults with different levels of computer skills, the R24W was found to be easy to understand and to complete (23).

Research Context

Studies in which participants were initially involved had different feeding protocols. Most of these studies aimed at assessing the metabolic effects of some diets for which nutrient composition was manipulated. Menus were formulated using typical French Canadian food items. Meals were prepared and provided by the research team according to a 7-day cyclic menu for 4 to 8 weeks followed by 4 to 8 weeks of wash-out where subjects returned to their normal diet. The portion sizes of the different food items offered were individualized to ensure that all participants maintained a stable body weight while the exact diet composition was kept the same for each experimental condition in each study. Participants were not aware of the precise amount of food they received. They were instructed to eat all the food items provided every day and nothing else. Participants' body weight was measured throughout each project to achieve isoenergetic conditions and energy intake was increased or decreased by 250 kcal/day if a subject lost or gained greater than 1 kg and maintained that body weight for at least 3 days. In order to standardize the testing between studies, the R24W was completed in the first two weeks of one of the feeding phases for each project. Menus were composed of three meals and a snack per day. Except for a few exceptions, lunch (40% of daily calories) was consumed in the lab facility while dinner, breakfast and snack were packed in a cooler and consumed outside the clinical facility. Items were all labelled and participants received a checklist to remind them to eat the entire menu in order to enhance compliance (see Annexe 1). On this checklist, the general name of the meal and side dishes were given but the list of ingredients for mixed dishes was not included. This gave us the opportunity to assess how well participant manages to find the food items they consumed among the list of food available in the R24W with a reduced memory bias. Since no cues were provided on the check list about portion size of food items consumed, a memory bias could however influence how subjects were choosing the portion sizes when filling the R24W.

Validation strategy

In each study included in this protocol, the nutrient composition of the meals were manipulated without the knowledge of the participants. Therefore, it would not be the most appropriate study design to evaluate the accuracy of reported nutrient intakes. Instead, we decided to use a validation strategy in which we compared food items reported to food items actually offered. This was done by classifying reported food items as “matches”, “omissions” and “inclusions” as previously suggested (6). A “perfect match” corresponded to a situation where subjects selected the exact appellation of the item they received in the R24W (e.g. boiled potatoes for boiled potatoes). A “close match” described the selection of an item with related characteristics (e.g. mashed potatoes instead of boiled potatoes). A “far match” was used to classify items in the same food categories but with different characteristics and nutritional composition (e.g. fried potatoes instead of boiled potatoes). An “omission” was used to define a food item that was provided but not reported. Finally, an “intrusion” corresponded to a food item that was reported but not provided. For all items classified as matches (either perfect, close or far), offered and reported portion sizes were compared. Finally, only for indicative purposes, energy and macronutrient intakes as reported by participants who filled the R24W were compared with actual energy and macronutrient intakes as provided by the menu offered.

Statistical Analyses

Proportions of matches and omissions were calculated and the average number of inclusions was reported. Omissions were then analyzed in-depth to determine which categories of food items were more frequently omitted by participants. The impact of these omissions on energy intake assessment was then evaluated. To do so, we first classified the omitted items by categories and then calculated the mean contribution to the daily energy intake of all the mentioned items in this category. More precisely, the energy content of each item was determined and then a weighted average was calculated to represent the contribution of the category to the daily energy intake. As all menus were standardized, food items from a given food category had the same relative contribution to the total energy intake for all participants.

The difference between each reported and offered portion size was assessed (absolute number) and, in the present study, we refer to this difference as the bias which provides an indication of the systematic underestimation (in case of a negative bias) or overestimation (in case of a positive bias) in portion sizes. The difference between reported and offered portion size was also characterized as the estimation error that is the ratio between the bias and the offered portion size (in percentage). A Student T-Test was used to compare mean portion size reported to mean portion size offered. Analysis were conducted on all data and also separately on the smaller portions (characterized as less than 100g) and on the larger portions (characterized as 100g and above). A Student T-test was performed to determine if a larger estimation error occurs in larger portion sizes compared to smaller portion sizes. To assess accuracy in portion size estimation, we used correlation coefficients, weighted kappa scores for classification in quartiles and the Bland-Altman plots. The Kappa score describes the agreement between two measures as poor (<0.00), slight (0.00-0.20), fair (0.21-0.40), moderate (0.41-0.60), substantial (0.61-0.80) and almost perfect (0.81-1.00) (26). In order to investigate if individual characteristics could influence portion size estimation, a stepwise linear regression model was tested with age, sex and BMI as predictive factors for estimation error.

In the controlled feeding trials, lunch was served on a plate and consumed at the research institute while dinner was provided in individual plastic containers to be taken home. The extent to which meal presentation affected the accuracy of portion size estimation with the R24W was also assessed using T-tests comparing estimation bias between meals. Finally, energy and macronutrient intakes reported were compared to values corresponding to the offered food items using a Student T-test. Correlation analyses were also performed between reported and offered energy and nutrient intakes. Statistical analyses were conducted with the software SAS version 9.4 (SAS Institute).

Results

Characteristics of the participants are shown in Table 1. Data from 62 adults aged 21 to 71 years with body mass index from 21 to 52 kg/m2 are included in the analyses.

Participants received on average 16 different food items per day. The proportion of matches and omissions as well as the number of intrusions in participants' responses to the R24W are presented in Table 2. A total of 89.3% of the offered food items were reported with the R24W and 76.8% were reported using the exact descriptor in the database. Descriptions of the main omissions are presented in Table 3. Omissions were classified according to different food categories and the weighted average contribution of the category to the offered daily energy intake was calculated. Finally, Table 3 indicates whether the omitted food items were specifically named in the checklist that was provided to participants.
Table 4 presents examples of small and large portions offered at breakfast and at lunch/dinner meals. Most of the main dishes were offered in portions larger than 100g while side vegetables, fruits, sauces and spreads were mostly in portions smaller than 100g.

Table 5 describes the agreement between reported and offered portion sizes (kappa score, correlation coefficient and estimation bias). Analyses were first conducted with all portions irrespective of their size and then with small and large portion sizes separately. When analysing all portions irrespective of their size, we found a small nonsignificant (P=0.12) systematic bias of 3.2g (9.3% ±66.0%) meaning that R24W tends to slightly underestimate portion sizes. The correlation coefficient of 0.80 and the weighted kappa score of 0.62 suggest a substantial agreement between reported and offered portion sizes. Offered portions of less than 100g (kappa score of 0.43) as well as portions larger than 100g (kappa score of 0.50) showed a moderate agreement with their corresponding reported portion sizes. The estimation error was significantly larger for small (17.1% ±78.5%) than for large portions (-2.4% ±55.8%; $P<0.01$).

Figure 1 to Figure 3 illustrate the Bland-Alman plots for differences between reported and offered portion sizes for all food items, and also for small portions and large portions separately. Because the exact offered portions were known, these were used as the independent variables. The plots demonstrated acceptable agreement. The linear regression model showed that neither age, sex nor BMI were significantly predicting the estimation error in this sample. Results showed that there was no significant difference in the estimation error between meals offered for lunch (2.9g ± 134.8g) and meals offered for dinner (-11.0g ± 93.7g), $P=0.29$ (not shown).

Finally, comparisons between reported and offered energy and macronutrients are presented in Table 6. Significant correlations were observed ($r=0.38$-0.64 $P<0.01$) and reported energy and protein intakes were not statistically different from the offered amounts. However, reported carbohydrate intakes were significantly lower while reported fat intakes were significantly higher than offered values.

Discussion

The objective of this study was to validate in terms of food items reporting and portion size evaluation a new web-based 24-hour recall, the R24W, using the context of fully controlled feeding studies. We observed that the majority of the offered food items – close to 90%, were reported by the participants and that the mean difference between offered and reported portion sizes was less than 10% (i.e. 9.3%), as we hypothesized. This slight difference resulted in a non-significant 13.9 kcal underestimation of energy intake. However, contrary to our initial assumptions, we observed that portions smaller than 100g were estimated at a greater error rate than those of 100g and above.

Nutritional assessment errors can be attributed to participants' recall bias (reactivity, memory or social desirability bias) or to inherent characteristics of the tool (e.g. inadequate strategy for data collection or visual support). While it is difficult to distinguish them in a validation study conducted in the context of real life, fully controlled studies allow to minimize some participants' related bias. However, few studies have used controlled feeding studies to validate automated self-administered 24 h dietary recalls. Indeed, tools are generally compared to another self-reported tool or with biomarkers that provide precise information about only one nutrient at a time (13). Kirkpatrick et al. conducted a similar study intended to validate the ASA24 (6), another web-based dietary recall, in a context where subjects were invited to eat in a research cafeteria setting and asked to report their intakes during a follow-up visit, the day after. They observed that the proportion of matches between food consumed in the lab facility and food reported was 80%, a value that is slightly lower than what we observed in our study (i.e. 89%). However, memory was more of a confounding factor in that study because subjects were exposed to the experimental meals for the first time and did not have any cues to help them remember their past intakes. This was not the case in our study since subjects might have received the same meals in the previous phase of their studies and because they had access to a checklist to help them remember to consume all food items.

Omitted items identified in the present study were different from those reported in previous studies. Underreporting of fat and carbohydrates with food records and 24-hour recalls have been repeatedly demonstrated (5,27). This is supported by studies showing high-fat foods such as cakes, pastries, cookies and savoury snacks are more often underreported than other food groups (28,29). However, it is important to note that in the present study, the variety of snacks and desserts was limited as participants were imposed a specific menu. Nevertheless, they received cakes and potato chips and those items were not among the most frequently omitted food items. Hebert et al. (9) suggested that underreporting is associated with social desirability, which may explain that typical unhealthy foods tend to be underreported or omitted. In our study, this bias was limited because participants did not have to take responsibility for their food choices, which were predetermined as part of the experimental procedures. As suggested by others, the web interface may also contribute to reducing the social desirability bias compared with a human interviewer (14,15) but our study was not designed to specifically address this issue.

The most frequently omitted items by our participants were vegetables included in recipes (72 omissions) as well as side vegetables (36 omissions). This is in accordance with the observations of Kirkpatrick et al. (6). Some of these items were not extensively described in the checklist that was provided to the participant (87 items not described in the checklist/108 omissions in vegetables included in meals and side vegetables), so a memory bias could in part explain these omissions. We can also suggest that for these omitted food items the checklist was misleading in a way, suggesting to the participant that some items were more important than others. For example the “Mexican tortillas” included peppers and onions even if it was not mentioned on the checklist (see Annexe 1). We calculated that the energy contribution of vegetables included in recipes and side vegetables was however minimal (i.e. less than 5% of the daily energy intake).

When analysing all food items, irrespective of the portion size, we noted a mean estimation bias of 3.2g, which is close to the -3.7g differences observed by Kirkpatrick et al. (6). Williamson et al. (30) suggested that digital photos helped to accurately estimate portion sizes of food items. In the present study, participants tended to overestimate small portion sizes and to underestimate larger portions. This observation has also been highlighted in a previous study by Nelson et al. (31). However, our estimation error in large portion size was only -2.4% suggesting that we selected enough pictures of larger portion sizes (24).

Our results suggest that images used to illustrate the portion sizes in the R24W contribute to influencing adequately estimation of real intakes. It is of importance to remember that participants did not receive information about the size of the portion they ate. Moreover, they received their lunch meal in a plate similar to the one that appears on R24W portion size images while breakfast and dinner were served in plastic containers where items were often mixed, which can increase the difficulty in assessing the portion sizes of each ingredient. However, our results showed that there was no difference in portion size estimation that was noted between presentation formats. As meals are not always consumed in a plate in real life settings, it is of interest to assess portion sizes estimation in different contexts.

The observed overestimation of small portions deserves attention. In fact, the estimation error was close to 20% and the correlation coefficient between offered and reported portion sizes was below 0.50 (32). Although it was not a specific objective of the study due to the blind manipulation of some food items, the analysis comparing reported and offered energy seems to bring confidence that estimation errors are counterbalanced by omissions or are of low importance in the estimation of energy intakes. Indeed, the items most frequently overestimated are the same as those most frequently omitted (vegetables, sauces and spread) and the overall energy intake as obtained from the R24W filled by participants is not significantly different from the energy content of the diet offered. However, some differences were found between reported and offered amounts of carbohydrate and fat. These differences can be explained, at least partially by the fact that participants were unaware of the dietary manipulation of the meals they received. For example, in two out of three studies, they received a milkshake supplemented in fat to assess the metabolic effect of different types of oils. Meanwhile, the proportion of fat in other recipes, like muffins was reduced for balancing the diet. These manipulations could explain some of the differences observed between reported and offered amounts of carbohydrate and fat.

Another limitation to consider is the burden associated with self-reporting food intake for many days. In the context of this study, participants were asked to fill the

R24W twice on top of the initial research requirements. They were highly motivated and did not seem to significantly underreport. However, it will be a concern with wider and more diversified cohorts. Indeed, considering that at least 3 non-consecutive days of 24-hour recall are needed to represent typical intakes (33), the time commitment for participants could impact their motivation. Nevertheless, the web-based format of the R24W seems to be an important asset. Based on a pre-test conducted during its development, 59% of responders completed the recall in less than 30 minutes (23). In comparison, the food frequency questionnaire used recently in our large cohort studies takes on average 45 minutes to complete (34). Moreover, as the coding is automated, the web-based approaches lead to a considerable time saving for researchers.

Conclusion

To conclude, when controlling in part for some of the personal bias (memory, reactivity and social desirability), participants reported most of the items they ate with a good level of accuracy in portion sizes reported. This data also provides preliminary evidence supporting the validity of R24W to assess food intakes. Analyses in larger cohorts of free living individuals including biomarker analysis would be completed soon. This will allow to validate dietary assessment with a larger variety of consumed food items. In the near future, the R24W could be used to assess the food intake in large-scale research projects and in nutrition practice.

List of abbreviation

BMI: Body mass index

R24W: Newly developed automated self-administered web-based 24-hour dietary recall

Declarations

Ethics approval and consent to participate

Data from three studies were included in this article. These studies received the approval of the Laval University ethics committee and participants provided written informed consent prior to taking part in the study. The analysis performs in this article was directly presented in one of the three consent forms (the latest study) and was proposed to the participants already included in the two other studies in an addendum to their initial consent form. Therefore, all participants gave their informed consent before completing their first 24-hour recall knowing that it was part of a validation process (p.5 ln 1-8).

Consent for publication

Not applicable

Availability of data and material

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' Contributions

JL analyzed and interpreted most of the data and was actively involved in drafting the manuscript. BL, CL, JR and SL critically revised the manuscript and were major contributors to the revised version. JL, SL and CL made substantial contributions to the conception and design and the acquisition of data. All authors read and approved the final manuscript.

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Tables

Table 1: Characteristics of the participants (n=62)

	N (%)
Sex	
Men	33 (53.2%)
Women	29 (46.8%)
Mean BMI	
Normal weight (18.5-24.9 kg/m^2)	7 (11.2%)
Overweight (25.0-29.9 kg/m^2)	25 (40.3%)
Obese (30 kg/m^2 and above)	30 (48.4%)
Mean age (y)	
<25	5 (8.0%)
25-50	30 (48.4%)
>50	27 (43.5%)

Table 2: Proportion of matches (exact, close and far) and omissions related to the amount of food items offered and number of intrusions for all subjects[1] (n=62)

	Proportion or number of items
Number of items offered/day (n)	16.1± 3.1
Exact matches (%)	76.8± 15.3
Close matches (%)	8.2± 8.7
Far matches (%)	4.3± 5.2
All matches combined (%)	89.3± 11.1
Omissions (%)	10.7± 11.1
Intrusions (n)	0.2± 0.7

[1]Perfect match: a situation where subjects selected the exact appellation of the item they received in the R24W. Close match: an item with related characteristics. Far match: items in the same food categories but with different characteristics and nutritional composition. Omission: a food item that was provided but not reported. Intrusion: a food item that was reported but not provided.

Table 3: Counts of the items most frequently omitted by participants in relation to offered items.

Food items	Number of subjects who received the item	Items included in the checklist	Number of omissions	Mean contribution to the daily energy intake[2]
Vegetables in a salad / mix dish			**72**	**0.7%**
Peppers	45	No	24	
Celery	32	No	17	
Cucumber	13	No	11	
Corn	26	Yes/No[1]	10	
Onion	13	No	7	
Tomato	13	Yes	3	
Side			**36**	**3.1%**
vegetables	32	No	21	
Sweet potatoes	32	Yes	4	
Potatoes	32	Yes	3	
Coleslaw	13	Yes	2	
Tomatoes	13	Yes	2	
Cucumbers	18	Yes	2	
Broccoli Cauliflower	18	Yes	2	
Snacks/ drinks			**30**	**6.2%**
Cheddar cheese	19	Yes	7	
Sweet bread	73	Yes	6	
Raspberries	18	Yes	6	
Milk	18	Yes	3	
Milk shake	26	Yes	3	
Yogurt	31	Yes	3	
Blueberries	18	Yes	2	
Sauces			**26**	**1.8%**
Vinaigrette	13	Yes	7	
Salsa	13	Yes	7	
BBQ sauce	32	Yes	6	
Mayonnaise	13	No	6	
Ingredients in a salad			**16**	**3.7%**
Feta cheese	13	No	10	
Cranberries	13	Yes	3	
Chicken	13	Yes	3	

1. Corn was offered in two different menus, one where it was written as an ingredient on the checklist (3 omissions/13 presentations) and one where it was not included on the checklist (7 omissions/13 presentations) 2. The energy content of each item was determined and then a weighted average was calculated to represent the energetic contribution of the category.

Table 4: Examples of small and large portions of food items offered[1]

	Small portions (g)		Large portions (g)	
Breakfast	Bread/bagel	27-88	Orange	100-320
	Peanut butter	16-50	Milk	125-400
	Ham	12-40	Milkshake	130-416
	Cereals	30-96	Orange juice	160-512
	Cream cheese	8-26	Apple sauce	125-400
	Raspberries	25-80		
	Blueberries	27-88		
Lunch/Dinner	Cranberries	8-25	Vegetable juice	125-400
	Cucumbers	15-48	Rice with shrimps	320-570
	Tomatoes	25-80	Potatoes	172-307
	Vinaigrette/mayo	10-32	Fajitas with beans	200-355
	Cheese	20-64	Meatloaf	165-528
	Broccoli	22-72	Pesto pasta	207-368
	Carrots	22-72	Chili con carne	330-840
	Salsa	14-45	Mexican turkey	108-270
			Parsley salad	165-528
			Ham quiche	102-256
			Roasted peppers	97-272
			Carrot soup	165-528
			Rice	129-292
			Couscous	137-309

[1]A range is presented as portions were individualized according to participants' energy needs varying from 1750 to 4500 kcal per day.

Table 5: Agreement between reported and offered portion sizes as determined by the Kappa scores for portion size classification in quartiles, correlation coefficients and estimation bias for all, small and large portions.

	Kappa score	Correlation coefficient (P)	Estimation bias (estimation error)[1]
All portions N=1373	0.62	0.80*	3.2g (9.2%)
Small portions (<100g) N=640	0.43	0.46*	7.6g* (17.1%)
Large portions (≥100g) N=733	0.50	0.68*	-0.6g (-2.4%)

[1]Estimation bias: the average of the difference between reported and offered portion size. Estimation error: the mean ratio between the bias and the offered portion size. * Significant at P<0.05 (Difference between reported and offered portion was calculated to obtain the estimation bias).

Table 6: Comparison between reported and offered intakes for energy and macronutrients (n=62)

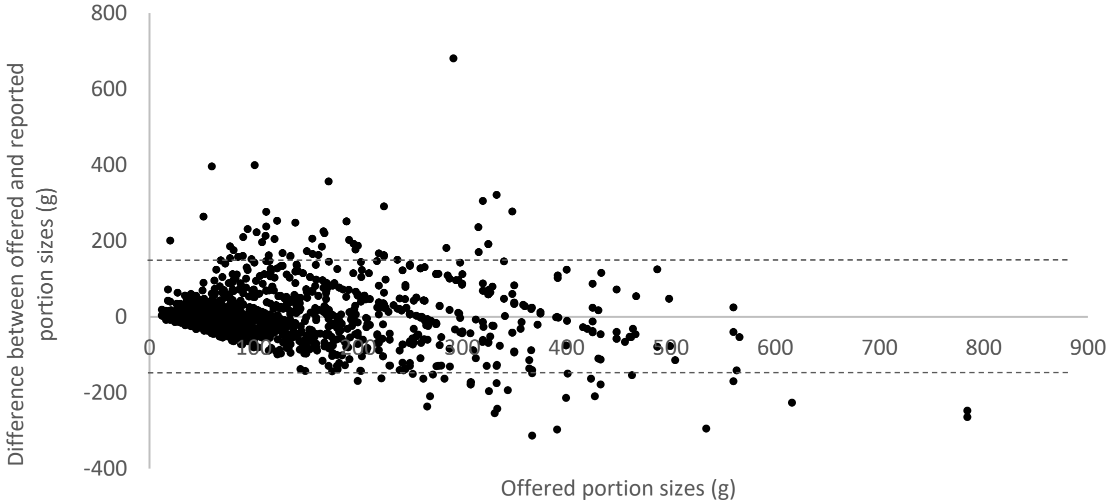
	Reported intake	Offered intake	Difference between reported and offered intakes	Correlation coefficient between reported and offered intakes
Energy (kcal)	2762.4 ±781.1	2776.4± 603.8	-13.9 ±646.3	0.59*
Proteins (g)	110.9 ± 39.2	110.0± 25.2	2.1 ±26.3	0.60*
Carbohydrates (g)	340.9 ± 101.6	366.9± 75.9	-26.1 ±79.0*	0.64*
Fat (g)	111.0 ±32.0	102.8± 26.6	9.1 ±38.0*	0.38*

* Significant at P<0.05

Figures

1. Bland Altman Plot of the comparison between offered and reported portion sizes for all portions. Bias= 3.2g Limits of agreements (dotted line): -148.3 to 154.7 g R: -0.15 P: <0.001
2. Bland Altman Plot of the comparison between offered portions of less than 100g and reported portion sizes Bias= 7.6g Limits of agreements (dotted line): -76.9 to 92.1g R: -0.02 P=0.54
3. Bland Altman Plot of the comparison between offered and reported portion sizes of 100g and larger. Bias= -0.6 Limits of agreements (dotted line): -192.1 to 190.8g R: -0.18 P<0.001

Figure 1



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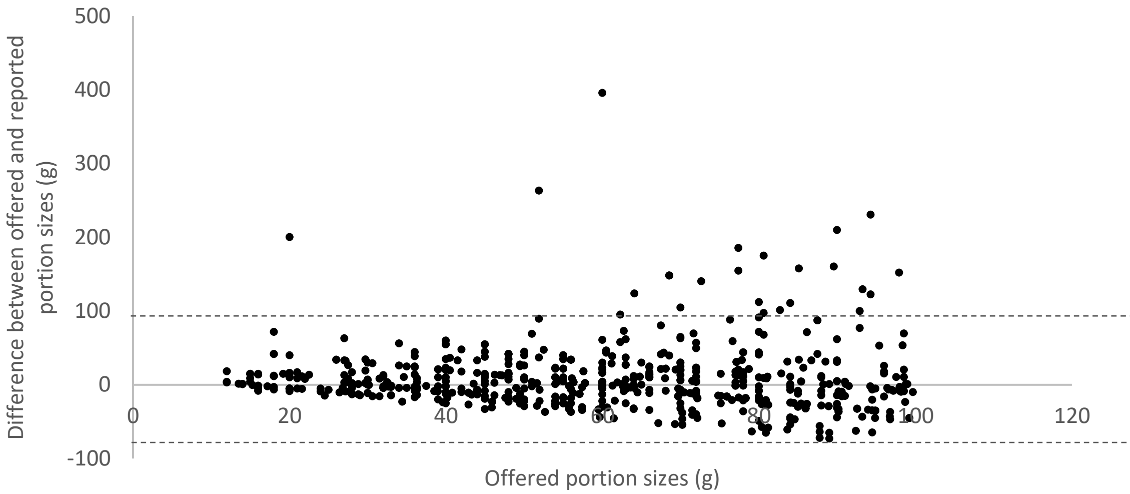
Difference between offered and reported portion sizes (g)
Offered portion sizes (g)

Figure 2



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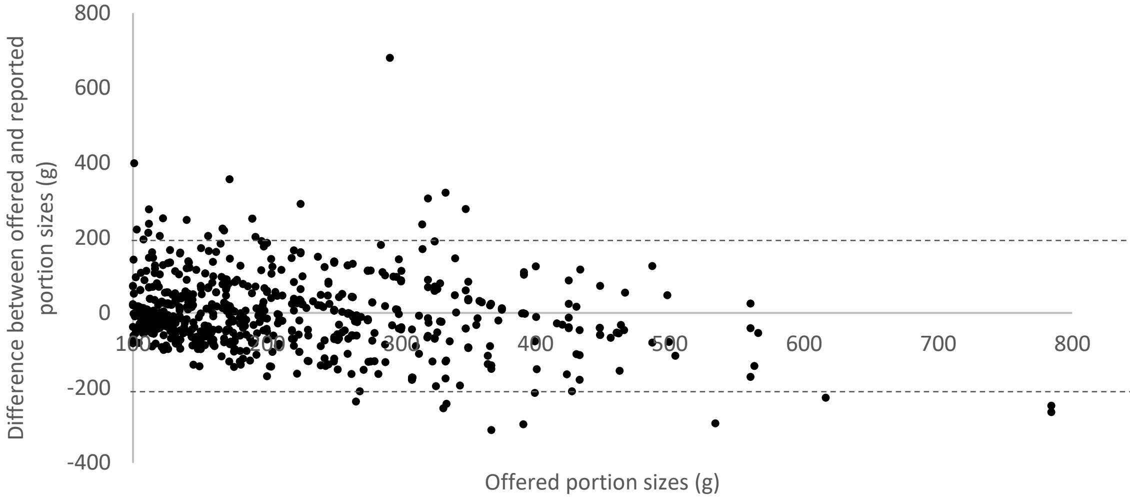
Difference between offered and reported portion sizes (g)
Offered portion sizes (g)

Figure 3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Difference between offered and reported portion sizes (g)
Offered portion sizes (g)

Annexe 1: Checklist offered to the participant with their meals for each project.

Project	Day tested	Meals	Food items
1	**Wednesday**	**Breakfast**	Multigrain bread
			Creton
			Orange
			Milk
		Snack	Raisin cookie
		Lunch	Lime and beans fajitas
			Tomatoes and cucumbers
			Blueberry square
			Milk
		Dinner	Meatloaf with tomato sauce
			Pesto fusilli
			Chocolate cake
			Milk
	Thursday	**Breakfast**	Muslix cereals
			Milk
			Roasted peanuts
			Red grapes
		Snack	Banana bread
		Lunch	Shrimp rice
			Vegetable juice
			Graham cake / raspberries
			Milk
		Dinner	Chicken, BBQ sauce
			Potatoes
			Coleslaw
			Chocolate pudding
			Milk
2	**Tuesday**	**Breakfast**	Granola
			Raspberry and blueberry yogurt
		Snack	Oat muffin
		Lunch	Carrot soup
			Chili con carne
			Basmati rice
			Cranberry bread
		Dinner	Curry chicken
			Couscous
			Broccoli and cauliflower
			Chocolate cake
	Sunday	**Breakfast**	Multigrain bread
			Cretons
			Apple sauce
			Orange juice
		Snack	Molasse muffins
		Lunch	Ham quiche

			Taboulé salad
			Vanilla pudding
		Dinner	Lemon chicken
			Garlic pasta
			Roasted peppers
			Carrot cake
3	**Tuesday**	**Breakfast**	Apple muffins
			Vanilla Greek yogurt
			Strawberry-peach milkshake
		Snack 1	Red grapes
		Lunch	Chicken and cranberry spinach salad
			Balsamic vinaigrette
			Crackers
		Dinner	Chili con carne
			Cheese
			Plain chips
		Snack 2	Date cookie
			Berry milkshake
	Sunday	**Breakfast**	Oat bran bagel
			Cream cheese
			Strawberry coulis
			Banana milkshake
		Snack 1	Yogurt
		Lunch	Turkey sandwich
			Humus
			Raw vegetables
			Orange
		Dinner	Mexican tortillas
			Tomato and corn salad
			Salsa vinaigrette
		Snack 2	Banana muffins
			Strawberry-blueberry milkshake

Chapitre 4 - Assessing the relative validity of a new web-based self-administered 24-hour dietary recall in a French-Canadian Population.

Résumé

L'objectif de cette étude était de tester la validité relative d'un nouveau rappel de 24 heures auto-rapporté et automatisé sur plateforme web (R24W) en utilisant un journal alimentaire comme outil de référence. Chacune des 57 femmes et chacun des 50 hommes (ayant un âge moyen de 47,2 ±13,3 ans) ont complété un journal de trois jours ainsi que trois rappels de 24 heures au moyen du R24W sur une période de quatre semaines. Les apports en énergie et en 24 nutriments ont été analysés et comparés. En somme, ces données suggèrent que le nouveau rappel de 24 heures auto-rapporté et automatisé sur plateforme web présente une validité relative acceptable lorsque comparé à un journal alimentaire pour l'estimation des apports moyens dans une cohorte de Canadiens francophones.

Title page

Title: Assessing the relative validity of a new web-based self-administered 24-hour dietary recall in a French-Canadian Population.

Full reference: Lafrenière J, Laramée C, Robitaille J, Lamarche B, Lemieux S. Assessing the relative validity of a new, web-based, self-administered 24 h dietary recall in a French-Canadian population. Public Health Nutrition. 2018 Oct;21(15):2744–52.

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Keywords: Relative validity, energy intake, nutrient intakes, 24-hour dietary recall, underreporting.

Abstract

Objective: To assess the relative validity of a new web-based self-administered 24-hour dietary recall, the R24W, for assessment of energy and nutrient intakes among French Canadians.

Design: Each participant completed a 3-day food record (FR) and the R24W on three occasions over a 4-week period. Intakes of energy and of 24 selected nutrients assessed by both methods were compared.

Setting: Quebec City metropolitan area.

Subjects: Fifty-seven women and 50 men (mean age: 47.2 ±13.3 years).

Results: Equivalent proportions of under-reporters were found with the R24W (15.0%) and the FR (23.4%). Mean energy intake derived from the R24W was 7.2% higher than the value obtained with the FR (2595±761 vs. 2408±710 kcal/d; $P<0.01$). Significant differences in mean intakes of nutrients between the R24W and the FR ranged from -54.8% (i.e. lower value with R24W) for niacin to +40.0% (i.e. higher value with R24W) for alcohol. Sex- and energy-adjusted de-attenuated correlations between the two methods were significant for all nutrients except zinc and ranged from 0.35 to 0.72 ($P<0.01$). Cross-classification demonstrated that 40.0% of participants were classified in the same quartile with both methods while 40.0% were classified in the adjacent quartile and only 3.6% were grossly misclassified (1st vs. 4th quartile). Analysis of Bland-Altman plots revealed proportional bias between the two assessment methods for 8/24 nutrients.

Conclusion: These data suggest that this new web-based self-administered 24-hour dietary recall presents an acceptable relative validity as compared with FR for estimating usual dietary intakes in a cohort of French Canadians.

Introduction

In the past few decades, researchers have started to rethink how food intake should be assessed and interpreted. Historically, food frequency questionnaires (FFQ) have been predominantly used in large cohort studies (1–3). According to Kirkpatrick et al. (3), up to 64% of the previous and ongoing Canadian studies rely on FFQ or dietary screeners while only 14% are using 24-hour recalls. However, studies with recovery biomarkers have consistently reported that multiple 24-hour recalls described energy and protein intakes with higher precision than FFQ (4,5). While multiple 24-hour recalls are considered expensive and time consuming, web technology now opens the way to a new wave of self-administered automatic tools for use in large cohorts (6,7). However, the validity of these new automated 24-hour recalls has to be demonstrated. To be considered valid and reliable, they have to measure what they are meant to measure consistently over time (8). On the one hand, they should provide an adequate estimation of nutrient intakes and identify deficiencies (9). On the other hand, they are also supposed to capture usual intakes. Therefore, reported energy intake (rEI) should be consistent with energy needs to sustain normal activities.

Underreporting is usually described as implausibly low rEI. To be categorized as such, energy intake has to be significantly lower than estimated or measured daily energy expenditure (DEE)(10). The use of doubly labelled water (DLW) is an unbiased way of assessing DEE in real life settings (11). In a review published in 2001, Hill et al. (12) revealed that compared to DLW, usual rEI from any food assessment tool was associated with a certain degree of underreporting. Nevertheless, it has been suggested that repeated 24-hour recalls would be one of the food assessment method with the lowest rate of underreporting, ranging from 10 to 20% (4,5,13–15). In the absence of nutritional biomarkers, underreporting is usually assessed as the ratio between rEI and basal metabolic rate (BMR) considered as below the lower limit of plausible physical activity level. Goldberg et al. (10) suggested that when a rEI:BMR ratio is below 1.35, this would be indicative of underreporting while over-reporting would correspond to a rEI:BMR ratio above 2.5. As described by Willett et al. (16), nutrient intakes can be further adjusted for energy intake in order to improve diet description and to strengthen the associations with health outcomes.

Ideal gold standard for dietary intake assessment is difficult to find. Some studies use direct observation, but this is only possible in a clinical setting and not representative of usual intakes. Recovery biomarkers such as DLW for energy intake are also interesting options. However, such biomarkers mirror specific aspects of the diet but they cannot reflect global dietary patterns (8). Newly developed techniques are therefore usually compared with an established one to determine if they can produce equivalent results within predetermined limits (17). This approach refers to relative validity (9). In studies evaluating relative validity, authors often used similar established statistical approaches (18,19). Most often, reported macro and micronutrient intakes from the new tool are compared with reported intakes obtained from a reference tool. It is expected that this reference method demonstrates a good level of validity, although not necessarily providing a perfect assessment of dietary intakes (9,20). The food record (FR) has been shown to perform reasonably well when compared to biological markers, especially when subjects are asked to weigh their foods and report specific recipes corresponding to what they actually ate (21–24). This method has been favoured in two recent web-based 24-hour recall validation studies because of its independence with the new tools in term of assessment bias (25,26).

The R24W is a new automated, self-administered web-based 24-hour recall designed to assess nutritional intakes in the French-Canadian population. This tool uses a data collection approach inspired by the automated multiple pass method (AMPM) from the United States Department of Agriculture (USDA) (27). A total of 2568 different food items and 687 recipes are available in the R24W (28). Respondents are guided to recall their previous day's intake, meal by meal. Pictures of up to eight portion sizes are proposed for each food item described by unit and/or volume. Its development has been discussed in detail elsewhere (28).

A first validation study was conducted in a context of fully controlled feeding studies, in which we have shown that there was no systematic bias in portion size estimation with the R24W (29). The aim of the present study was to assess the relative validity of the R24W, for assessment of energy and nutrient intakes among French Canadians, using established statistical validation approaches and intakes from FR as reference. We hypothesized that the R24W accurately estimates participants' usual energy and nutrient intakes with fewer than 20% of under-reporters.

Methods

Population

Seventy-five women and 75 men between the age of 18 and 65 from the Quebec City metropolitan area were recruited through electronic messages sent to the Laval University community as well as via the electronic newsletter of the research institute that reaches individuals outside of the university. Exclusion criteria were pregnancy, lactation and digestive problems causing malabsorption in order to avoid any interaction in the analysis of blood biomarkers taken for an upcoming analysis. All women and 72 men completed all the study requirements.

Study Protocol and Measurements

Participants were invited to an initial visit at the research institute where their body weight, height and body composition were assessed (TANITA body composition analyzer BC-418, Tanita Corporation, Il, USA). Then, they received verbal and written instructions by a dietitian on how to fill out the 3-day FR, with the intent to reduce social desirability biases (30). They had to complete the record on a weekend day and on two weekdays and they were asked to weigh and measure what they ate as well as to attach recipes or food labels of items consumed to improve accuracy of food assessment. Every FR was revised by a trained dietitian upon return to ensure that information provided was complete and clear. This was done in order to minimize estimation and reporting errors, the FR being used as the reference method in this validation study. Coding was also conducted by a trained staff with Nutrific software (Laval University, Qc, Canada), which was linked to the Canadian Nutrient File database (Health Canada, 2010).

Afterwards, participants received e-mails on unannounced days inviting them to complete the R24W four times during a 20-day period. If participants did not complete the 24-hour recall on the day they received the e-mail, the access was cancelled and another e-mail was sent on another unannounced day. Briefly, R24W is inspired by the AMPM of the USDA (27), but as opposed to the AMPM, R24W is using a meal-based approach in the first step. When completing the R24W, the respondent can add an unlimited number of meals or snacks per 24-hour period. In terms of data management, R24W allows automatic calculation of different diet quality scores in addition to energy and nutrient intakes. A detailed description of the R24W has been published elsewhere (28). As there was no schedule imposed for the completion of the R24W, for the purpose of this analysis, data of subjects who completed two weekdays and one weekend day were gathered for the comparison with the FR (107 participants; 57 women and 50 men). In cases where all 4 recalls were eligible, we chose the first two weekdays and the first weekend day completed. Mean intakes from the 3-day FR and from the three days of R24W were used in the analyses. During the testing period, subjects were asked not to make any noticeable changes in their usual diet. Use of diet supplements was not taken into account for this validation analysis. Each participant also had to complete questionnaires to gather information about medical history (including questions about weight stability) and socio-demographic variables.

Statistical Approaches

Mean intakes and standard deviations for energy and 24 nutrients were assessed with the R24W and the FR. More precisely, carbohydrates, proteins, fat, % of energy from carbohydrates, % of energy from proteins and % of energy from fat, fibre, vitamin A, thiamin, riboflavin, niacin, vitamin B6, folic acid, vitamin B12, vitamin C, vitamin D, magnesium, zinc, iron, calcium and potassium were selected because they are recognized as key nutrients in the Canada's Food Guide (31). Saturated fatty acids, sodium and alcohol were also assessed because of their importance in the etiology of metabolic diseases (32,33). Student's paired t-test was used to determine whether there was a significant difference between the two methods in the assessment of each selected nutrient. Then, the strength of the association between reported intakes using the R24W and reported intakes with the FR was assessed for each nutrient with Pearson correlation coefficient. Analyses were conducted on raw and on de-attenuated sex- and energy-adjusted data. The adjustment for energy was calculated using the residual method (16). The de-attenuation was computed using the ratio of within and between person variability of each tool and the number of days of data collection in order to adjust for day-to-day variation in intakes (19). Cross-classification (percentage of agreement) and weighted Kappa were assessed in order to determine if both methods tended to classify respondents in the same quartile. Then, Bland-Altman plots were used to assess agreement at an individual level across the range of intakes. Bland-Altman plots show the relation between the difference and the average of two measures. A significant association demonstrates a proportional bias between these two measures (34). Lastly, relative validity outcome of each test was compared with criteria proposed by Lombard et al. (20), based on the work of other authors (35–38) and categorized as good (G), acceptable (A) or poor (P) to provide an overview of the relative validity of all nutrients tested. Relative validity was considered good in each of these situations: de-attenuated sex- and energy-adjusted correlation coefficient ≥0.50, classification of ≥50% of respondents in the same quartile, classification of <10% of respondents in the opposite quartiles, weighted Kappa ≥0.61, ≤10.9% of difference between measures from both methods, non-significant (P≥0.05) Student's t-test and non-significant slope in the Bland-Altman plot (P≥0.05). Relative validity could be judged as being acceptable when de-attenuated sex- and energy-adjusted correlation coefficient was between 0.20 and 0.49, when the weighted Kappa was between 0.20 and 0.60 and when the difference between measures from both methods was between 11 and 20%. Finally, relative validity was considered poor when de-attenuated sex- and energy-adjusted correlation coefficient was <0.20, when <50% of respondents were classified in the same quartile, when ≥10% of respondents were classified in the opposite quartile, when weighted Kappa was <0.20, when the difference between measures from both methods was ≥ 20% and when results from Student's t-test and the slope from the Bland Altman plot were significant (≤0.05). Agreement between tests and overall relative validity were then evaluated by the total of good, acceptable and poor validity scores obtained for each nutrient.

In order to determine the relative validity of energy intake assessed by the R24W, a comparison between reported intakes and estimated energy needs was conducted to identify under-reporters, adequate reporters and over-reporters. BMR was estimated with the Mifflin-St Jeor equation (39) and under-reporters were classified as individuals with rEI:BMR ratio <1.35 while over-reporters were classified as those with rEI:BMR ratio > 2.5 (10). Lastly, to determine if a similar number of under-reporters was identified with the new tool and the FR, the McNemar chi-square test for paired data was used to compare under-reporters (rEI:BMR <1.35) and non-under-reporters (rEI:BMR ≥ 1.35) between the two dietary assessment methods.

Log-transformed data were used to improve normality for all variables. Statistical analyses were conducted with the software SAS version 9.4 (SAS Institute Inc., NC, USA).

Results

The main characteristics of the participants are presented in Table 1. Mean age of the participants was 47.4 ±13.3 years and they had a mean body mass index of 25.5 ± 4.4 kg/m2. Fifty-seven percent of them have reported being weight stable for the last three months. Ninety-six percent of participants were Caucasian and 63.6% had a university degree.

Table 2 presents differences in percentage as well as correlations between R24W and FR for energy and nutrient intakes. Mean values of 18 out of 25 variables assessed with R24W (72%) were within 10% of the mean values obtained with FR. The largest differences were observed for niacin (-54.8%) and alcohol (40.0%). rEI, fat intake, alcohol intake, % of energy from carbohydrates and proteins, saturated fatty acid intake as well as intakes of eight micronutrients were significantly different between the R24W and the FR ($P<0.05$). However, all raw correlations ($r=0.28$-0.61) and all but one (zinc at $r=0.02$) sex- and energy-adjusted de-attenuated correlations ($r=0.35$-0.72) were significant ($P<0.01$).

The cross-classification analysis indicated that, on average, the participants were classified in the same quartile in 40.0% of the cases (range 29.9-50.5%) and in the adjacent quartile in 40.0% of the cases (range 27.1-46.7%) while they were grossly misclassified (e.g. classified in quartile 1 with one method and quartile 4 with the other method) in 3.6% of the cases (range 0.9-6.5%; Table 3). Kappa statistics ranged from 0.16 to 0.47 with an average of 0.33 (Table 3). The Bland Altman analysis showed a proportional bias for some of the nutrients, but with different patterns. For fat, alcohol, vitamin D and zinc, intakes assessed with the R24W were on average higher than intakes from the FR and the degree of overestimation was proportional to levels of intake. For vitamin A and magnesium, there was only a noticeable difference in intakes assessed by both tools in those who reported consuming the largest amounts of these nutrients. Intakes of niacin were underestimated by the R24W compared to the FR and this underestimation became more important in those who consumed a larger amount of niacin. Finally, the intake of vitamin C seemed to be overestimated by the R24W in those who consumed a smaller amount and underestimated in those who consumed a larger amount relatively to the FR (plots in supplementary material). Next, Table 4 combines the relative validation assessment of the six tests performed. Protein was the nutrient for which assessment with both tools demonstrated the highest agreement while all tests resulted in good or acceptable relative validity outcomes. Carbohydrate, percent of fat, folic acid, vitamin C, iron, potassium and fibre also received mostly results of good or acceptable relative validity outcomes and only had one poor outcome which was related to the proportion of classification in the same quartile (below 50%). However, for niacin, vitamin C and zinc, results for the majority of the tests (4/7) corresponded to poor outcomes.

Lastly, based on data from the R24W, 15.0% of participants were characterized as under-reporters, compared with 23.4% with the FR (Table 5). When we classified the participants as under-reporters or non-under-reporters, we observed that the difference in the proportion of under-reporters between methods did not reach statistical significance (P=0.07). Almost three out of every four participants (72.9%) were classified within the same category by both tools, 26.2% were one category apart (for example, under-reporter with one method and adequate reporter with the other one) while only one participant (0.9%) was grossly misclassified (identified as an under-reporter with the R24W and as an over-reporter with the FR). Lastly, the proportion of participants who reported a recent weight loss was not higher in the under-reporter group (18.8% in under-reporters vs. 22.0% in adequate reporters and 0% in over-reporters, P=0.79 as assessed by the R24W; 28.0% in under-reporters vs. 18.8% in adequate reporters and 0% in over-reporters, P=0.48 as assessed by the FR).

Discussion

It is of first importance to test the validity of newly developed food assessment tools. This study showed an acceptable level of agreement for energy and nutrient intakes between data generated by a newly developed 24-hour recall, the R24W, and data from the FR, used as the reference method.

In terms of nutrient intakes, our results are comparable to those of the EPIC-soft study, in which intakes from computer-assisted 24-hour recalls were compared to intakes assessed with a FR. In that study, raw correlation coefficients between the two methods for energy and nutrient intakes ranged from 0.16 to 0.62 (25). Many nutrients for which significant differences were observed in the EPIC-soft study are the same as the ones for which we observed differences in our study. Indeed, in both studies, there was a difference in reported intakes of energy, fat, saturated fatty acids, vitamin C, thiamin and riboflavin. Furthermore, results from both studies revealed that energy intake was higher when assessed with 24-hour recalls than with the FR, and it was associated with a higher reported intake of fat. As stated by De Keyzer et al. (25), the higher value of reported fat intake with 24-hour recalls than with the FR could be related to the numerous questions included about frequently forgotten food items like added fat, spreads or sauces. This higher value of reported fat intake could indeed reflect a more reliable assessment of fat, a nutrient known to be often underestimated in biomarkers studies (40).

Our analysis showed that the average sex- and energy-adjusted de-attenuated correlation coefficient was 0.52, which respects the criterion for a good relative validity outcome (35). Regarding cross-classification, although all nutrients except one (protein) did not reach the criterion for good relative validity, our results are comparable to those of others. Indeed, for all nutrients, an average of 80% of participants were classified in the same or the adjacent quartile. Moreover, fewer than 10% (range 0.9-6.5%) of the participants were classified in the opposite quartile showing a very low proportion of extreme misclassification. These results are similar to those of a study in which a FFQ was validated with a FR in a similar population where, on average, 77.0% of participants were classified in the same or the adjacent quartile and 5.0% were grossly misclassified (opposite quartiles) (41). The Bland-Altman analysis revealed that the magnitude of the difference between both tools was not equal through the range of mean intakes for eight nutrients. This means that the average difference between the two tools increases in the larger or the smaller values. This is not an unusual observation. In a study aiming to evaluate the validity of a new FFQ designed for assessing adolescents' intakes, Ambrosini et al. (42) observed that 19/22 nutrients tested showed a significant proportional bias in either boys or girls as illustrated by the regression line of the Bland-Altman plot.

The relative validity was not the same for all nutrients studied. However, for fibre, saturated fatty acids and sodium, which are nutrients frequently associated with metabolic health (32,43), we mostly obtained results associated with good or acceptable relative validity. This suggests that the R24W would be an adequate tool to assess dietary intakes in nutritional epidemiological studies addressing issues related to metabolic health. It is worth mentioning that reported intakes for saturated fatty acids, sodium and alcohol are higher with the R24W than with the FR. This supports the idea that social desirability bias is reduced with the web-based dietary assessment tool.

Overall, there are three nutrients in our study for which the relative validity is questionable. For niacin and vitamin C, poor validity outcomes are mainly related to criteria of agreement at a group level while for zinc, associations and agreement at the individual level as well as agreement at a group level seem to be poor. Since each self-reported dietary assessment tool has some limitations, it is not possible to determine based on our results that the R24W would systematically produce erroneous estimation for these specific nutrients. However, it would be wiser to interpret with caution estimation of those nutrients evaluated with the R24W. Our next step will be to identify food items that could explain the large discrepancies between the two methods compared. In a larger perspective, it seems that the tests used to evaluate agreement at a group level (% difference, Student's t-test and Bland-Altman) and those evaluating agreement at an individual level (Pearson correlations, cross-classification and Kappa) were characterized by an equivalent number of good and poor outcomes for the majority of nutrients tested. This, combined with the small proportion of the cohort characterized as under-reporters, suggests that this new web-based 24-hour recall would be suitable to assess dietary intakes in research projects aiming to evaluate intakes either at a group or at an individual level.

Underreporting of dietary intakes has been identified as a major issue for which dietary assessment tools are often criticized. However, this study demonstrated that the R24W did not produce a higher prevalence of under-reporters compared to the FR. Prentice et al. (2011) conducted a study where they compared reported energy intake using a 4-day FR and 3 days of 24-hour recall with DLW as a biomarker of energy intake. Similar to what we found, they noticed only a slight difference between the two methods in the proportion of participants identified as under-reporters (5).

It is important to mention that this study aimed to compare usual intakes as assessed by two different tools and that a perfect agreement was not expected. Indeed, data were collected on different days with two self-reported methods associated with some degree of imprecision. Furthermore, even if the FR is considered as a gold standard, it has been widely reported that individuals who filled in FR tend to modify what they eat because they know they are being evaluated. This is called a reactivity bias. This could result in an underestimation of some nutrients such as fat and alcohol (44) and in an apparent overestimation generated by other tools in a comparative context (19). This could explain the discrepancies observed between the FR and the R24W for these two nutrients. The reactivity bias is not a problem with a 24-hour recall because participants do not know in advance which days will be assessed. However, if participants experience difficulties with short-term memory, assessment by the 24-hour recall would be affected (45). Moreover, the R24W offers a wide selection of food items and mixed dishes (28) but, contrary to the FR where participants could virtually write any possible item, in the R24W, choices are limited, which could force some respondents to use predetermined recipes slightly different from what they actually ate.

We also have to stress that we conducted this study with a rather small homogenous cohort of highly educated adults that is not fully representative of the French-Canadian population. These characteristics of the sample limit the generalizability of the results to different populations. Furthermore, we only used three days of FR and of R24W. For the purpose of this study, we stipulated that this period represented a good estimation of usual intakes. We decided to do so to limit the burden on participants and also because we wanted to validate the tool in a context suitable for larger studies. It is also of importance to mention that we decided not to exclude the under-reporters from the analysis in order to keep a representative sample.

Compared to most of the validation studies published so far, we improved the analysis by pooling the results of six validation tests to get an overview of the validity for each nutrient. This approach allowed us to identify for which nutrient the tool was more effective using the FR as a reference method.

Conclusion

This paper assessed the relative validity of a new web-based self-administered 24-hour recall, the R24W, for energy intake and 24 selected nutrients using six different statistical tests in a cohort of French-Canadian adults. This comparative analysis with FR suggests that the R24W has an acceptable level of relative validity for most nutrients as well as for energy. However, assessment of niacin, vitamin C and zinc with the R24W should be interpreted with caution considering results obtained in the present study.

Abbreviations

BMR: Basal metabolic rate

DEE: Daily energy expenditure

DLW: Doubly labelled water

FR: Food record

FFQ: Food frequency questionnaire

rEI: Reported energy intake

Disclosures

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Conflicts of Interest

None

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Tables

Table 1: Participants' characteristics (N=107)

	All participants (N=107) [1]
Women (%)	53.3
Age (years)	47.4 ± 13.3
Body mass index (kg/m^2)	25.5 ± 4.4
Waist circumference (cm)	89.1 ± 13.4
Weight stable over the last three months (%)	57.0
Weight gain over the last three months (%)	22.4
Weight loss over the last three months (%)	20.6
Estimated basal metabolic rate – Mifflin (kcal/day)	1483.8 ± 293.5
Ethnicity – Caucasian (%)	96.3
Education - High school (%)	5.6
College (%)	30.8
University (%)	63.6

[1] Values are presented as means ± standard deviation, or percentage (%)

Table 2: Average intakes of energy and nutrients and correlation coefficients between values derived from the web-based self-administered 24-hour dietary recall (R24W) and the food record (FR)

	R24W[1] (SD[2])	**FR[3] (SD)**	**% difference**	**Raw correlation**	**Sex- and energy-adjusted de-attenuated correlation**
Energy (kcal)	2595 (761)	2408 (710)	7.2*	0.57*	0.64*
Carbohydrates (g)	290.6 (76.1)	277.7 (82.7)	4.4	0.53*	0.61*
Fat (g)	105.5 (44.2)	95.8 (36.7)	9.2*	0.54*	0.54*
Proteins (g)	104.3 (32.8)	99.7 (29.1)	4.4	0.61*	0.54*
% Carbohydrates	43.8 (6.9)	46.7 (7.4)	-6.6*	0.52*	0.62*
% Fat	35.8 (6.0)	35.3 (6.4)	1.4	0.48*	0.63*
% Proteins	16.2 (2.6)	16.8 (2.8)	-3.7*	0.45*	0.64*
Fibre (g)	25.3 (8.7)	26.9 (8.7)	-6.3	0.47*	0.64*
Vitamin A (µg)	1019.4 (726.7)	1053.5 (982.1)	-3.3	0.35*	0.41*
Thiamin (mg)	2.0 (0.6)	1.9 (0.7)	5.0*	0.45*	0.48*
Riboflavin (mg)	2.7 (0.9)	2.4 (0.8)	11.1*	0.55*	0.55*
Niacin (mg)	30.5 (10.9)	47.2 (15.5)	-54.8*	0.53*	0.51*
Vitamin B6 (mg)	2.2 (0.6)	2.1 (0.7)	4.5*	0.46*	0.44*
Folic acid (µg)	440.9 (130.6)	456.8 (136.2)	-3.6	0.33*	0.35*
Vitamin B12 (µg)	6.1 (4.5)	5.6 (4.4)	8.2	0.28*	0.38*
Vitamin C (mg)	131.8 (65.6)	174.9 (96.5)	-32.7*	0.61*	0.72*
Vitamin D (µg)	6.3 (4.3)	5.5 (3.1)	12.7	0.35*	0.46*
Magnesium (mg)	463.7 (149.5)	461.1 (177.8)	0.6	0.52*	0.65*
Zinc (mg)	14.1 (4.8)	12.8 (3.9)	9.2*	0.38*	0.02
Iron (mg)	17.2 (4.9)	16.5 (4.9)	4.1	0.34*	0.46*
Calcium (mg)	1281.4 (450.3)	1117.3 (396.7)	12.8*	0.53*	0.50*
Potassium (mg)	3676.4 (954.7)	3776.9 (990.2)	-2.7	0.53*	0.66*
Alcohol (g)	16.1 (15.6)	11.5 (13.0)	40.0*	0.53*	0.69*
Saturated fatty acids (g)	35.4 (17.8)	30.7 (15.1)	13.3*	0.58*	0.47*
Sodium (mg)	3455.4 (1127.0)	3154.9 (1110.0)	8.7*	0.55*	0.36*
Average (SD)			1.7 (16.9)	0.48 (0.09)	0.52 (0.15)

* Student's t-test and Pearson correlation with a P-value < 0.05 [1] R24W= Web-based self-administered 24-hour dietary recall [2] SD= Standard deviation [3] FR= Food record

Table 3: Cross-classification of energy and nutrient intakes into quartiles of the distribution using either the web-based self-administered 24-hour dietary recall or the food record

	%				
	Same quartile	**Adjacent quartiles**	**± 1 Quartile apart**	**Misclassification (quartile 1 vs. 4)**	**Kappa score**
Energy (kcal)	40.2	43.0	83.2	3.7	0.35
Carbohydrates (g)	42.1	42.1	84.1	6.5	0.35
Fat (g)	45.8	36.4	82.2	2.8	0.40
Proteins (g)	50.5	38.3	88.8	4.7	0.47
% Carbohydrates	34.6	42.1	76.6	4.7	0.25
% Fat	35.5	42.1	77.6	2.8	0.28
% Proteins	45.8	31.8	77.6	3.7	0.35
Fibre (g)	43.0	42.1	85.0	2.8	0.40
Vitamin A (µg)	47.7	27.1	74.8	4.7	0.34
Thiamin (mg)	31.8	45.8	77.6	2.8	0.25
Riboflavin (mg)	40.2	40.2	80.4	0.9	0.35
Niacin (mg)	41.1	43.0	84.1	1.9	0.38
Vitamin B6 (mg)	33.6	45.8	79.4	6.5	0.25
Folic acid (µg)	39.3	35.5	74.8	5.6	0.26
Vitamin B12 (µg)	38.3	42.1	80.4	6.5	0.29
Vitamin C (mg)	42.1	39.3	81.3	1.9	0.37
Vitamin D (µg)	29.9	41.1	71.0	5.6	0.16
Magnesium (mg)	42.1	34.6	76.6	4.7	0.31
Zinc (mg)	31.8	40.2	72.0	2.8	0.20
Iron (mg)	36.4	42.1	78.5	4.7	0.28
Calcium (mg)	39.3	44.9	84.1	1.9	0.37
Potassium (mg)	36.4	46.7	83.2	1.9	0.34
Alcohol (g)	50.5	33.6	84.1	1.9	0.47
Saturated fatty acids (g)	37.4	45.8	83.2	2.8	0.34
Sodium (mg)	46.7	33.6	80.4	1.9	0.40
Average (SD[1])	40.0 (5.7)	40.0 (5.0)	80.0 (4.3)	3.6 (1.7)	0.33 (0.1)

[1] SD= Standard deviation

Table 4: Statistical test outcomes and proportion of poor outcomes for the relative validity of the web-based self-administered 24-hour dietary recall (R24W)

	Validity at the individual level			Validity at a group level			
Characteristics assessed	Association	Agreement	Agreement	Agreement	Agreement	Presence, direction and extent of bias	
Tests	Correlation coefficient	Cross-classification	Kappa Statistic	% difference	Student's t-test	Bland Altman (slope of the regression)	Proportion of poor outcomes (/7)
Criteria for good outcome (G)	≥0.50	≥ 50% in the same quartile; <10% in opposite quartile	≥0.61	0-10.9%	P>0.05	P>0.05	
Criteria for acceptable outcome (A)	0.20-0.49		0.20-0.60	11.0-20%			
Criteria for poor outcome (P)	<0.20	<50% in the same quartile; ≥10% in opposite quartile	<0.20	>20%	P≤0.05	P≤0.05	
Energy (kcal)	G	P-G	A	G	P	G	2
Carbohydrates (g)	G	P-G	A	G	G	G	1
Fat (g)	G	P-G	A	G	P	P	3

Proteins (g)	G	G-G	A	G	G	G	0
% Carbohydrates	G	P-G	A	G	P	G	2
% Fat	G	P-G	A	G	G	G	1
% Proteins	G	P-G	A	A	P	G	2
Fibre (g)	G	P-G	A	G	G	G	1
Vitamin A (µg)	A	P-G	A	G	G	P	2
Thiamin (mg)	A	P-G	A	G	P	G	2
Riboflavin (mg)	G	P-G	A	A	P	G	2
Niacin (mg)	G	P-G	A	P	P	P	4
Vitamin B6 (mg)	A	P-G	A	G	P	G	2
Folic acid (µg)	A	P-G	A	G	G	G	1
Vitamin B12 (µg)	A	P-G	A	G	G	G	1
Vitamin C (mg)	G	P-G	A	P	P	P	4
Vitamin D (µg)	A	P-G	P	A	G	P	3
Magnesium (mg)	G	P-G	A	G	G	P	2
Zinc (mg)	P	P-G	A	G	P	P	4
Iron (mg)	A	P-G	A	G	G	G	1
Calcium (mg)	G	P-G	A	A	P	G	2
Potassium (mg)	G	P-G	A	G	G	G	1
Alcohol (g)	G	G-G	A	P	P	P	3
Saturated fatty acids (g)	A	P-G	A	G	P	G	2
Sodium (mg)	A	P-G	A	G	P	G	2

G=Good outcome; A=Acceptable outcome; P=Poor outcome

Table 5: Proportion of under-, adequate and over-reporters assessed by the ratio between reported energy intake and basal metabolic rate as determined with the web-based self-administered 24-hour dietary recall (R24W) and the food record (FR).

	Total (107)		Men (50)		Women (57)	
	R24W[1]	FR[2]	R24W	FR	R24W	FR
Under-reporters (ratio[3]<1.35)	15.0%	23.4%	20.0%	24.0%	10.5%	22.8%
Adequate reporters (ratio 1.35-2.5)	80.4%	74.8%	72.0%	72.0%	87.7%	77.2%
Over-reporters (ratio>2.5)	4.7%	1.9%	8.0%	4.0%	1.7%	0.0%

[1] R24W=Web-based self-administered 24-hour dietary recall [2] FR= Food record
[3] Ratio=reported energy intake/basal metabolic rate

Additional files

1. Bland-Altman plot for the agreement between **fat** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d=9.7; r=0.19; P=0.03; LOA= -70.9 to 90.2

2. Bland-Altman plot for the agreement between **alcohol** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= 4.6; r= 0.22; P= 0.02; LOA= 22.6 to 31.8

3. Bland-Altman plot for the agreement between **vitamin A** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= -34.1; r= -0.15; P<0.01; LOA= -2416.4 to 2348.2

4. Bland-Altman plot for the agreement between **niacin** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= -16.7; r= -0.33; P<0.01; LOA= -43.4 to 10.0

5. Bland-Altman plot for the agreement between **vitamin C** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= -43.2; r= -0.44; P<0.01; LOA= -193.4 to 107.1

6. Bland-Altman plot for the agreement between **vitamin D** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= 0.82; r= 0.20; P<0.01; LOA= -8.5 to 10.2

7. Bland-Altman plot for the agreement between **magnesium** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= 2.6; r= -0.22; P= 0.02; LOA= -268.6 to 290.9

8. Bland-Altman plot for the agreement between **zinc** intakes assessed by the Food Record (FR) and the web-based self-administered 24-hour dietary recall (R24W), d= 0.64; r= 0.16; P= 0.03; LOA= -4.1 to 5.3

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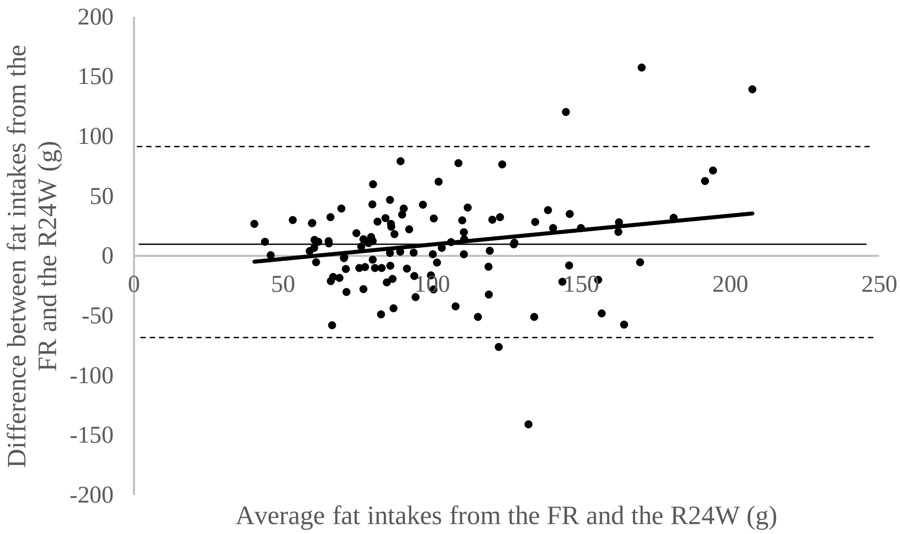

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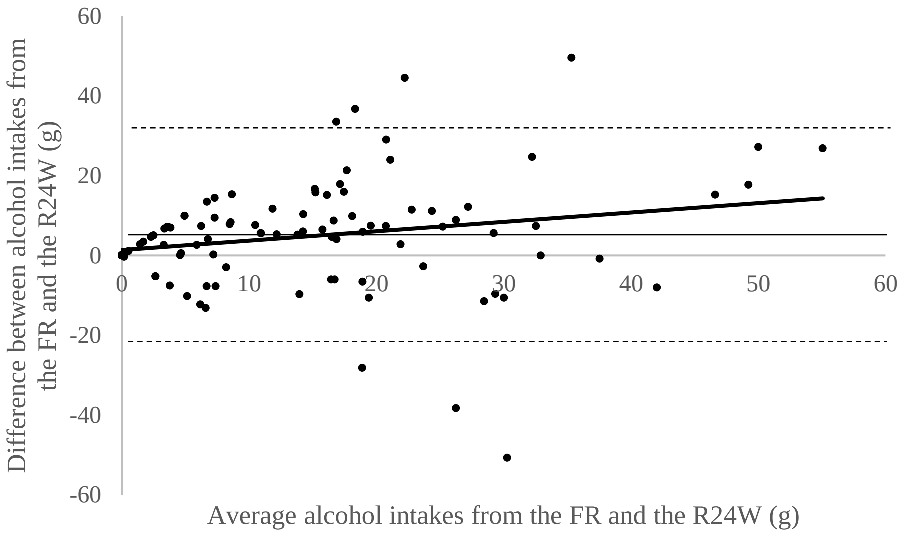

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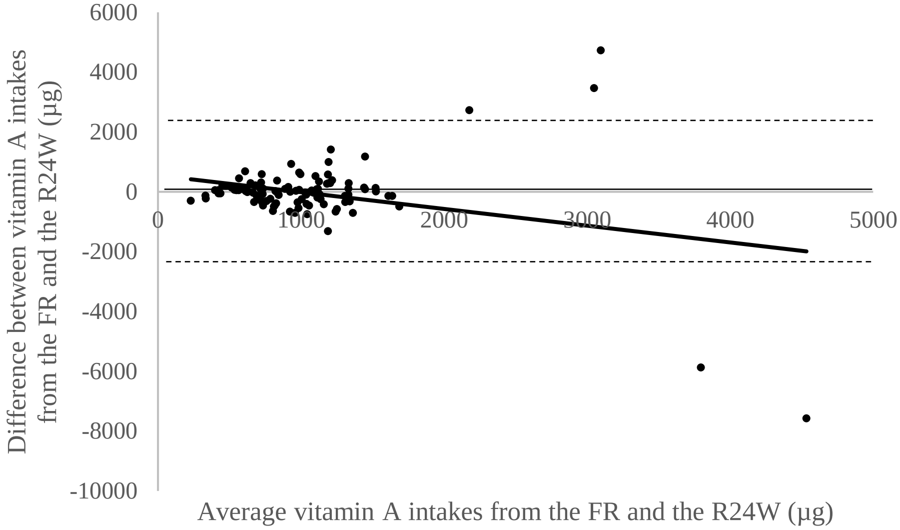

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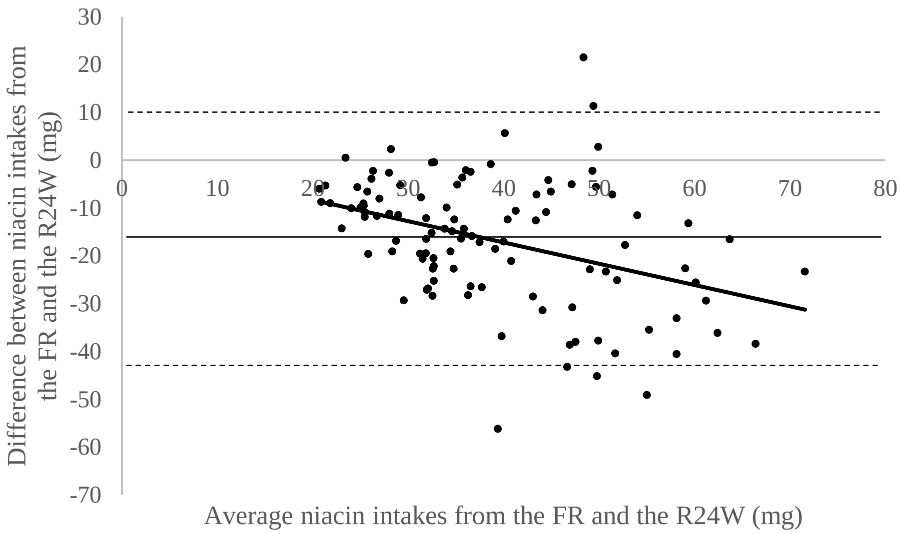

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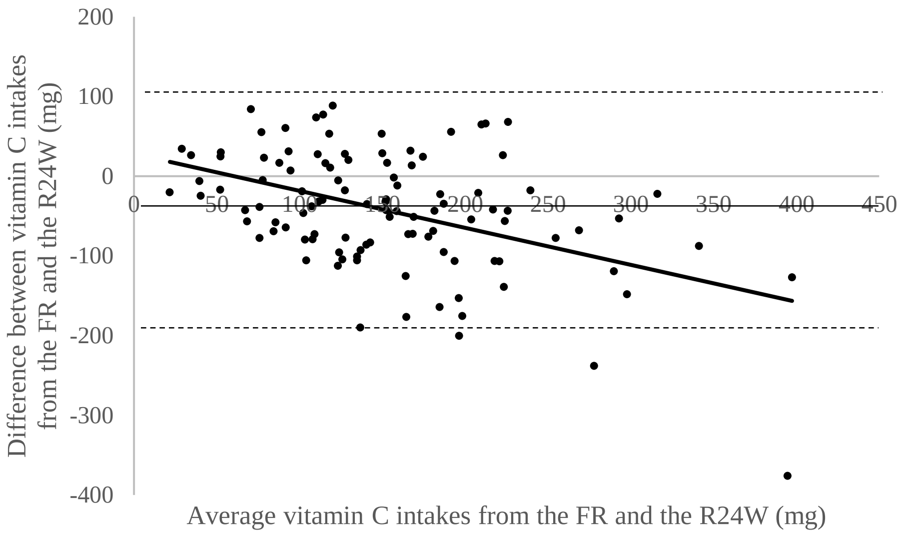

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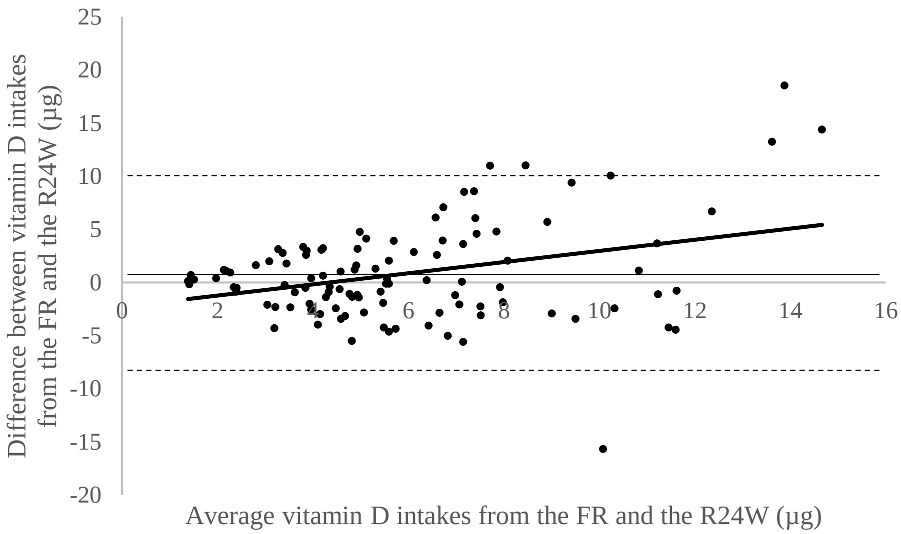

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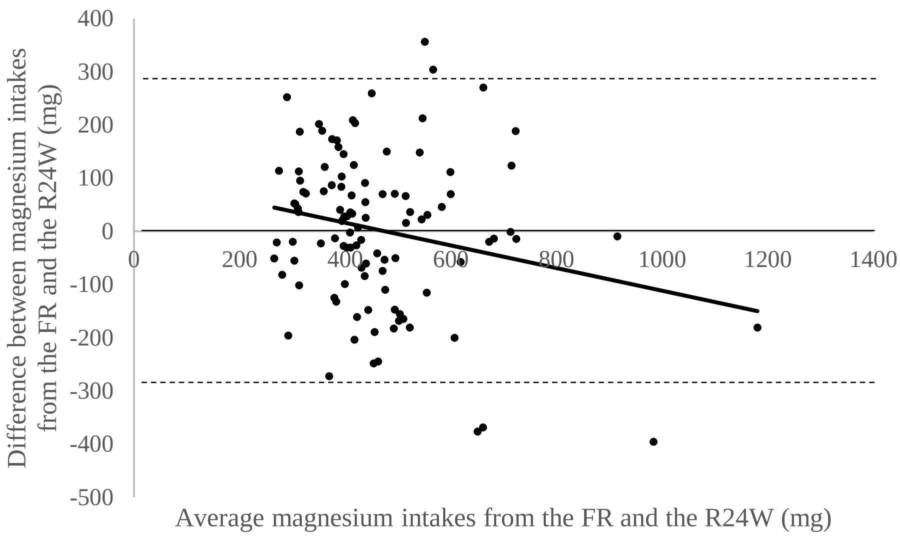

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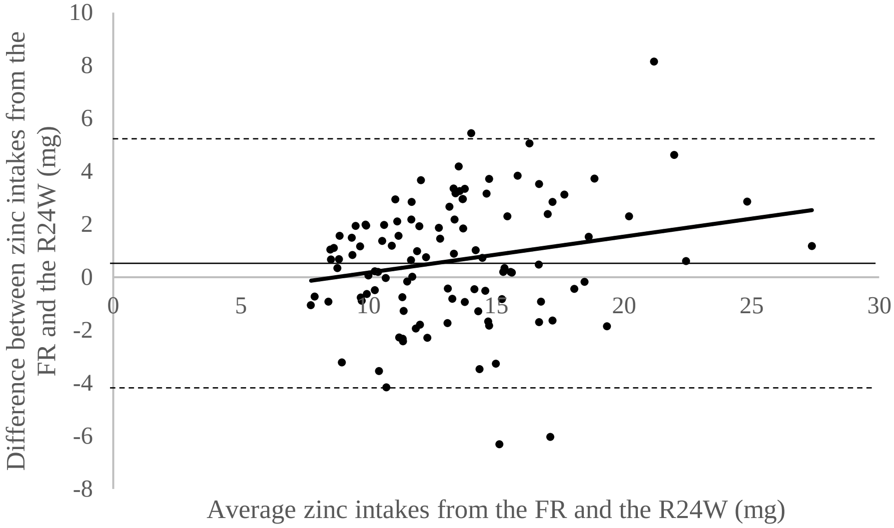

Chapitre 5: Relative validity of a web-based self-administered 24-hour dietary recall to evaluate adherence to Canadian dietary guidelines.

Résumé

Un nouveau rappel de 24 heures sur plateforme web (R24W) a été développé et programmé afin d'évaluer l'adhésion aux recommandations nutritionnelles canadiennes en produisant automatiquement le score Healthy Eating Index canadien 2007 (C-HEI 2007). L'objectif de cette étude était de déterminer la validité relative du R24W concernant son habilité à générer un score C-HEI 2007 comparable à celui d'une mesure de référence soit le journal alimentaire. Pour ce faire, 57 femmes et 50 hommes ont complété un journal alimentaire de trois jours et ont rempli le R24W à trois reprises. En somme, bien que le R24W ait produit des scores C-HEI 2007 plus faibles que le journal alimentaire, la classification des répondants était hautement cohérente entre les deux outils.

Title page

Title: Relative validity of a web-based self-administered 24-hour dietary recall to evaluate adherence to Canadian dietary guidelines.

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Keywords: Healthy Eating Index, 24-hour dietary recall, food record, diet quality, Canada's food guide

Abstract

Objective: A new web-based 24-hour recall (R24W) was developed and programmed to assess adherence to Canadian dietary guidelines by generating automatically the Canadian Healthy Eating Index 2007 (C-HEI 2007). The aim of the present study was to determine the relative validity of the R24W in terms of its ability to generate C-HEI 2007 scores that match those derived from a food record (FR).

Research Methods & Procedures: Fifty-seven women and fifty men filled a three-day FR and three 24-hour food recalls with the R24W. C-HEI 2007 was calculated with both dietary assessment tools and compared using de-attenuated correlations and kappa scores. Internal validity (correlations between total score and components) and external validity (comparison of the C-HEI 2007 by sex and age groups) were compared between the two dietary assessment methods.

Results: The average C-HEI 2007 score obtained with the R24W (59.4 ±11.8) was significantly lower than the one obtained with the FR (62.6 ±11.1). However, the de-attenuated correlation coefficient between C-HEI 2007 obtained either with R24W or FR was 0.80 ($P<0.01$) and 91.6% of the participants were classified in the same or the adjacent quartile of C-HEI 2007 with both tools. Women obtained a higher C-HEI 2007 mean score ($P<0.01$) with both methods and older adults (> 51 y) received a higher score than younger adults (18-30 y) ($P<0.01$) with the R24W, but not with the FR ($P=0.22$).

Conclusion: Although the R24W yields lower C-HEI 2007 scores compared with data from FR, classification of individuals was highly consistent between the two measurements.

Introduction

In Canada, dietary guidelines are issued by Health Canada. The latest revision was proposed in 2007 in Canada's Food Guide (CFG) (1). Food patterns proposed in the CFG were first developed to achieve age and sex-specific targets. These recommendations are based on the evidence of the relationship between food intakes and chronic diseases (2). Second, food patterns developed were analyzed and needed to yield fewer than 10% of diets not reaching the Estimated Average Requirement (EAR) from the Institute of Medicine (3) (or the Adequate Intake (AI) for nutrients that did not have EAR). A subsequent analysis by Elvidge Munene et al. (4) demonstrated that diets in line with the CFG achieve this last objective.

A recent meta-analysis demonstrated that appropriate intakes of whole grains, vegetables, fruit, nuts and fish lead to a considerable reduction in preventable deaths (5). These food items are all promoted by the CFG. This is one of the key reasons why it is critical to assess adherence to dietary guidelines. However, few validated tools have been developed to measure it. The Healthy Eating Index (HEI) was first proposed by Kennedy et al. in 1995 to assess adherence to the United States Department of Agriculture (USDA) nutritional guidelines (6). Updated versions were then published with the revision of the guidelines in 2005 (7), 2010 (8) and 2015 (9). Some Canadian adaptations of the initial American HEI-1995 were proposed since 2000 (10–12). The Canadian Healthy Eating Index 2007 (C-HEI 2007) which is an updated version inspired by the American HEI-2005 was proposed and validated by Garriguet in 2009 (13). This tool was developed to measure adherence to the 2007 CFG, which is the latest version of the Canadian guidelines.

It is imperative to validate new dietary assessment tools in order to get an adequate representation of dietary intakes. Different types of validation strategies exist and the choice of the strategy depends on the aspect of the tool that has to be validated. For example, the use of biomarkers is relevant when focusing on specific nutrients in the validation strategy. However, it is not the most appropriate approach when aiming to validate the ability of a tool to describe the overall diet quality. In such a context, an assessment of relative validity is a more appropriate approach to use. Relative validity refers to the comparison between food intakes assessed with the new method and intakes assessed with a reference method (14). The food record (FR) is often selected as a comparator because it produces minimal memory biases and because its unstructured form reduces any systematic bias (15).

We recently developed a self-administered web-based 24-hour recall (R24W) intended to assess adherence to Canadian dietary guidelines by generating automatically a C-HEI 2007 score (16). Its validity has first been evaluated in the context of fully controlled feeding studies (17). The aim of this study was to test the relative validity of the R24W in terms of its ability to generate C-HEI 2007 scores that match those obtained with a reference method, the FR.

Material and Methods

Participants

Seventy-five women and 75 men aged between 18 and 68 years from the Quebec City area volunteered to take part in the validation study of a newly developed self-administered web-based 24-hour recall, the R24W. To be included in the study, they had to be free from gastrointestinal disorders in order to avoid interference with blood biomarkers collected for future analyses and women could not be pregnant or lactating. Two men failed to complete all four dietary recalls and were therefore excluded from the analysis. The protocol was in accordance with the declaration of Helsinki and was certified by the Laval University Ethic Committee. All subjects signed a consent form before being involved in the study.

Anthropometric and Food Intakes Assessment

Weight, height and waist circumference were measured by research assistants during a visit to the study laboratory using standardized methods (18). The scale (Body composition analyzer BC-418, Tanita Corporation of America, Inc., Arlington

Heights, IL) had a capacity of 200 kg and the minimum graduation was 100 g. Height was measured without shoes using a height rod stadiometer (Model 216, SECA, SECA Corp, Hamburg, Germany) at the nearest 0.1 cm. Waist circumference measurement was taken at the end of a normal expiration with a tape placed horizontally directly on the skin at the mid-distance between the last rib and the top of the iliac crest. Waist circumference was determined as the mean of three measurements at the nearest 0.1 cm. After, participants received detailed instructions by trained staff on how to fill a three-day paper-based FR. Participants could decide which days they wanted to report as long as they included one weekend day. Participants were encouraged to weigh all the items and to report brand names or recipes when possible to improve the precision and accuracy of the record. Every FR was revised by a trained dietician upon return to ensure that information provided was complete, accurate and clear. This was done in order to minimize any possible bias, the FR being used as the reference method in this validation study. During the following three weeks, participants received, on four unannounced days, a web link by e-mail to fill a 24-hour recall using the R24W. A detailed description of the development process of R24W was published elsewhere (16). In order to standardize the methodology for this study, three out of the four collected days were used and only participants who completed at least one weekend day and two weekdays were included in the analysis (107 participants). For all participants, the first three days that included one weekend day were used in the analysis.

The C-HEI 2007 Score

The scoring system is detailed in Table 1. The same codification technique was used to assess C-HEI 2007 with the R24W and with the FR. The calculation was programmed to be automatically obtained with the R24W. For the FR, trained staff manually coded all the entries. First, complex meals were decomposed into their main components. Then, all food items and main components of complex dishes were individually scored in order to determine the number of CFG servings from each of the eleven C-HEI 2007 sub-scores (1). Foods with a very high fat content (fats, dressings, mayonnaise, cream, etc.), foods with very high sugar content (sugars, honey, jams, syrups, sweets, various sweetened beverages, etc.), foods high in fat, sugar or salt (i.e. classified in the tier 4 according to the 2014 Health Canada Surveillance Tool Tier System (19)) and other ingredients and beverages (unsweetened beverages, sauces, condiments, etc.) were included in the "Other foods" sub-score of the C-HEI 2007. (16). Lastly, the number of daily servings consumed was used to calculate the C-HEI 2007 sub-score according to age and sex. Rather than calculating the average score based on the average number of servings consumed over 3 days, the scores of each day were computed and averaged. This technique was selected to better reflect day-to-day variation in intakes.

Statistical Analyses

Differences between C-HEI 2007 and components derived from the R24W and the three-day FR were assessed with paired T-Test. Then, associations between C-HEI 2007 computed from the R24W and the three-day FR were tested with Spearman de-attenuated correlations (i.e. adjusted for within-subject variability). Cross-classification and kappa scores were also used to assess concordance in C-HEI 2007 between the two food assessment methods. Associations between the total score and all components were also evaluated for the two food assessment methods with Spearman correlations. Then, in order to assess the similarities between the C-HEI 2007 assessed with the R24W and the three-day FR, analyses of external validity were conducted on both. More precisely, total C-HEI 2007 scores were compared between men and women and between age groups to test the hypothesis that women and older adults get higher scores (13,20). Age groups selected were the same as those presented by Guenther et al. in the validation process of the American HEI 2005 and 2010 (21). Statistical procedures were performed using SAS, version 9.4 (SAS Institute Inc, NC, USA) and comparisons of correlation coefficients were computed with MedCalc for Windows, version 15.0 (MedCalc Software, Ostend, Belgium)(22).

Results

The participants' characteristics are presented in Table 2. Women were on average older than men (P=0.04), they had a lower body weight (P<0.01) and waist circumference (P<0.01) while body mass index (BMI) did not differ between women and men (P=0.18).

Table 3 presents the comparison between C-HEI 2007 assessed by the FR and the R24W. The average total score assessed with the R24W was 5.2% lower than the average score obtained with the FR (P<0.01). The association between the two tools was characterized by a de-attenuated correlation coefficient of 0.80 (P<0.01) and a weighted kappa of 0.49. It was found that 91.6% of the participants were classified in the same or the adjacent quartile of C-HEI 2007 scores determined by the two methods. Sub-score for the components vegetables and fruit, saturated fat, sodium and "other foods" were significantly lower when assessed with R24W compared to the FR. De-attenuated correlation coefficients for the associations between components assessed by the R24W and the FR were all significant except for meat & alternatives.

Associations between the total C-HEI 2007 score and its components as assessed by the FR or the R24W are presented in Table 4. All Spearman correlations were significant with the FR. For the R24W, there was no significant association between C-HEI 2007 and the component milk & alternatives as well as with the component meat & alternatives. However, there was no difference between R24W and the FR for the strength of the associations between the total score and their components. No significant association was observed between C-HEI 2007 either assessed by the FR or the R24W and reported energy intake (FR: rs=-0.14 P=0.14; R24W: rs=-0.13 P=0.19; data not shown).

Table 5 presents the analysis of external validity of the C-HEI 2007 measured by the R24W and the FR. Women on average obtained higher total score than men (P<0.01) with both food assessment methods. Older adults obtained on average a higher total score than younger adults with the R24W ($P<0.01$) but not with the FR ($P=0.22$).

Discussion

In many contexts, diet quality scores gradually tend to replace specific nutrient intakes in nutritional evaluation (23). Indeed, they allow investigators to capture interactions between nutrients and food consumption patterns. These scores are useful to evaluate the degree of adherence to dietary guidelines. In the present study, the relative validity of three days of 24-hour dietary recalls assessed with the new R24W was investigated in relation to a three-day paper-based FR to assess adherence to the CFG.

Results from this study suggest that the average C-HEI 2007 produced by the R24W is lower than the score produced by the FR. However, the new tool demonstrated a high level of agreement with the reference method in the classification of respondents. Indeed, 91.6% of individuals were classified in the same or the adjacent quartile by both dietary assessment methods, even if the analysis was conducted on different days. The de-attenuated correlation between both methods was also high (0.80) and the weighted kappa statistics (0.49) indicated moderate agreement (24). For all the components, the de-attenuated correlation coefficient ranged between 0.42 and 0.67 except for the meat & alternatives sub-score. However, it is interesting to note that with both tools, several participants (20% with the R24W and 28% with the FR) reported consuming on average more servings of meat & alternatives than recommended in CFG. Considering that a perfect score is obtained when intakes meet or exceed the recommendations (Table 1), all those participants received 10/10 for this component. This produced a plateau effect that can explain a very low correlation ($r_s=0.09$).

C-HEI 2007 assessed by the R24W was significantly lower than C-HEI 2007 assessed by the FR (-5.2%). Sub-score for saturated fatty acids (-13.5%), sodium

(-15.0%) and “other foods” (-13.4%), were all lower when assessed with the R24W which indicates a greater consumption of these nutrients or food items when assessed with the R24W. Meanwhile, sub-score for the vegetables and fruit component was also lower (-6.7%), in this case, showing a lower consumption when assessed with the R24W. These differences between the R24W and FR could be attributed to the inherent differences of the two methods compared. Even if the FR is often used as a reference method, it induces a certain level of reactivity bias with respondents. Indeed, being aware that their food intakes are evaluated, they could change their usual habits in order to appear more in line with some social standard or to simplify their meals to save time while reporting them (25). With an unannounced, retrospective 24-hour dietary recall, respondents cannot change their feeding habits. The introduction of web-based and technology assisted dietary assessment method, like the R24W, also reduces desirability bias often reported in studies with administered questionnaires because of the higher perceived anonymity with which they are associated (26,27). However, 24-hour recalls are not free from bias. Respondents with less effective short-term memory may be at risk of forgetting some of the food items they ate the day before. Consequently, it could be suggested from results of the present study that respondents forgot some of the vegetables and fruit consumed when completing 24-hour food recalls. However, it appears that they were less likely to forget sources of saturated fatty acids, sodium and items of the “other foods” as their reported intakes were higher with the R24W than with the FR. These contradictory observations, somehow, invalidate the hypothesis that a significant memory bias with the R24W could explain the results obtained. Lastly, we believe that the lower average diet quality score obtained with the R24W is an interesting result which suggests that the web-based 24-hour recall reduces the propensity to prettify food intakes, a recurring criticism of self-reported dietary assessment methods (28).

The patterns of correlations between the total C-HEI score and individual components of the score were similar for both tools. Indeed, we observed that in both cases, “other foods”, total vegetables and fruit and whole fruit demonstrated the strongest associations with the total C-HEI score. This supports the observations from Garriguet who showed in a cohort representative of the Canadian population similar patterns of correlations between individual components and the total score (13). Furthermore, the strength of the associations between each component and the total score did not differ by food assessment method. C-HEI 2007 assessed with the R24W did not correlate with the component milk & alternatives and meat & alternatives. In the validation of the American HEI-2010, Gunther et al., also observed that the milk and alternatives (dairy) component did not correlate with the total score (21) and Garriguet noted the same observation when validating the C-HEI 2007 (13).

As reported by others (13,20,21), we observed that women obtained higher overall scores as determined by the R24W and the FR. However, participants aged 51 years and older obtained a higher C-HEI 2007 score compared to the youngest ones (18-30 years old) only with the R24W. Differences in diet quality between age groups have been reported by Hiza et al. (29). They suggested that older adults tend to become more health conscious as they age and try to improve their dietary quality in order to prevent or to manage chronic diseases. As explained earlier, FR is more susceptible to reactivity (30) and social desirability bias (31,32). This could result in an overall improvement of the observed diet quality and the attenuation of the age-related difference. Since our study was not designed to specifically address the contribution of these bias, further studies will be needed to shed some light on these issues.

It is important to remember that dietary intakes were captured on different days with the R24W and the FR. Perfect agreement was therefore not expected. Even if longer observations would have been needed to assess specific nutrients (33), we propose that this time frame was long enough to be representative of usual diet quality (34). Furthermore, having three days during which food intakes were reported could be considered as a strength of this study since most of the studies on dietary quality scores are conducted on data from food frequency questionnaires and with only one or two days of 24-hour recalls (12,21). Having data on food intakes over a longer period of time improves accuracy of dietary intakes (35,36). It should, however, be mentioned that the validation of the R24W has been conducted in a cohort of French-Canadian adults. Thus, a culturally adapted version may be needed for other populations.

Conclusion

In conclusion, results from this study suggest that the C-HEI 2007 assessed by the R24W demonstrates a good level of agreement with the reference method, the FR. This new web-based method is appropriate to classify respondents according to their level of adherence to the Canadian nutritional guidelines as demonstrated by agreement between the scores obtained on different days with a different method. Moreover, the R24W has the ability to detect expected differences in diet quality between subgroups formed on the basis of sex and age.

Declarations

Authorship

JL, JR, BL and SL were involved in formulating the research question and designing the study, CL was involved in carrying out the study JL was in charge of analyzing the data and writing the article and all authors reviewed and approved the final version.

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Tables

Table 1: Description of the C-HEI 2007 scoring for adults

Component	Range of scores	Scoring criteria
Adequacy	**0 to 60 points**	
Total vegetables and fruit	0 to 10 points	Minimum: 0 Maximum: 7 to 8 servings
Whole fruit	0 to 5 points	Minimum: 0 Maximum: 1.5 to 1.7 servings (21% of recommendation for total vegetables and fruit)
Dark green and orange vegetables	0 to 5 points	Minimum: 0 Maximum: 1.5 to 1.7 servings (21% of recommendation for total vegetables and fruit)
Total grain products	0 to 5 points	Minimum: 0 Maximum: 6 to 8 servings
Whole grains	0 to 5 points	Minimum: 0 Maximum: 3 to 4 servings (50% of recommendation for total grain products)
Milk and alternatives	0 to 10 points	Minimum: 0 Maximum: 2 to 3 servings
Meat and alternatives	0 to 10 points	Minimum: 0 Maximum: 2 to 3 servings (150 to 225 grams)
Unsaturated fats	0 to 10 points	Minimum: 0 Maximum: 30 to 45 grams
Moderation	**0 to 40 points**	
Saturated fats	8 to 10 points	Minimum 7% to 10% of total energy intake
	0 to 8 points	10% to maximum 15% of total energy intake
Sodium	8 to 10 points	Adequate intake to tolerable upper intake level
	0 to 8 points	Tolerable upper intake level to twice tolerable upper intake level
“Other food”	0 to 20 points	Minimum: 5% or less of total energy intake Maximum: 40% or more of total energy intake

Adapted from: Garriguet (2009)
For adequacy components, 0 points for minimum, 5 or 10 points for maximum or more, and proportional for amounts between minimum and maximum.
For moderation components, 10 or 20 points for minimum or less, 0 points for maximum or more, and proportional for amounts between minimum and maximum.

Table 2: Characteristics of participants

	All participants (n=107)	Women (n=57)	Men (n=50)
Age (years)	47,4 (13,3)	50,1 (11,1)	45,1 (14,2)*
Weight (kg)	72,6 (17,5)	64,7 (11,3)	81,4 (19,0)*
BMI (kg/m^2)	25,5 (4,4)	24,7 (4,1)	25,6 (4,4)
Overweight and obese (%)	47,7	40,4	56,0
Waist circumference (cm)	89,1 (13,4)	83,7 (10,8)	92,3 (13,5)*

Data presented as mean (standard deviation)
*Significantly different from women (P<0,05)

Table 3: Estimated mean C-HEI 2007 components and total score as assessed by the food record (FR) and the new web-based 24-hour recall (R24W) and comparison between tools with percent difference, correlation coefficient, cross-classification and weighted kappa (N=107)

	FR (SD)	R24W (SD)	Percent difference (%)	De-attenuated correlation coefficient	Classification in the same or the adjacent quartile	Weighted kappa
C-HEI 2007 (/100)	62.6 (13.8)	59.4 (11.8)	-5.2**	0.80**	91.6	0.49
Total Vegetables and Fruit (/10)	7.9 (2.3)	7.4 (2.2)	-6.7**	0.67**	88.8	0.46
Whole fruit (/5)	3.6 (1.6)	3.4 (1.6)	-6.6	0.62**	79.4	0.29
Dark Green and Orange Vegetables (/5)	3.1 (1.6)	3.0 (1.4)	-3.9	0.58**	81.3	0.30
Total Grains Products (/5)	3.7 (1.2)	3.9 (0.9)	5.1	0.41**	72.0	0.20
Whole Grains (/5)	3.0 (1.7)	2.7 (1.5)	-10.9	0.48**	75.7	0.22
Milk & Alternatives (/10)	6.7 (2.8)	7.0 (2.4)	5.3	0.57**	78.5	0.37
Meat & Alternatives (/10)	8.1 (1.9)	8.0 (1.9)	-1.3	0.09	63.5	0.04
Unsaturated Fats (/10)	5.1 (2.9)	5.6 (2.6)	9.8	0.42**	73.8	0.20
Saturated Fats (/10)	5.9 (2.9)	5.1 (2.7)	-13.5**	0.62**	81.3	0.29
Sodium (/10)	5.4 (2.7)	4.6 (2.5)	-15.0**	0.65**	83.2	0.40
“Other Foods” (/20)	10.0 (5.8)	8.8 (4.6)	-13.4*	0.49**	78.5	0.25

Data presented as mean (standard deviation)
* $P < 0.05$ ** $P<0.01$

Table 4: Associations between total C-HEI 2007 score and each of its components by food assessment tool (food record (FR) and new web-based 24-hour recall (R24W)) (N=107)

Components	C-HEI 2007 total score assessed by the FR	C-HEI 2007 total score assessed by the R24W	P for the comparison in correlation strength
Total Vegetables and Fruit	0.51**	0.61**	0.29
Whole Fruit	0.57**	0.58**	0.91
Dark Green and Orange Vegetables	0.45**	0.55**	0.33
Total Grain Products	0.21*	0.20*	0.94
Whole Grains	0.54**	0.53**	0.92
Milk & Alternatives	0.27**	0.14	0.32
Meat & Alternatives	0.33**	0.13	0.13
Unsaturated Fats	0.30**	0.42**	0.32
Saturated Fats	0.57**	0.50**	0.48
Sodium	0.34**	0.29**	0.69
“Other Foods”	0.79**	0.76**	0.58

*P<0.05 **P<0.01

Table 5: Estimated mean C-HEI 2007 score by sex and age group as assessed with the new web-based 24-hour recall (R24W) and with the food record (FR) (N=107)

	Men (N=50)	Women (N=57)	Aged 18-30 y (N=13)	Aged 30-50 y (N=38)	Aged ≥51 y (N=56)
C-HEI 2007 assessed by the R24W (/100)	55.7 (11.6)	62.6 (11.1)*	51.5 (9.4)	58.5 (12.4)	61.8 (11.2)**
C-HEI 2007 assessed by the FR (/100)	57.8 (13.3)	66.9 (13.0)*	57.6 (13.4)	62.3 (14.0)	64.0 (13.9)

Data presented as mean (standard deviation)

* P<0.05 compared with Men ** P<0.05 compared with Aged 18-30 y

Chapitre 6 - Associations between self-reported vegetable and fruit intake assessed with a new web-based 24-hour dietary recall and serum carotenoids in free living adults: A validation study.

Résumé

L'objectif de cette étude était d'évaluer la validité relative d'un nouveau rappel de 24 heures sur plateforme web (R24W) pour mesurer les apports en légumes et en fruits en utilisant le taux de caroténoïdes sériques comme biomarqueur de concentration. Soixante-quatre femmes et 73 hommes (âge moyen 47,5 ±13,3 ans; IMC moyen 25,5 ±4,4 kg/m^2) ont complété le R24W à quatre reprises pour évaluer leurs apports en légumes et en fruits. Les taux sériques de caroténoïdes ont été obtenus à partir d'un prélèvement sanguin suivant un jeune de 12 heures grâce à la méthode de chromatographie liquide de haute performance. En somme, ces résultats suggèrent que le R24W est un outil approprié pour mesurer les apports en légumes et en fruits.

Title page

Title: Associations between self-reported vegetable and fruit intake assessed with a new web-based 24-hour dietary recall and serum carotenoids in free living adults: A relative validation study.

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Abstract

The aim of this study was to assess the relative validity of a new web-based 24-hour dietary recall (R24W) in terms of vegetable and fruit (VF) intake assessment using serum carotenoid concentrations as biomarkers. Seventy-four women and 73 men (mean age 47.5 ±13.3 years; mean BMI 25.5 ±4.4 kg/m2) completed the R24W four times to assess their VF intake. Serum carotenoids were obtained from 12-hour fasted blood samples and measured by high performance liquid chromatography. Raw and de-attenuated partial Spearman's correlations were performed to determine how VF intake was associated with serum carotenoids. Relevant confounders were selected using a stepwise regression analysis. Finally, cross-classification was used to determine agreement between intake of VF and serum carotenoids. Intake of total dietary carotenoids was significantly associated ($r=0.40$, $P<0.01$) with total serum carotenoids (without lycopene). Total VF intake was also associated with total serum carotenoid without lycopene ($r=0.44$ $P<0.01$). HDL-cholesterol, waist circumference and age were identified as confounders in the association between total VF intake and total serum carotenoids (without lycopene). De-attenuated partial correlation adjusted for these confounders increased the associations between dietary carotenoids and total serum carotenoids without lycopene ($r=0.49$, $P<0.01$) and between total VF intake and total serum carotenoids without lycopene ($r=0.48$, $P<0.01$). Almost 80% of respondents were classified in the same or the adjacent quartile for total VF intake and total serum carotenoids without lycopene, while less than 6% were classified in the opposite quartile. Overall, these observations support the appropriateness of the R24W to assess dietary intake of VF.

Introduction

Increasing the population's vegetable and fruit (VF) intake is one of the main nutritional objectives of public health organizations (1). There is significant evidence that consumption of VF is associated in a dose-dependent manner with better cardiovascular health (2) and a lower risk of all-cause mortality (3). Getting an adequate amount of VF is also essential to reaching dietary reference intakes of most of the important vitamins and minerals (4). In the 2007 edition of the Canada's Food Guide, specific advice has been added to encourage Canadians to eat more dark green and orange VF in order to optimize their nutrient intake (5). To track positive outcomes of these recommendations, we must rely on self-assessed dietary assessment. This approach is useful to analyze dietary patterns or nutrient intake at the population level. However, it is also associated with misreporting as well as with suboptimal accuracy and reproducibility at the individual level (6,7). Therefore, many researchers are working on strategies to improve the objectivity of dietary assessment's measuring tools.

According to different reviews (8,9), serum carotenoid concentrations appear to be the best blood marker of VF given that they are primarily found in plants and that they cannot be synthesized by the human body (10). Up to now, more than six hundred species of carotenoids have been discovered and about sixty of them have already been measured in human serum (11). The six most common are α-carotene, β-carotene, β-cryptoxanthin, lycopene, lutein, and zeaxanthin (12). They are characterized by a chemical structure containing a conjugated double bound that gives plants their yellow or orange colour, although this colour is sometimes masked by a stronger pigment, that is the chlorophyll in dark green vegetables (13). Serum carotenoids can be classified as concentration biomarkers as opposed to recovery biomarkers, which can be directly linked to tissue concentration (14). Up to now, besides doubly labelled water (for energy expenditure), 24-hour urinary nitrogen (for protein intake) sodium and potassium, very few recovery biomarkers have been implemented in nutritional research. Concentration biomarkers are also associated with intakes but with a larger between-individual variability caused by differences in absorption and metabolism (15).

The main challenge facing researchers who are trying to use carotenoids as biomarkers is the lack of a proportional relationship between dietary intake and serum levels. Indeed, VF contain varying amounts of different carotenoids (see **Table 1**). Moreover, their concentration differs for a vegetable or fruit to the next (16). As an example, it has been shown that broccoli and green peas are more effective than spinach (in milligrams of carotenoids consumed) in increasing serum lutein levels (17). From these observations, it seems clear that it would be impossible to characterize one's VF intake with a specific carotenoid. It is also the conclusion reached by Baldrick et al. (12) in a review about the effect of different VF on serum carotenoid levels. They stated that the best strategy for assessing total VF intake was to use a panel of carotenoids.

Besides using multiple serum carotenoids, adjusting for some factors involved in their metabolism is essential to get an adequate biomarker of VF. Using data from 264 adults put on a diet containing between 6 and 21 servings of VF per day, Couillard et al. (18) highlighted that, for the same intake of VF, women had higher serum levels of carotenoids. Building on this work, Allore et al. (19) demonstrated that HDL-cholesterol mediates the sex difference in serum carotenoids potentially because of the difference in lipid density of the lipoprotein between men and women (20). They also demonstrated that greater body weight (BW) and greater waist circumference (WC) were associated with lower serum levels of carotenoids. Souverein et al. (21) used a similar approach to develop a mathematical model to predict VF intake from serum carotenoids, folate, vitamin C, and other factors such as age, body mass index (BMI), and sex. The model better predicted VF intake than any of the individual biomarkers, emphasizing the importance of including confounders when assessing the association between VF intake and serum biomarkers.

Recently, we have developed a new web-based 24-hour dietary recall (R24W) facilitating food assessment in the French-speaking population of the province of Quebec (22–25). The present study aims at assessing the relative validity of the R24W to estimate VF intake using carotenoids as concentration biomarkers. We hypothesize, based on the recent literature that VF intake is significantly associated with serum carotenoid levels and that adjusting this association for relevant metabolic confounders increases its strength.

Experimental methods

Participants

Seventy-five women and 75 men aged between 18 and 68 years from the Quebec City area volunteered to take part in this validation study. Exclusion criteria were pregnancy, lactation and digestive problems causing malabsorption in order to avoid any interaction in the analysis of blood biomarkers. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the of the Laval University Ethics committee. Written informed consent was obtained from all subjects.

Sample size calculation

The present analysis is based on data from a validation study for new web-based questionnaires including the R24W. Based on previous data (26), a sample size of 150 was calculated to provide 80% power at a significance level of 0.05 to distinguish a 10% difference in energy intake using different dietary assessment methods and to insure adequate participant-to-item ratio in the questionnaire validations (27). This calculation also exceeds the recommendations of the EURopean micronutrient RECommendations Aligned Network of Excellence (EURRECA) for the number of individuals who should be included in a validation study that includes the analysis of biomarkers (28).

Study Protocol

Participants were invited to an initial visit at the research institute where their body height (Height rod Model 216, SECA, SECA Corp, Hamburg, Germany), weight and body composition (TANITA body composition analyzer BC-418, Tanita Corporation, Il, USA) were assessed. Then, the WC measurement was taken at the end of a normal expiration with a tape placed horizontally directly on the skin at the mid-distance between the last rib and the top of the iliac crest. WC was determined as the mean of three measurements to the nearest 0.1 cm. During this same visit, fasting blood samples (12-h fast) were collected from an antecubital vein into vacutainer tubes for the measurement of fasting blood lipids and carotenoids. Samples were then immediately centrifuged at 17°C for 10 min at 1100 × g and stored at -80°C until processed. Blood lipid concentrations were assessed with the use of a Roche Modular P system (Roche Diagnostics, Mannheim, Germany).

Serum Carotenoids Analysis

Details about standards preparation are described in detail a previous study conducted in our research facility.(18) Carotenoids identification was performed with high performance liquid chromatography (HPLC).Serum samples kept at -80°C were thawed in the freezer at the end of the day, a day before the analysis. Samples were vortexed and then centrifuged at 1370G for 10 minutes at 4°C. Aliquots of 100 µL of serum were then transferred in Eppendorf tubes (1.5 ml) along with 20 µL of 2-propanol and 20 µL of internal standard and the tubes were vortexed. Samples were transferred on a 400µL fixed well plate (ISOLUTE® SLE+, Biotage, Charlotte, NC) and wait 5 minutes. Then, 900 µL of hexane:isopropanol (90/10, v/v) was added twice to each well. Each extracted sample was evaporated under nitrogen and once dried, was reconstituted with 300 µL of methanol:dichloromethane (65/35, v/v). Plates were shaken for one minute, twice and samples were transferred into HPLC glass vials to be analyzed.

HPLC analysis of the samples was performed using an Agilent 1260 Infinity system (Agilent, Mississauga, Ontario, Canada) equipped with a binary pump system and a C30 reversed phase column (YMC America Inc., Allentown, PA) kept at constant temperature (35°C). Carotenoids of the different samples were separated with a mobile phase consisting of methanol:water (98/2, v/v; Eluent A) and methyl-tert-butyl ether (MTBE; Eluent B; VWR, Mississauga, Ontario, Canada). UV detector was set at 450 nm and identification of each compound was confirmed using retention time and UV spectra (190-640nm) of the pure compounds. Data acquisition was carried out with the Chemstation software (Agilent, Mississauga, Ontario, Canada). Coefficient of variation for each carotenoid was tested in our laboratory facilities using split samples and it varied between 3.68 and 10.03% (detailed data available in **Supplemental Table 1**).

Dietary Intake Assessment

Following the initial visit during which blood sampling for carotenoid measurement was taken, participants received e-mails on random unannounced days inviting them to complete the R24W four times during a period varying from 5 to 20 days between April and July 2015. In order to complete their first 24-hour dietary recall, all participants had to watch a tutorial video describing all main aspects of the software (22). If participants did not complete the 24-hour recall on the day they received the e-mail, the access was cancelled, and another e-mail was sent on another unannounced day. The first dietary recall was sent ten days after the initial visit when the blood sampling was collected. About 60% of the cohort completed all the four 24-hour recalls when they received them the first time while the other 40% of the cohort did not fill at least one 24-hour recall when they received it the first time. Overall, an interval of 15 to 30 days between blood sampling and dietary recall completion was observed.

This fully automatic software was inspired by the Automated Multiple-Pass Method developed by the United Stated Department of Agriculture for national dietary surveys (29). A total of 2865 different food items and 687 recipes are available in the R24W (22). Respondents are guided to recall their previous day's intake, meal by meal. Pictures of up to eight portion sizes are proposed for each food item described by unit and/or volume. Dietary intakes were estimated by the average of the four days of dietary recalls. The R24W automatically provided Canada's Food Guide servings for total VF, fruit, whole fruit, vegetables, orange vegetables and dark green vegetables. This includes servings from single foods as well as recipes. One hundred percent fruit juices were considered in the total VF and fruit categories but were not included in the whole fruit category. It should also be noted that, accordingly to Canada's Food Guide, some orange-coloured fruit such as apricot and mango are included in the total number of orange vegetables (5). Energy and dietary carotenoids intakes were also automatically computed by the R24W using data from the Canadian Nutrient File database (Health Canada, 2010). The percentage of foods containing dietary carotenoids for which a value is available in the R24W ranges between 78.6% (lycopene) and 94.4% (β-carotene). Dietary supplement use was assessed through a web-based food frequency questionnaire (26) in which questions about different types of supplements were asked. Information about consumption of multivitamins and carotenoids (β-carotene) only was kept for this analysis.

Statistical Analysis

Normality of the distribution of dietary intakes and serum carotenoids was tested using Kolmogorov-Smirnov test. As data were mostly not normally distributed, differences in dietary intake and serum carotenoids between men and women as well as between supplement users and non-users were assessed with Whitney U-Test. For these variables, data are presented using median and interquartile range (IQR). Spearman's correlations were used to assess the associations of dietary carotenoids, categories of VF (servings/day of total VF, fruit, whole fruit, vegetables, orange vegetables and dark green vegetables), age, adiposity metrics (BMI, WC and fat mass (FM)) as well as triglycerides (TG), total cholesterol, LDL-cholesterol and HDL-cholesterol with serum carotenoids. As serum lycopene demonstrated a different pattern of association compared with the other serum carotenoids, data for total serum carotenoids were presented while including or excluding lycopene(30). A stepwise regression analysis was used to determine the relevant confounders of the association between total serum carotenoid concentrations without lycopene and total VF intake. Serum TG, total cholesterol, LDL-cholesterol, HDL-cholesterol, WC, BW, FM, BMI, age, sex, intake of supplements and total energy intake were considered in this analysis. De-attenuated partial Spearman's correlations were used to assess the associations between dietary and serum carotenoids as well as between VF intake (servings/day) and serum carotenoids adjusted for significant confounders found with the stepwise regression analysis. De-attenuation of correlations adjusts for day-to-day variability among the four days of 24-hour dietary recall (31). Serum carotenoids were then compared across quartiles of total VF intake using cross-classification and the Kappa statistic. We conducted this analysis twice. We first performed the analysis with raw total serum carotenoids. We then performed the analysis using a composite variable derived from the stepwise regression model in order to take into consideration the significant confounders of the association between VF intake and serum carotenoids. Statistical analyses were conducted with the software SAS version 9.4 (SAS Institute Inc., NC, USA).

Results

Participants' characteristics are presented in **Table 2**. A total of 147 participants from the 150 who were recruited were included in the analysis. Three participants were excluded because they did not complete all four 24-hour dietary recalls and did not provide the blood sampling. There was no difference between women and men in age, TG, LDL-cholesterol and BMI, whereas men had higher WC and total energy intake than women. Conversely, women had higher FM and higher concentrations of HDL-cholesterol and total cholesterol. Intake of the different categories of VF did not differ between sexes except for whole fruit intake which was higher in women than in men. Likewise, serum concentrations of β-carotene, β-cryptoxanthin and total serum carotenoids were higher in women whereas serum concentration of lycopene was higher in men. Serum concentration of carotenoids did not differ between supplement users and non-users except for the concentration of lycopene which was slightly higher in supplement users. Therefore, subsequent analyses were not adjusted for the use of supplements.

Univariate correlations between dietary carotenoids, categories of VF intake, age, anthropometric measures as well as blood lipid concentrations and serum carotenoid concentrations are shown in **Table 3**. Each dietary carotenoid was significantly associated with its serum equivalent except for lycopene. Likewise, total VF intake was positively associated with all carotenoids except lycopene. Also, all categories of VF were positively associated with total serum carotenoids (with and without lycopene). Moreover, all categories of VF were positively associated with serum α-carotene, β-carotene and lutein. Besides orange vegetables, all categories of VF were also positively associated with serum β-cryptoxanthin while fruit, orange vegetables and dark green vegetables were significantly associated with serum zeaxanthin. None of the VF categories was correlated with serum lycopene concentrations. Metrics of adiposity (BMI, WC and FM) were mostly negatively associated with serum carotenoids except lycopene. Age was positively associated with serum concentrations of β-carotene and β-cryptoxanthin as well as with total serum carotenoids. TG was negatively associated with all serum carotenoids except β-cryptoxanthin and lycopene. Total cholesterol was positively associated with all serum carotenoids expect α-carotene. LDL-cholesterol was positively associated with β-cryptoxanthin, lycopene and total serum carotenoids. Lastly, HDL-cholesterol was positively associated with all serum carotenoids except lycopene.

The stepwise regression model showed that VF intake, HDL-cholesterol, WC and age were the strongest predictors of total serum carotenoids without lycopene (**Table 4**). De-attenuation as well as adjustment of the univariate correlation for HDL-cholesterol, WC and age slightly increased the strength of the relationship between dietary carotenoid intake and serum carotenoid concentrations. Similarly, the adjustment strengthened the associations of total VF intake, vegetable as well as orange vegetables with total serum carotenoid concentrations without lycopene. However, the adjustment slightly decreased the association between intake of fruit, whole fruit as well as dark green vegetables with total serum carotenoid concentrations without lycopene (**Table 5**).

Approximately 80% of respondents were classified in the same (40.8%) or the adjacent (38.8%) quartile of total VF intake and total serum carotenoid concentration without lycopene, while only 5.4% of the respondents were classified in the opposite quartile. The Kappa statistic was of 0.32 (**Table 6**). Moreover, there was a significant difference in total serum carotenoid concentration without lycopene of 43% between the first (average of 3.2 servings of VF per day) and the fourth (average of 9.5 servings of VF per day) quartile of total VF intake. When total serum carotenoids was substituted by a composite variable created by the regression equation described in **Table 4** (including VF, HDL-cholesterol, WC and age as predictors) , the proportion of the participants classified in the same (44.9%) or the adjacent (39.5%) quartile reached 84.0% and the proportion of participants classified in the opposite quartile was of 1.4%.

Discussion

This study was intended to validate the VF intake assessment from the R24W, a new web-based 24-hour dietary recall, by using serum carotenoids as concentration biomarkers. We observed associations of moderate strength (32) between dietary carotenoids and total serum carotenoids as well as between intake of VF and total serum carotenoids. Moreover, these associations were generally increased by the adjustment for relevant confounders.

Correlations between dietary and serum carotenoids observed in the present study are overall of similar magnitude than those observed in previous studies. Burrows et al. (9) published a review of 142 validation studies using serum carotenoids as biomarkers. They reported average correlation between dietary carotenoids and serum carotenoids as follows: α-carotene r=0.34 (95%CI: 0.31-0.37), β-carotene r=0.27 (95%CI: 0.25-0.29), β-cryptoxanthin r= 0.38 (95%CI: 0.31-0.37), lutein/zeaxanthin r=0.29 (95%CI: 0.26-0.33), lycopene r=0.29 (95%CI: 0.26-0.32). The only notable difference between results of the present study and those of Burrows et al. is that we did not find a significant association between dietary intake of lycopene and its serum concentration. However, this absence of association between dietary and serum lycopene is not uncommon. For example, Resnicow et al.(30) also observed that dietary and serum lycopene were not significantly associated in a group of 74 adults who completed three days of 24-hour recall. Furthermore, they came to the same conclusion with a larger group of 802 adults who completed a 36-item food frequency questionnaire.

In the present study, total VF intake was more strongly associated with α-carotene and β-carotene than with other serum carotenoids. In a recent study in which Burrows et al.(33) validated a food frequency questionnaire, α-carotene and β-carotene were also the strongest correlates of VF intake while lycopene was not associated with total VF intake. In fully controlled feeding trials, Couillard et al. (18) reported a negative association between total VF intake and serum lycopene. Accordingly, lycopene is known to be a stronger correlate of tomatoes and tomato-based sauce intake than of the total amount of VF consumed (12). We also found that the intake of vegetables was generally more strongly associated with total serum carotenoids than was the intake of fruit. Van Lee et al. (34) noticed the same difference between vegetables and fruit using α-carotene, β-carotene, β-cryptoxanthin, lutein and zeaxanthin as biomarkers and two 24-hour recalls as the dietary assessment method. As suggested by other researchers (10,35), total VF intake in the present study was better predicted by total serum carotenoids than by individual carotenoids.

The association between reported VF intake and serum carotenoids was not expected to be perfect. Indeed, self-assessed dietary intake is associated with certain bias related to memory, estimation and desirability (7,36). The concentration of carotenoids is also variable across the different types of VF and some food items not considered as a VF portion like ketchup contribute to the serum carotenoid concentration. However, using four days of 24-hour dietary recall as a measure of the usual intake slightly attenuated the variability in the intake of dietary carotenoids as compared with only one day (variance ratios are presented in **Supplemental Table 2**). Furthermore, the bioavailability of carotenoids is limited because of multiple factors related to absorption and metabolism (37). One demonstration of that is that even in controlled feeding trials, the associations between VF intake and serum carotenoids are not of high magnitude. In a study published by Souverein et al. (21) in which data from 12 controlled feeding studies were used, it was found that unadjusted correlation coefficients between VF intake and serum carotenoids ranged between 0.08 and 0.29. Lastly, in the present study, blood measurements of carotenoids were conducted before the dietary intake assessment. The optimal delay between assessment of VF and measurement of carotenoids is difficult to establish. Indeed, Rock et al. (38) proposed that the most common carotenoids stay in the serum for 12-33 days. Therefore, sampling carotenoids in the 12-33 days following dietary assessment would probably reflect more closely the reported intake of VF, which should result in stronger associations between VF intakes and carotenoid concentrations. We acknowledge that if our objective had been to specifically determine if serum carotenoids were good biomarkers of VF intake, it would then have been better to perform blood sampling after the administration of the dietary recalls. However, our main objective was to determine if our web-based 24-hour dietary recall was able to adequately reflect the usual VF intake using carotenoids as concentration biomarkers. In such a context, we believe that performing blood samples before dietary assessment was an appropriate strategy. Finally, the fact that the magnitude of our correlations was similar to the one observed in other studies, including some performed in more controlled feeding conditions, suggests that dietary intakes measured in the present study (after blood sampling) are comparable to the intakes prior to blood sampling. This further suggests that our web-based 24-hour dietary recall was able to adequately reflect the usual intake of VF intake.

To account for several factors influencing the association between VF intake and serum carotenoids, some authors have suggested adding selected confounders when examining this association. In a recent study conducted with data from fully controlled feeding trials, Allore et al.(19) identified HDL-cholesterol, LDL-cholesterol and body weight as significant confounders of the association between the dietary intake in carotenoids and serum carotenoids. Similarly, the stepwise linear regression conducted in the present study showed that HDL-cholesterol and waist circumference influenced the association between total VF intake and serum carotenoids. We also noticed significant associations between total serum carotenoids and other markers of adiposity such as FM and BMI as well as age, which corroborates observations from other studies (33,39,40). Furthermore, the association between BMI and total serum carotenoids (r=-0.33) was exactly the same as the one reported by Couillard et al. (18) using data from fully controlled feeding trials. Also, as suggested by Allore et al. (19), the difference in HDL-cholesterol concentration could be the most important factor explaining the difference in serum carotenoids between men and women. Indeed, in their cohort as well as in ours, women displayed higher concentrations of serum carotenoids even if they had lower intakes of dietary carotenoids than men. Interestingly, this sex difference was eliminated when the authors adjusted the serum carotenoid level for HDL-cholesterol concentration (19).

In this study, we found that the association between total VF intake and total serum carotenoids was slightly increased after adjustment for confounders. Similarly, Souverein et al. (21) demonstrated in controlled feeding trials that, in a model adjusted for confounders, the correlation between intake of VF and serum carotenoids (including lycopene, folate and vitamin C) was strengthened from r=0.23 to r=0.77. This suggests that a correlation of low magnitude between VF intake and serum carotenoids does not necessarily reflect an inadequate reporting of food intake and can be explained to some extent by factors associated with the metabolism of serum carotenoids.

It is important to remember that the objective of this study was to use serum carotenoids as concentration biomarkers of VF usual intake and not to predict the exact intake of total VF intake. Given the similarities between the relevant confounders identified in the current study and the ones identified in previous studies cited above as well as the strength of the associations between total VF intake and serum carotenoids concentration, we can be confident that the R24W assessed total VF intake with adequate relative validity.

Our cross-classification analysis reinforced observations from correlation analyses. First, we observed that almost 80% of respondents were classified in the same or the adjacent quartile but also that less than 6% were classified in the opposite quartiles. These observations were slightly better than those of Lai et al. (41) for the validation of a food frequency questionnaire in older adults where 68% of respondent were classified in the same or the adjacent quartile using VF intake and serum carotenoids. We also noticed that levels of total serum carotenoids without lycopene among those with the highest VF intake (4th quartile) was 43% higher than the serum levels of the smallest VF consumers (1st quartile). Lastly, the Kappa statistic was characteristic of an acceptable level of validity (42).

It is important to mention that our sample was not fully representative of the Canadian population. Indeed, we recruited mostly well-educated French-speaking Caucasians. Acknowledging the possible racial influence on the associations between dietary and serum carotenoids (43), this could limit the generalizability of the present results. Moreover, in our sample, the proportion of participant reporting more than five VF per day (62.7% in women and 67.1% in men) was higher than what has been observed in a survey of the Canadian population (36.9% in women and 22.9% in men (44)). The proportion of participants who reported using a multivitamin (20.4%) was, however, comparable to the Canadian average (23.1% (45)). Lastly, it could merit mentioning that our sample size calculation was based on energy intake and not on variation in carotenoid intakes, as the present study was conducted in the context of a larger validation study for which the underreporting of energy intake was a key factor (23). Nevertheless, knowing that our sample size was comparable to other studies using carotenoids as biomarkers of food intake(9) and fulfil recommendations from EURRECA(42) we are confident that it was large enough to identify significant associations.

Conclusion

Overall, results of the present study support the appropriateness of the R24W to assess dietary intake of VF on a group level and emphasize the importance of considering pertinent confounders when looking for the associations between VF intake and serum carotenoids.

Declarations

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Conflict of Interest

None.

Authorship

JL, CC, BL and SL designed the study, CL collected the data, JL did the analysis and the interpretation of the data, JL wrote the manuscript, all authors critically revised and approved the manuscript.

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Tables

Table 1: Food sources of most common carotenoids

Carotenoids	Food sources
α-Carotene and β-Carotene	Orange fruit and vegetables, dark green vegetables such as spinach, peas, green beans
β-Cryptoxanthin	Oranges, papayas, nectarines
Lutein and zeaxanthin	Spinach, broccoli, corn, apricots, nectarines
Lycopene	Tomatoes and food derived from tomatoes

Adapted from: Breithaupt et al.(46), Jansen et al.(47), Rodriguez-Amaya(48)

Table 2: Participant's characteristics (N=147)

	Women (N=74)	Men (N=73)	Difference (P)[1]
Age (years)	49.8 (11.5)	45.2 (14.5)	0.07
Body mass index (kg/m^2)	25.0 (4.4)	26.0 (4.4)	0.10
Waist circumference (cm)	84.6 (11.8)	93.7 (13.5)	<0.01
Fat mass (kg)	22.3 (8.7)	18.0 (9.5)	<0.01
Triglycerides (mmol/L)	1.3 (0.7)	1.3 (0.7)	0.84
Total cholesterol (mmol/L)	5.6 (1.2)	5.0 (0.8)	<0.01
LDL-cholesterol (mmol/L)	3.1 (1.0)	2.9 (0.7)	0.15
HDL-cholesterol (mmol/L)	1.9 (0.5)	1.5 (0.4)	<0.01
Energy intake (kcal/day)	2142.7 (431.4)	2980.4 (837.7)	<0.01
Use of supplement (%)[2]	21.6	19.2	0.71
Vegetable and fruit Intakes (servings/day)[3]			
Total vegetables and fruit	6.1 [3.1]	5.7 [3.3]	0.87
Fruit	2.5 [1.7]	2.2 [2.6]	0.67
Whole fruit	1.6 [1.1]	1.1 [1.3]	<0.01
Vegetables	3.3 [1.9]	3.6 [2.2]	0.69
Dark green vegetables	0.8 [0.8]	0.6 [0.8]	0.07
Orange vegetables	0.3 [0.4]	0.3 [0.6]	0.44
Serum Carotenoids (μmol/L)			
Serum α-carotene	0.37 [0.29]	0.31 [0.31]	0.06
Serum β-carotene	0.98 [0.74]	0.70 [0.70]	0.01
Serum β-cryptoxanthin	0.30 [0.22]	0.21 [0.11]	<0.01
Serum lycopene	0.61 [0.34]	0.69 [0.32]	0.03
Serum lutein	0.40 [0.17]	0.33 [0.17]	0.05
Serum zeaxanthin	0.11 [0.06]	0.11 [0.05]	0.11
Total serum carotenoids	2.96 [1.22]	2.48 [1.36]	0.03

1. P value based on Whitney U-Test or Chi^2 2. Supplement considered were multivitamin and carotenoid supplements (β-carotene) 3. Data are presented as mean (SD) except for vegetable and fruit intakes and serum carotenoids which are presented as median [IQR]

Table 3: Crude spearman correlations of dietary carotenoids, vegetable and fruit intake, age, anthropometric measures and blood lipids concentrations with serum carotenoid concentrations (N=147).

	Serum carotenoid concentrations (µmol/L)							
	α-carotene	**β-carotene**	**β-cryptoxanthin**	**Lutein**	**Zeaxanthin**	**Lycopene**	**All carotenoids**	**All carotenoids without lycopene**
Dietary carotenoids (µg)[1]	0.30 [c]	0.35 [c]	0.26 [b]	0.28 [c]	0.24 [b]	0.10	0.17 [a]	0.40 [c]
Vegetable and fruit intake (Servings/d)								
Vegetables and fruit	0.43 [c]	0.44 [c]	0.26 [b]	0.30 [c]	0.24 [b]	0.01	0.40 [c]	0.44 [c]
Fruit	0.23 [b]	0.25 [b]	0.19 [a]	0.27 [c]	0.22 [b]	-0.02	0.24 [b]	0.28 [c]
Whole Fruit	0.33 [c]	0.32 [c]	0.19 [a]	0.28 [c]	0.16	-0.09	0.30 [c]	0.35 [c]
Vegetables	0.41 [c]	0.42 [c]	0.20 [a]	0.20 [a]	0.15	0.05	0.38 [c]	0.39 [c]
Orange Vegetables	0.32 [c]	0.27 [c]	0.11	0.24 [b]	0.21 [a]	-0.08	0.26 [b]	0.30 [c]
Dark green Vegetables	0.28 [c]	0.34 [c]	0.29 [c]	0.29 [c]	0.23 [b]	-0.08	0.30 [c]	0.34 [c]
Participant's characteristics								
Age (y)	0.07	0.19 [a]	0.22 [b]	0.14	0.08	0.11	0.19 [a]	0.20 [a]
Body mass index (kg/m^2)	-0.26 [b]	-0.32 [c]	-0.18 [a]	-0.35 [c]	-0.27 [b]	-0.05	-0.33 [c]	-0.35 [c]
Waist circumference (cm)	-0.32 [c]	-0.36 [c]	-0.30 [c]	-0.42 [c]	-0.38 [c]	0.02	-0.36 [c]	-0.41 [c]
Fat mass (kg)	-0.25 [b]	-0.25 [b]	-0.08	-0.27 [b]	-0.25 [b]	-0.13	-0.26 [b]	-0.27 [b]
Triglycerides (mmol/L)	-0.37 [c]	-0.34 [c]	-0.13	-0.20 [a]	-0.17 [a]	0.15	-0.27 [c]	-0.34 [c]

Total cholesterol (mmol/L)	0.09	0.24 [b]	0.34 [c]	0.22 [b]	0.24 [b]	0.29 [c]	0.29 [c]	0.24 [b]
LDL-cholesterol (mmol/L)	0.01	0.13	0.20 [a]	0.06	0.12	0.30 [c]	0.17 [a]	0.11
HDL-cholesterol (mmol/L)	0.34 [c]	0.41 [c]	0.35 [c]	0.45 [c]	0.36 [c]	-0.04	0.40 [c]	0.45 [c]

a <0.05; b <0.01; c <0.001

1. The variable “Dietary carotenoids” represents the corresponding serum carotenoid listed at the top of the table.

Table 4: Variables included in the prediction model to determine total serum carotenoids without lycopene (significant at 0.15)

Variables[1]	Regression coefficient (B)	P value	Model P value	Model R-squared
Intercept	2.57	<0.01	<0.01	0.36
Total vegetable and fruit intake (servings/day)	0.15	<0.01		
HDL-cholesterol (mmol/L)	0.27	0.14		
Waist circumference (cm)	-0.03	<0.01		
Age (year)	0.01	0.02		

1. Variables considered but non-included in the prediction model were: Triglycerides, total cholesterol, LDL-cholesterol, body weight, fat mass, body mass index, sex, intake of supplements and total energy intake

Table 5: De-attenuated1 partial correlations between dietary intake and serum carotenoids adjusted for HDL-cholesterol, waist circumference and age (N=147)

	α-carotene	**β-carotene**	**β-cryptoxanthin**	**Lutein**	**Zeaxanthin**	**Lycopene**	**All carotenoids**	**All carotenoids without lycopene**
Dietary carotenoids (μg)[2]	0.41 [c]	0.43 [c]	0.34 [c]	0.29 [b]	0.24 [a]	0.13	0.24 [a]	0.49 [c]
Vegetable and fruit intake (Servings/d)								
Vegetables and fruit	0.45 [c]	0.46 [c]	0.24 [b]	0.30 [c]	0.23 [a]	0.00	0.42 [c]	0.48 [c]
Fruit	0.22 [a]	0.24 [b]	0.16	0.27 [b]	0.21 [a]	-0.02	0.23 [b]	0.27 [b]
Whole Fruit	0.30 [c]	0.27 [b]	0.11	0.23 [b]	0.10	-0.01	0.24 [b]	0.30 [c]
Vegetables	0.48 [c]	0.50 [c]	0.22 [a]	0.24 [b]	0.18	0.04	0.45 [c]	0.48 [c]
Orange Vegetables	0.39 [c]	0.34 [c]	0.13	0.32 [c]	0.27 [b]	-0.10	0.34 [c]	0.40 [c]
Dark green Vegetables	0.26 [b]	0.32 [c]	0.26 [b]	0.26 [b]	0.19	-0.09	0.27 [b]	0.31 [c]

a <0.05; b <0.01; c <0.001

1.De-attenuated means adjusted for day-to-day variability. 2. The variable "Dietary carotenoids" represents the corresponding serum carotenoid listed at the top of the table.

Table 6: Cross-classification between quartiles of total vegetable and fruit intake and quartiles of total serum carotenoids (N=147)

	Same quartile	1 quartile apart	2 quartiles apart	Opposite quartile
Proportion of respondents (%)	40.8	38.8	15.0	5.4
Kappa statistic		0.32		

Supplemental files

Supplemental table 1: Coefficient of variation of each of the serum carotenoids using split samples.

	α-carotene	β-carotene	β-cryptoxanthin	Lutein	Zeaxanthin	Lycopene
Coefficients of variation (%)	6.64	3.68	4.26	4.03	5.85	10.03

Supplemental table 2: Variance ratio of dietary carotenoids according to the number of days of 24-hour dietary recall*.

	α-carotene	β-carotene	β-cryptoxanthin	Lutein & Zeaxanthin	Lycopene
Variance ratio (4-days vs 1-day)	34%	32%	22%	37%	44%
Variance ratio (3-days vs 1-day)	37%	34%	28%	44%	43%
Variance ratio (2-days vs 1-day)	54%	50%	43%	50%	52%

*Variance ratio are calculated as the average variance of 2, 3 or 4 24-hour dietary recalls divided by the variance of 1 24-hour dietary recall.

Chapitre 7 - Is the Canadian Healthy Eating Index 2007 an Appropriate Diet Indicator of Metabolic Health? Insights from Dietary Pattern Analysis in the PREDISE Study.

Résumé

L'objectif de cette étude était d'identifier les éléments-clés issus du Guide alimentaire canadien 2007 qui devraient être inclus dans un score de qualité alimentaire voué à refléter le risque de syndrome métabolique. Les apports alimentaires de 998 adultes (âge moyen : 43,2 ans, 50% femmes) ont été utilisés pour obtenir le score *Healthy Eating Index* Canadien 2007 (C-HEI 2007) et le score *Alternative Healthy Eating Index* 2010 (AHEI) ainsi qu'un patron alimentaire (DP) généré grâce à la méthode de Régression par rang réduit (*Reduced Rank Regression*; RRR). En se basant sur ces trois scores, une version modifiée du C-HEI 2007 (Modified C-HEI) ensuite été proposée. Les résultats de cette étude suggèrent que le score Modified C-HEI qui intègre des éléments-clés du score C-HEI 2007, du score AHEI et du DP peut identifier des individus qui sont plus à risque de développer le syndrome métabolique.

Title page

Title: Is the Canadian Healthy Eating Index 2007 an Appropriate Diet Indicator of Metabolic Health? Insights from Dietary Pattern Analysis in the PREDISE Study

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Introduction

Canada's dietary guidelines, presented in Canada's food guide (CFG), were originally developed with the aim of ensuring the adequacy of the population's macro and micronutrient intakes [1,2]. Theses guidelines are also aimed at promoting metabolic health, but the evidence supporting their ability to prevent chronic diseases is lacking. Metabolic syndrome (MetS) is characterized by a combination of at least three factors predicting chronic diseases, namely elevated blood pressure, fasting blood glucose, triglycerides, and waist circumference, and low high-density lipoprotein (HDL)-cholesterol concentrations [3]. It is a recognized measure of metabolic health. Indeed, a meta-analysis concluded that having this condition was associated with a two-fold increase in cardiovascular disease and a 1.5-fold increase in all-cause mortality [4]. Health-related habits, such as increased consumption of vegetables and fruits, whole grains, low-fat dairy, fish, legumes, and poultry, can reduce the risk of MetS [5]. Focusing on these factors in our dietary guidelines might, therefore, lead to improved metabolic health.

Diet quality scores are often used to assess dietary habits. The Healthy Eating Index (HEI), first proposed in 1995 by Kennedy et al. [6], is intended to assess adherence to Dietary Guidelines for Americans. Since it was first introduced, three updated versions were published to ensure that the score remains coherent with evolving U.S. dietary recommendations [7]. Each version was successively validated [8–10] to demonstrate that it adequately measured adherence to dietary guidelines over the years. Through different studies, a higher HEI has been associated with reduced waist circumference [11], reduced risk of colorectal cancer [12], and reduced all-cause mortality [10,13], but only weakly with reduced cardiometabolic risk factors [14,15]. In line with recommendations included in the 2007 version of the CFG, a Canadian version of the HEI (C-HEI 2007) was proposed and validated [16]. Interestingly, Chiuve et al. [17] demonstrated that another score based on the scientific literature of metabolic disease prevention, the Alternative Healthy Eating Index 2010 (AHEI), was more strongly associated with the risk of coronary heart disease and type 2 diabetes than the American-HEI 2005. This suggests that some aspects of metabolic health might not be captured by the original HEI.

Both C-HEI 2007 and AHEI can be classified as a priori scores because they are based on predetermined components [18]. An increasing number of authors claim that these a priori scores are not optimal tools to promote healthy diet because they are not representative of the actual dietary intakes of the population [18,19]. Indeed, they do not take into consideration interactions between behaviour, food, and nutrients, and they may sometimes be difficult to translate into food-based dietary choices [20]. Therefore, there is a keen interest in using epidemiological approaches, such as dietary pattern analysis, to identify food habits associated with metabolic disease risk factors and to use this information to improve dietary guidelines for a specific population [20].

Besides the aim of improving metabolic health, dietary guidelines also aim to ensure sufficient intakes of the most important nutrients in a population's diet and to limit overconsumption of nutrients of public health concern. Considering that the new version of the CFG has just been released [21], it is relevant to start updating measures of diet quality. Using comparison with other diet quality scores and dietary patterns derived from the reduced rank regression (RRR) approach, this study aimed to determine key elements from the 2007 CFG that should be included in a diet quality score for Canadians aiming to reflect the risk of metabolic diseases. More specifically, we first analyzed the C-HEI 2007 and the AHEI in order to identify reliable components for each of the two scores [22]. Second, we derived new dietary patterns that predict metabolic health and identified key components of these dietary patterns. Third, we used information from the first two steps to propose a modified version of the C-HEI 2007 that combines important elements of diet quality and that predicts metabolic health as reflected by the prevalence of the MetS.

Materials and Methods

Participants

This study was conducted with data from a large cross-sectional research project (PRÉDicteurs Individuels, Sociaux et Environnementaux (PREDISE) study) aiming to identify determinants of healthy eating in a probabilistic sample of French-speaking adults from the Province of Quebec. Details about recruitment and collected measures are presented elsewhere [23,24]. Briefly, this multicenter web-based study was designed to examine how individual, social, and environmental factors are associated with the adherence to Canadian dietary guidelines. Participants were French-speaking men and women from 5 major administrative regions of the Province of Quebec, Canada. To be eligible, participants had to be aged 18–65 years, speak French as the primary language at home, have a computer, have access to the internet, and have a valid e-mail address. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the Research Ethics Committees of Université Laval (ethics number: 2014-271), Centre hospitalier universitaire de Sherbrooke (ethics number: MP-31-2015-997), Montreal Clinical Research Institute (ethics number: 2015-02), and Université du Québec à Trois-Rivières (ethics number: 15-2009-07.13). Written informed consent was obtained from all subjects. From the 1216 participants of the PREDISE study, 998 were included in this analysis. Participants who did not have complete data for all of the required measurements (i.e., blood sampling, fulfillment of all three dietary recalls and all questionnaires; N = 214) or with type 1 diabetes (*N* = 4) were excluded.

Dietary Assessment and Participant Characteristics

Participants had to complete three 24-hour dietary recalls. The three days of recall were determined randomly and were completed over a 21-day period with a validated self-administered, web-based application, the *Rappel de 24 heures Web* (R24W) [25]. This allowed the assessment of the mean intake of energy, macro and micronutrients, as well as the intake of different food groups necessary for the calculation of the C-HEI 2007 and the AHEI [26–29]. Scoring systems for both scores are described in Tables S1 and S2. The C-HEI 2007 is calculated on a total of 100 points, while the maximal score for the AHEI is 110 points. Both are obtained by the addition of different sub-scores, with higher total scores reflecting better-quality diets. Intake of 19 nutrients highlighted as key elements in the development of the 2007 CFG (vitamin A, thiamin, riboflavin, niacin, vitamin B6, folate, vitamin B12, vitamin C, vitamin D, magnesium, iron, calcium, potassium, sodium, zinc, phosphorus, fibres, linoleic acid and alpha-linolenic acid) [1] were assessed and compared with the average requirement or the adequate intake for age groups and genders [30].

Physical activity level was self-reported using a short version of the International Physical Activity Questionnaire (IPAQ) in metabolic equivalent (MET) minutes per week [31,32]. Information about social and demographic characteristics were obtained from online questionnaires. More precisely, we collected information about educational level, marital status, ethnicity and smoking status.

Metabolic Health Measurements

Participants were invited to an initial visit at one of the affiliated research centres, where their body height (Height rod Model 216, SECA, SECA Corp, Hamburg, Germany), weight (TANITA body composition analyser, BC-418; Tanita Corporation, IL, USA), and waist circumference were measured. Waist circumference measurement was taken at the end of a normal expiration with a tape placed horizontally directly on the skin at the mid-distance between the last rib and the top of the iliac crest. Waist circumference was determined as the mean of three measurements to the nearest 0.1 cm. During this same visit, fasting blood samples (12-h fast) were collected from an antecubital vein into vacutainer tubes for the measurement of fasting blood lipids and glucose. Samples were then immediately centrifuged at 17 °C for 10 min at 1100× *g* and stored at −80 °C until processed. Blood lipid concentrations were assessed with the use of a Roche Modular P system (Roche Diagnostics, Mannheim, Germany). Fasting blood glucose concentrations were measured with the use of colorimetry (Hexokinase Method, Roche Modular P System), whereas insulin concentrations were tested with the use of electrochemiluminescence (Cobas 6000, Roche Diagnostics). Systolic and diastolic blood pressures were determined from the means of 3 consecutive measurements that were taken 3 min apart in a sitting position after a 10-minute rest with the use of an automated blood pressure monitor (Digital Blood Pressure Monitor HEM-907XL model, Omron, Toronto, Canada).

MetS definition is based on a consensus from the International Diabetes Federation and the American Heart Association/National Heart, Lung, and Blood Institute [3]. To be designated as having the MetS, participants had to have at least three of the following factors: (1) central obesity (waist circumference ≥ 88 cm for women and ≥ 102 cm for men); (2) triglycerides ≥ 1.7 mmol/L or self-reported specific treatment for high triglycerides; (3) HDL-cholesterol < 1.3 mmol/L for women and < 1.0 mmol/L for men or self-reported specific treatment for this lipid abnormality; (4) systolic blood pressure ≥ 130 mm Hg and/or diastolic blood pressure ≥ 85 mm Hg or self-reported treatment of previously diagnosed hypertension; or (5) fasting blood glucose ≥ 5.6 mmol/L or self-reported treatment of previously diagnosed type 2 diabetes. The definition from the Diabetes Federation and the American Heart Association/National Heart, Lung, and Blood Institute states that there is no universal cut point for waist circumference and that regional or national thresholds must be used. Therefore, we selected ≥ 88 cm for women and ≥ 102 cm for men, as they are cut-off points suggested for the Canadian population [33].

Dietary Pattern Development

Dietary patterns were obtained using reduced rank regression (RRR), a statistical technique that maximizes the variation explained by response variables selected based on the a priori hypothesis that they are related to the outcome of interest [18]. This approach shares similarities with the principal component analysis (PCA), but it is more appropriate to identify dietary patterns predictive of metabolic diseases [18]. Indeed, PCA are derived to explain as much variation as possible in food intake, while RRR describes the variation in response variables, which can either be a group of nutrients known as predictors or correlates of the outcome of interest, or biomarkers of this outcome [34]. For the development of dietary patterns in this study, biomarkers related to the MetS were used as response variables. We selected HDL-cholesterol, triglycerides, homeostasis model for insulin resistance (HOMA-IR), waist circumference, and mean arterial blood pressure, as they were either included in the calculation of the MetS or closely linked to it [34,35]. HOMA-IR was preferred to fasting blood glucose because the chronic increase in insulin resistance usually precedes that of fasting blood glucose, and HOMA-IR is slightly more closely associated with the MetS than fasting insulin [36]. Therefore, using HOMA-IR allows for an earlier identification of subjects prone to developing MetS [37]. HOMA-IR was obtained using glucose (in mmol/L) multiplied by insulin (in pmol/L) and divided by 135 [38]. Mean arterial blood pressure also seems to be a better predictor of the MetS in normotensive individual than systolic or diastolic blood pressure alone [39]. Based on the 2007 CFG, seventeen mutually exclusive food groups were used as predictors [1]: (1) dark green vegetables; (2) orange vegetables; (3) other vegetables; (4) whole fruit; (5) fruit juices; (6) whole grains; (7) refined grains; (8) yogurt; (9) milk; (10) other dairy products and alternatives; (11) nuts and legumes; (12) poultry; (13) eggs; (14) red and processed meat; and (15) fish and seafood. Food items not meeting criteria to be considered as a portion of the CFG were included as either: (16) sugar-sweetened beverages; or (17) ''other foods'' excluded from the CFG. Foods with a very high fat content (fats, dressings, mayonnaise, cream, etc.), foods with very high sugar content (sugars, honey, jams, syrups, sweets, etc.), foods high in fat, sugar, or salt (i.e., classified in the lowest level of diet quality (tier 4) according to the 2014 Health Canada Surveillance Tool Tier System [40]), and other ingredients and beverages (unsweetened beverages, sauces, condiments, etc.) were included in the “other foods” category. Details on the classification and portion sizes can be found in Table S3.

For the development of dietary patterns, we adjusted blood pressure levels in participants that reported taking any blood-pressure-lowering drugs by adding a correction constant (systolic blood pressure +15 mmHg; diastolic blood pressure +10 mmHg) [41]. Similarly, HDL-cholesterol and triglycerides were also adjusted in those taking lipid-lowering medication (triglycerides +0.208; HDL-cholesterol −0.060) [42], as suggested by Drake et al. As we used HOMA-IR, a variable derived using fasting insulin and fasting glucose, as one of the response variables, and since there was no adjusted criterion to account for the effect of the medication on HOMA-IR [43], we excluded all participants who self-reported using medication for diabetes (N = 38) for the RRR analysis. The score for the selected dietary pattern (DP) was generated by summing the product of standardized food group portion (z-score) coefficients and individual intakes for all participants [44].

Statistical Approaches

The C-HEI 2007 and AHEI scores were first assessed for internal consistency using the Cronbach-α. This statistical approach allowed determination of whether individual components of each score measure the same underlying construct. It is generally accepted that a Cronbach-α of ≥ 0.70 characterizes a score in which most of the components describe the same construct [45]. Furthermore, the analysis provides information about how each component independently correlates with the total score (comparing the component with the total score minus this component). For this analysis, correlation coefficients were categorized as moderate-strong (≥ 0.30) or null (< 0.10) [46]. In a second step, results from the RRR derived from all participants except those reporting taking diabetes medication (*N* = 960) were analyzed. Key elements from the DP were identified as those with factor loadings ≥ 0.20 [44] and were compared across quintiles of the distribution using general linear model. Based on these results, a modified version of the C-HEI 2007 (Modified C-HEI) was proposed by including only components of the C-HEI 2007 and AHEI that demonstrated a high internal consistency (components correlated with total score with coefficient *r* ≥ 0.30) or key elements identified in the DP (factor loadings ≥ 0.20). Prevalence ratio (PR) of MetS and each of its components were calculated across quintiles of C-HEI 2007, AHEI, DP score, and the Modified C-HEI using binomial regression analysis, while adjusting for age (in years, continuous), sex (female or male), physical activity levels (in MET minutes per week, continuous), energy intake (in kcal, continuous), smoking status (current smokers, current non-smokers), education levels (<college, college, university), marital status (single, married or in a couple), and ethnicity (Caucasian, other) in all participants (*N* = 998). All these co-variables were associated with at least one diet quality score or one marker of metabolic health in our sample. Adequacy of nutrient intakes associated with each score was evaluated using correlation analyses performed between each individual score and the cumulative number of nutrients (range 0 to 19) for which estimated average requirement or adequate intake was achieved per participant. Statistical analyses were conducted with the software Statistical Analysis System (SAS)version 9.4 (SAS Institute Inc., Cary, NC, USA) and comparisons of correlation coefficients were computed with MedCalc for Windows, version 15.0 (MedCalc Software, Ostend, Belgium) [47].

Results

Participants Characteristics

Participant characteristics are presented in Table 1. Women showed globally a better metabolic profile and higher dietary scores than men. However, men reported being more active than women.

Internal Consistency of the A Priori Scores

Internal consistency of C-HEI 2007 and AHEI is described in Table 2. C-HEI 2007 demonstrated a better internal consistency than AHEI with a Cronbach-α of 0.61. Components with the strongest associations with the total C-HEI 2007 score were total vegetables and fruit, whole fruit, dark green and orange vegetables, whole grains, and “other foods”. Components not associated with the total C-HEI 2007 score were milk and alternatives and sodium. Similarly, the strongest contributors to the AHEI score were fruits and nuts and legumes, while those not associated with the total score were the sodium and alcohol components.

Dietary Pattern

Five dietary patterns were obtained from the RRR analysis. As the second, third, fourth, and fifth patterns explained < 10% of the variation in predictors (food groups) and less than 1% of the variation in the response variables (biomarkers), they were no further investigated. The DP derived from the RRR analysis is detailed in Table 3. It depicts foods inversely associated with HDL-cholesterol and positively associated with HOMA-IR, triglycerides, mean blood pressure, and waist circumference (Table S4), and explained 11.5% of the variation in the predictors (food groups) and 3.8% of the variation in the response variables (markers of the metabolic health). Food groups with factor loadings ≥ 0.20 are presented as key food groups. DP was characterized by low intakes of whole fruits, orange and dark green vegetables, as well as yogurt, and high intakes of red and processed meat, sugar-sweetened beverages, refined grains, and “other foods”.

Modified C-HEI

The Modified C-HEI is presented in Table 4. Based on the internal consistency analysis (components showing a correlation with total score ≥ 0.30), components for vegetables and fruit, whole fruit, dark green and orange vegetables, whole grains, nuts and legumes, and “other foods” were kept, as they appear to be reliable elements of either the C-HEI 2007 or the AHEI scores. The other components were removed and replaced by new ones based on their factor loading from the dietary pattern analysis. Thus, we included yogurt (loading factor −0.20) as an adequacy component, as well as red and processed meat (loading factor 0.42), refined grains (loading factor 0.37), and sugar-sweetened beverages (loading factor 0.32) as moderation components.

The suggested Modified C-HEI comprises 10 components, each having a maximal score of 10 for a total maximal score of 100 points (Table 4). We attributed the same maximal score for all components, as we had no information to justify a specific weighing of each of them [7]. To determine the scoring system for the proposed Modified C-HEI we decided that points for each component could be awarded following the logic of the C-HEI 2007 for all the items initially present in the score. For nuts and legumes, red and processed meat, and sugar-sweetened beverages, scoring from the AHEI was used. For the two newly added components (i.e., refined grains and yogurt), we had to suggest a scoring method. Based on the recommendation from the 2007 CFG that half of grain products should be whole grains, we suggested that intake of refined grains should be no more than half of the recommendation for total grain products. Therefore, anything above half of the recommended number of portions according to sex and age received zero points, and points were awarded proportionally for amounts between minimum and maximum. This approach is similar to the one used in the American-HEI 2010 [48] and in one Canadian adaptation of this score [49]. Finally, for the yogurt component, we determined the reference intake as 0.5 servings/day, as it was the mid-point between the average intake from the first and second quintile, where we noticed the most important modification in the distribution. Once again, points were awarded proportionally for amounts between minimum and maximum. The average Modified C-HEI score in our cohort was 44.2/100 (range 0.4–95.2). The Modified C-HEI was characterized by a

Cronbach α of 0.68, which is slightly higher than each of the a priori scores tested. Moreover, all of its components were directly and significantly associated with the total score.

Prevalence of the Metabolic Syndrome

Prevalence of the MetS across quintiles of the four dietary scores is presented in Table 5. As the DP presented a reversed association with MetS, we used the fifth quintile (strongest adherence and lowest diet quality) as a reference instead of the first quintile. The first quintile was used as reference for the other scores (lowest adherence and lowest diet quality). The C-HEI 2007 was the only score not significantly associated with the prevalence of MetS (PR for comparison between fifth and first quintile = 0.68; 95%CI 0.47, 1.00; P for linear trend = 0.35). A higher AHEI and a lower DP score were associated with a lower prevalence of MetS (PR = 0.42 95% CI 0.28, 0.64 and 0.47; 95%CI 0.30, 0.73, respectively).

The Modified C-HEI was strongly associated with the C-HEI 2007 ($r = 0.76$; $P < 0.001$) and the AHEI ($r = 0.82$; $P < 0.001$), while being negatively associated with the DP score ($r = -0.68$; $P < 0.001$), and was also associated with the MetS (PR for comparison between fifth and first quintile = 0.39 95% CI 0.23, 0.63). Table S5 details the comparison between the fifth and the first quintile of each of the four scores for individual MetS components. Overall, being classified in the quintile associated with the highest diet quality with all scores was associated with reduced prevalence of elevated blood pressure and elevated triglycerides, but only the Modified C-HEI was associated with a reduced prevalence of elevated blood glucose. All scores except C-HEI 2007 were associated with a reduced prevalence of increased waist circumference. Also, being classified in the quintile associated with the highest diet quality with AHEI was associated with reduced prevalence of low HDL-cholesterol.

Adequacy of Nutrient Intake

Lastly, Table 6 illustrates nutrient adequacy across all the four diet quality scores. Scores for C-HEI 2007 and Modified C-HEI showed the strongest correlation with the cumulative number of nutrients for which estimated average requirement or adequate intake was achieved (respectively $r = 0.42$ and $r = 0.36$, P for comparison = 0.11), while the association was significantly lower for AHEI ($r = 0.24$) than for both C-HEI 2007 and Modified C-HEI (both P for comparison < 0.01). Meanwhile, the DP score was more weakly associated with the number of nutrients for which estimated average requirement or adequate intake was achieved than the three other scores ($r = -0.05$, P for comparison < 0.01).

Discussion

This study aimed to identify components of the 2007 CFG on which we should focus to improve metabolic health. From analysis of a priori and a posteriori scores, we concluded that guidelines emphasizing the consumption of dark green and orange vegetables, whole fruit, whole grains, yogurt, as well as nuts and legumes, while suggesting that limiting intake of refined grains, red and processed meat, sugar-sweetened beverages, and food of low nutritional quality (i.e., other foods) would promote dietary habits associated with a lower prevalence of the MetS and a higher adequacy of nutrient intakes. Moreover, as opposed to the C-HEI 2007, and similarly to the AHEI, the Modified C-HEI was associated with the prevalence of MetS, while being more closely related to the adequacy of important nutrients than the AHEI. The Modified C-HEI also demonstrated a stronger internal consistency than both a priori scores. These results suggest that the Modified C-HEI would be an appropriate indicator of diet quality as defined by the adequacy of nutrient intake and metabolic health promotion.

Although most versions of the Canadian and American HEI scores have been widely used as measures of diet quality [50], our data and previous analyses suggest that their internal consistency are suboptimal [9,10,16]. Indeed, a recent validation of the American-HEI 2010 and 2015 demonstrated, similar to our results, that the dairy and sodium components are systematically inversely or not associated with the total score [9,10]. Although it is well established that a high sodium consumption leads to an increased risk of metabolic diseases [51], it has been shown that self-reported sodium is not necessarily an adequate marker of the real sodium intake [52]. Indeed, sodium intakes estimated using self-report dietary assessment methods are closely linked to sodium content of food items included in food databases, which could differ significantly from actual sodium content of foods currently available on the market. This could explain the discrepancies between sodium component score and diet quality scores, and it suggests that self-reported sodium intake is not a good marker of diet quality. Meanwhile, the recent literature highlighted either favourable or neutral associations between dairy products and metabolic health. Indeed, in a recent systematic review of meta-analysis of prospective populational studies, total dairy consumption demonstrated a favourable association with MetS with moderate-quality evidence, especially with regard to milk [53]. Moreover, a systematic review of randomized controlled trials revealed that the intake of yogurts containing Lactobacillus bulgaricus and Streptococcus thermophilus had either neutral or positive effects on markers of metabolic health [54]. The RRR analysis suggested that in our sample, milk was slightly associated with a deteriorated metabolic health (loading factor +0.15), while a higher consumption of yogurt (loading factor −0.20) was slightly associated with a reduced prevalence of MetS. In the new 2019 CFG, the food group that was dedicated to milk and alternatives has been integrated into the broader protein food group [21]. It is, therefore, likely that the updated version of the C-HEI 2007 based on the 2019 CFG will probably not specifically include milk and alternatives as a component of the score.

Since a C-HEI 2019 is not yet available, the C-HEI 2007 is currently the only available score based on Canadian dietary guidelines. Scores assessing adherence to American dietary guidelines are updated every 5 years and many changes have been proposed, such as a positive scoring for plant-based proteins and a negative score for refined grains in the American-HEI 2010 and 2015 [10,48]. This might explain why Liese et al. [13] demonstrated great similarities between the American-HEI 2010 and the AHEI in terms of population classification and mortality risk. With our cross-sectional data, we observed that the C-HEI 2007 was not associated with the prevalence of MetS, while the AHEI was associated with a significant reduction in the prevalence of the MetS between the fifth and the first quintile of score. However, the C-HEI 2007 was more closely linked to an adequate intake of important nutrients than AHEI.

As expected, we observed that the DP derived with MetS-related biomarkers was highly associated with the MetS. This dietary pattern was characterized by a high intake of “other foods”, refined grains, sugar-sweetened beverages, and red and processed meat, and by a low intake of whole fruit, dark green and orange vegetables, as well as yogurt. The proportion of the variation explained in predictors (11.5%) and response variables (3.8%) may seem to be relatively small, but it is similar to what has been seen in other studies where biomarkers of the MetS were used as response variables [55,56]. For example, in a similar analysis conducted in Sweden, Drake et al. used the RRR and components of the MetS as response variables to derive a dietary pattern negatively associated with metabolic health that explained 3.2% of the variation in the response variables and 7.9% of the variation in the predictors [55]. The dietary pattern described as “Western” was characterized by large intakes of sugar-sweetened beverages, milk, artificially sweetened beverages, red and processed meat, as well as sweets and low intakes of wine, beer, cream, cheese, tea, and vegetables [55], which is relatively similar to the DP we obtained. In our sample, stronger adherence to the DP was associated with significantly higher prevalence of MetS. However, as opposed to the AHEI and the American-HEI 2015 [10,17], DP analysis suggest that an increase in the intake of fish and seafood (loading factor −0.15), as well as nuts and legumes (loading factor −0.15), are only weakly associated with a reduced prevalence of MetS. This could be explained in part by the relatively small contribution of fish and plant-based protein to the diet of our participants. In fact, fish corresponded to 8% of all their portions of meat and alternatives, while nuts and legumes corresponded to 22%. In contrast, poultry, eggs, and red and processed meat represent 70% of meat and alternatives servings in our sample. As dietary patterns necessarily reflect actual dietary habits of the population in which analyses are conducted, they might minimize the importance of some diet-health associations in samples where these habits are not well implemented [34].

Compared to the C-HEI 2007, the Modified C-HEI scores refined grains and red and processed meat negatively. This explains in part why the average score is lower with the Modified C-HEI than with the C-HEI 2007. Similarly, the average score documented for the American-HEI 2010 was lower than the 2005 version of the score. The update from the 2005 to the 2010 version was characterized by the introduction of the negative scoring for refined grains [9]. Moreover, the Modified C-HEI attributes higher importance to plant-based components (vegetables and fruit, whole fruit, dark green and orange vegetable, whole grains, as well as nuts and legumes), which were those that had the highest association with the total C-HEI 2007 and AHEI scores, just as in the American-HEI 2010 and 2015 [9,10,17]. Suggesting increasing the consumption of non-refined plant-based food and to reduce red and processed meat, as well as highly processed food and sugar-sweetened beverages, is highly consistent with international consensus on diet, nutrition, and prevention of chronic diseases [57], and also with the recommendations of the new 2019 CFG [21].

Strengths and Limitations

This study was conducted in a probabilistic sample of French-Canadians from the province of Quebec. The sampling by sex and age groups was proportional to the population of each administrative region according to the most recent demographic data from the Institut de la statistique du Québec (2013) at the beginning of the study. A survey firm recruited participants by selecting phone numbers via random digit dialling until the designated quotas were reached in each stratum. This method ensures a good level of representativeness of the sample.

Also, the RRR method is gaining popularity in epidemiological research as a modern approach to derive dietary patterns based on a priori hypothesis on relation between diet and health [58]. For our RRR analysis, we used a list of predictor food groups that was, however, shorter than what is usually seen in other studies. We wanted to use mutually exclusive subgroups of the CFG in order for the results to be meaningful [20]. In a similar analysis from Livingstone et al. [59] where 48 food groups were used as predictors, the dietary pattern associated with obesity was characterized by different types of vegetables and fruits, low-fat milk, and whole grains, while negative predictors were refined grains, processed meat, sugar-rich food, and beer and cider. These patterns are similar to the one we obtained using 17 food groups as predictors.

When suggesting a new dietary score, it is challenging to ensure that all aspects are only data-driven. Therefore, selection and weighting of each component should reflect their relative importance. However, there is always some subjectivity involved in the process at different decision steps [7]. In the present study, we wanted to propose a new score that would be consistent with the 2007 CFG, therefore we kept the scoring based on the recommended number of portions by age groups and sex for most components. However, as the RRR analysis suggested that intakes of dark green and orange vegetables, whole fruit, as well as whole grains was highly important, we modified their contribution to make sure it was as important as all the other components.

Data for this analysis were obtained from a validated web-based 24-hour dietary recall. Three randomized days were used in order to average usual intake [27–29]. Some authors have suggested that a food frequency questionnaire is more appropriate to derive dietary patterns because it pictures food intake over weeks or months as compared to only a few days with dietary recalls [50,60]. However, it has been demonstrated that multiple days of 24-hour dietary recalls produce energy and protein estimates that correlate better with biomarkers than those from food frequency questionnaires [52]. Moreover, the potential limitation induced by the small time scale assessed with 24-hour dietary recall might be minimal in this case. Indeed, our data suggest that there is no difference in the average intake of the main 2007 CFG groups as well as energy and important nutrients across the four seasons in this cohort ($P > 0.05$, data not shown). On the other hand, these are cross-sectional observations, therefore we cannot input predictive value to our association. Moreover, the sample was slightly more homogenous in terms of ethnicity and more educated than the average population of Quebec [61,62], therefore it is possible that a dietary pattern derived in a more representative cohort would have been slightly different.

Conclusions

This study identified key elements from the 2007 CFG associated with metabolic health and adequate nutrient intakes in a cohort of French-speaking adults from the province of

Quebec. These results support public health campaigns that encourage Canadians to consume more vegetables, whole fruit, whole grains, yogurt, as well as nuts and legumes. Meanwhile, Canadians should be clearly advised to reduce their consumption of refined grains, red and processed meat, and highly processed foods high in saturated fat, sugar, and sodium. Indeed, a score based on these factors was associated with reduced prevalence of MetS. Interestingly, these factors are in accordance with the key concepts presented in the 2019 CFG [21] and might be included in a new version of the Canadian-HEI score reflecting current dietary recommendations.

Declarations

Supplemental Materials

The following are available online at www.mdpi.com/xxx/s1. Table S1: Description of the Canadian Healthy Eating Index 2007 (C-HEI 2007) scoring. Table S2: Description of the Alternative Healthy Eating Index 2010 (AHEI) scoring. Table S3: Food groups used for the reduced rank regression analysis. Table S4: Response variables used to derive the dietary patterns across quintiles (Q) of the selected dietary pattern (DP) (*N* = 998). Table S5: Prevalence ratio of the metabolic syndrome components across quintiles of adherence (5^{th} vs 1^{st} quintiles) of Healthy Eating Index (C-HEI 2007), Alternate Heathy Eating Index 2010 (AHEI), the selected dietary pattern (DP), and the Modified Healthy Eating Index 2007 (Modified C-HEI) (*N* = 998).

Author Contributions

Conceptualization, J.L., J.R., B.L, S.L.; methodology, J.L. and S.L.; software, J.L.; validation, S.L.; formal analysis, J.L.; investigation, É.C., C.L., and L.C.; writing—original draft preparation, J.L.; writing—review and editing, É.C., C.L., L.C., J.R., M-È.L., B.L., and S.L.; supervision, S.L.; project administration, L.C.; funding acquisition, S.L.

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Conflicts of Interest

The authors declare no conflict of interest.

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Tables

Table 1. Participants' characteristics (*N* = 998).

	All Cohort (*N* = 998)	**Women (*N* = 501)**	**Men (*N* = 497)**	***P*** [1]
Age (year)	43.2 (13.5)	43.2 (13.5)	43.2 (13.4)	0.97
Body mass index (kg/m^2)	27.4 (6.0)	26.9 (6.4)	27.8 (5.7)	0.03
Waist circumference (cm)	92.0 (16.3)	87.3 (15.4)	96.7 (15.8)	<0.01
Systolic blood pressure (mmHg)	117.7 (14.1)	112.8 (14.0)	122.6 (12.3)	<0.01
Diastolic blood pressure (mmHg)	73.6 (10.1)	72.0 (10.1)	75.2 (9.7)	<0.01
Triglycerides (mmol/L)	1.4 (0.9)	1.3 (0.9)	1.4 (1.0)	0.02
HDL-cholesterol (mmol/L)	1.4 (0.4)	1.5 (0.5)	1.3 (0.4)	<0.01
Fasting blood glucose (mmol/L)	5.2 (0.8)	5.1 (0.8)	5.3 (0.8)	<0.01
Fasting insulin (pmol/L)	98.2 (67.2)	94.2 (57.3)	102.2 (75.7)	0.06
HOMA-IR [2]	3.9 (3.3)	3.7 (2.7)	4.2 (3.7)	0.02
Physical activity (METminutes /week) [3]	3474.9 (5377.7)	2921.7 (4737.4)	4041.3 (5906.0)	<0.01
Average number of nutrients for which EAR or AI per person is achieved (/19) [4]	13.8	13.9	13.6	0.07
Metabolic syndrome prevalence (%)	20.5	18.2	22.9	0.06
AHEI Score (/110)[5]	53.5 (13.6)	56.6 (13.2)	51.4 (13.7)	<0.01
C-HEI 2007 Score (/100)[6]	57.1 (14.1)	60.3 (13.0)	53.8 (14.4)	<0.01
Education (%)				
High school or less	23.8	23.4	24.3	
College	30.8	29.7	31.8	0.62
University	45.4	46.9	43.9	
Marital status (%) [7]				
Single	35.6	38.6	32.6	0.05
In couple (or married)	64.4	61.4	67.4	
Ethnicity (%)				
Caucasian	92.8	92.7	92.9	0.65
Other ethnicity	7.2	7.3	7.1	
Smoking status (%)				
Current smoker	12.7	10.8	14.7	0.07
Non-smoker	87.3	89.2	85.3	

Data are presented as proportion or means (standard deviation). [1] Comparison between women and men: *T*-test for all variables except variables expressed in % where chi-square test is used. [2] HOMA-IR = homeostasis model for insulin resistance. [3] MET = Metabolic equivalent. [4] EAR or AI = estimated average requirements or adequate intake. [5] C-HEI 2007 = Canadian Healthy Eating Index 2007. [6] AHEI = Alternate Heathy Eating Index 2010. [7] Seventeen participants did not answer the marital status question.

Table 2. Internal consistency (Cronbach-α) of the Canadian Healthy Eating Index 2007 (C-HEI 2007) and the Alternative Healthy Eating Index 2010 (AHEI) (*N* = 998).

	Internal Consistency (Cronbach-α)	**Components Highly Associated with the Total Score (*r* ≥ 0.30)**	**Correlation with the Total Score (Excluding the Component)**	**Components not Associated with the Total Score (*r* < 0.1)**	**Correlation with the Total Score (Excluding the Component)**
C-HEI 2007	0.61	Vegetables and fruits	0.53	Milk and alternatives	0.08
		Whole fruit	0.50	Sodium	−0.13
		Dark green and orange vegetables	0.45		
		Whole grain	0.37		
		"Other foods"	0.43		
AHEI	0.49	Fruits	0.34	Sodium	0.001
		Nuts and legumes	0.31	Alcohol	0.06

Table 3. Intake of key food groups (predictors) across quintiles (Q) of the selected dietary pattern (DP) (*N* = 998).

	Factor Loadings	Quintiles of DP [1]										*P* for Trend
		Q1		Q2		Q3		Q4		Q5		
		Means	SD	Means	SD	Means	SD	Means	SD	Means	SD	
Red and Processed Meat (servings/day)	0.43	0.5	0.5	0.7	0.5	0.9	0.5	1.2	0.7	1.9	1.0	<0.001
Refined Grains (servings/day)	0.37	2.5	1.7	3.3	1.8	3.9	1.9	4.6	1.8	5.8	2.4	<0.001
Sugar-sweetened Beverages (servings/day)	0.32	0.1	0.4	0.2	0.4	0.4	0.7	0.5	0.9	1.4	1.7	<0.001
Other foods (kcal/day)	0.36	438.0	272.6	554.8	288.2	646.6	318.2	735.4	384.3	1053.6	580.2	<0.001
Whole Fruit (servings/day)	−0.34	2.4	1.6	1.5	1.1	1.1	1.0	0.9	0.9	0.7	0.8	<0.001
Dark Green Vegetables (servings/day)	−0.34	1.3	0.9	0.7	0.5	0.6	0.5	0.5	0.5	0.4	0.4	<0.001
Orange Vegetables (servings/day)	−0.27	0.8	0.9	0.4	0.4	0.4	0.4	0.3	0.4	0.3	0.4	<0.001
Yogurt (servings/day)	−0.20	0.5	0.6	0.3	0.4	0.3	0.4	0.2	0.4	0.1	0.3	<0.001

[1] Only key food groups with a loading factor of ≥ 0.20 are presented.

Table 4. Description of the modified version of the Canadian Healthy Eating Index Score (Modified C-HEI).

Component	Range of Scores [1]	Scoring Criteria
Adequacy [2]	0 to 60 points	
Total vegetables and fruit	0 to 10 points	Minimum: 0 Maximum: 7 to 8 servings
Whole fruit	0 to 10 points	Minimum: 0 Maximum: 1.5 to 1.7 servings
Dark green and orange vegetables	0 to 10 points	Minimum: 0 Maximum: 1.5 to 1.7 servings
Whole grains	0 to 10 points	Minimum: 0 Maximum: 3 to 4 servings
Yogurt	0 to 10 points	Minimum: 0 Maximum: 0.5 servings
Nuts and legumes	0 to 10 points	Minimum: 0 Maximum: 1 serving
Moderation [3]	0 to 40 points	
Red and processed meat	0 to 10 points	Minimum: 0 Maximum: 1.5 servings
Refined grains	0 to 10 points	Minimum: 0 Maximum: 3 to 4 servings
Sugar-sweetened beverages	0 to 10 points	Minimum: 0 Maximum: 1 serving
"Other foods"	0 to 10 points	Minimum: 5% or less of the total energy intake Maximum: 40% or more of the total energy intake

[1] Range of scores for adults. [2] For adequacy components, 0 points for minimum, 10 points for maximum or more, and proportional for amounts between minimum and maximum. [3] For moderation components, 10 points for minimum or less, 0 points for maximum or more, and proportional for amounts between minimum and maximum.

Table 5. Prevalence ratio of the metabolic syndrome across quintiles (Q1 to Q5) of the Canadian Healthy Eating Index 2007 (C-HEI 2007), the Alternate Heathy Eating Index 2010 (AHEI), the selected dietary pattern (DP), and the Modified Canadian Healthy Eating Index score (Modified C-HEI) (*N* = 998).

	Mean Score (SD) **Prevalence Ratio (95% CI)**					
	Q1 [1]	**Q2**	**Q3**	**Q4**	**Q5**	***P* for Linear Trend**
C-HEI 2007 (/100)	36.9 (5.6) **1.00** **(ref)**	49.1 (2.5) **0.84** **(0.59, 1.19)**	57.6 (2.4) **0.83** **(0.59, 1.18)**	65.4 (2.6) **0.77** **(0.53, 1.10)**	76.3 (5.2) **0.68** **(0.47, 1.00)**	0.35
AHEI (/110)	35.2 (4.8) **1.00** **(ref)**	45.4 (2.3) **0.91** **(0.66, 1.25)**	53.1 (2.1) **0.72** **(0.49, 1.04)**	60.6 (2.5) **0.74** **(0.53, 1.04)**	73.3 (6.1) **0.42** **(0.28, 0.64)**	<0.001
DP [2]	−0.59 (0.3) **0.48** **(0.31, 0.74)**	−0.21 (0.1) **0.50** **(0.34, 0.75)**	−0.01 (0.1) **0.86** **(0.62, 1.21)**	0.20 (0.1) **0.76** **(0.54, 1.08)**	0.61 (0.3) **1.00** **(ref)**	<0.001
Modified C-HEI (/100)	19.7 (6.1) **1.00** **(ref)**	33.9 (3.2) **0.85** **(0.57, 1.26)**	44.1 (2.6) **0.59** **(0.39, 0.91)**	54.0 (3.2) **0.69** **(0.46, 1.05)**	69.3 (7.7) **0.39** **(0.23, 0.63)**	0.003

Binomial regression adjusted for age (continuous), physical activity (continuous), energy (continuous), smoking status (2 categories), sex (2 categories), ethnicity (2 categories), marital status (2 categories), and education (3 categories). Note: *P* for linear trend across the prevalence ratio for all quintiles. [1] Reference is the 5th quintile (strongest adherence and lowest diet quality) for DP and the first quintile (lowest adherence and lowest diet quality) for C-HEI 2007, AHEI, and Modified C-HEI. [2] Scores for the DP were generated by summing the product of standardized food group portion (*z*-score) coefficients and individual intakes for all participants.

Table 6. Correlation coefficients between the cumulative number of nutrients[1] for which estimated average requirement or adequate intake per person is achieved and each of the diet quality score (*N* = 998).

	C-HEI 2007	AHEI	DP	Modified C-HEI
Correlation coefficients (*P*)	0.42 [a] (<0.001)	0.24 [b] (<0.001)	−0.05 [c] (0.01)	0.36 [a] (<0.001)

Note: [a, b, c] = correlation coefficients with different superscript are significantly different (*P* for comparison < 0.01). C-HEI 2007 = Canadian Healthy Eating Index 2007; AHEI = Alternate Heathy Eating Index 2010; DP = selected dietary pattern; Modified C-HEI = Modified Canadian Healthy Eating Index. [1] The selected nutrients were: vitamin A, thiamin, riboflavin, niacin, vitamin B6, folate, vitamin B12, vitamin C, vitamin D, magnesium, iron, calcium, potassium, sodium, zinc, phosphorus, fibres, linoleic acid, and alpha-linolenic acid.

Supplemental material

Supplemental table 1: Description of the Canadian Healthy Eating Index 2007 (C-HEI 2007) scoring

Component	Range of scores[1]	Scoring criteria
Adequacy[2]	**0 to 60 points**	
Total vegetables and fruit	0 to 10 points	Minimum: 0 Maximum: 7 to 8 servings*
Whole fruit	0 to 5 points	Minimum: 0 Maximum: 1.5 to 1.7 servings (21% of recommendations for total vegetables and fruit)*
Dark green and orange vegetables	0 to 5 points	Minimum: 0 Maximum: 1.5 to 1.7 servings (21% of recommendations for total vegetables and fruit)*
Total grain products	0 to 5 points	Minimum: 0 Maximum: 6 to 8 servings*
Whole grains	0 to 5 points	Minimum: 0 Maximum: 3 to 4 servings (50% of recommendations for total grain products)*
Milk and alternatives	0 to 10 points	Minimum: 0 Maximum: 2 to 3 servings*
Meat and alternatives	0 to 10 points	Minimum: 0 Maximum: 2 to 3 servings (150 to 225 grams)*
Unsaturated fats	0 to 10 points	Minimum: 0 Maximum: 30 to 45 grams
Moderation[3]	**0 to 40 points**	
Saturated fats	8 to 10 points 0 to 8 points	Minimum 7% to 10% of total energy intake 10% to maximum 15% of total energy intake
Sodium	8 to 10 points	Adequate intake (1500 mg/day) to tolerable upper intake level (2300 mg)/day)
	0 to 8 points	Tolerable upper intake (2300 mg/day) level to twice tolerable upper intake level (4600 mg/day).
“Other foods”	0 to 20 points	Minimum: 5% or less of the total energy intake Maximum: 40% or more of the total energy intake

Adapted from: Garriguet (2009) Total score /100

*Minimum or maximum number of serving are sex and age specific and determined per day by the 2007 Eating well with the Canada's Food Guide (Government of Canada, H.C. Eating Well with Canada's Food Guide: A Resource for Educators and Communicators [Health Canada, 2007] Available online: http://www.hc-sc.gc.ca/fn-an/pubs/res-educat/res-educat-eng.php (accessed on Oct 14, 2016) 1. Range of score used for adults. 2. For adequacy components, 0 points for minimum, 5 or 10 points for maximum or more, and proportional for amounts between minimum and maximum. 3. For moderation components, 10 or 20 points for minimum or less, 0 points for maximum or more, and proportional for amounts between minimum and maximum.

Supplemental table 2: Description of the Alternative Healthy Eating Index 2010 (AHEI) scoring

Components	**Criteria for minimum score (0)**	**Criteria for maximum score (10)**
Vegetables, servings/ day	0	≥5
Fruit, servings/day	0	≥4
Whole grains, g/day	0	
Women		75 (approximately 5 servings/day)
Men		90 (approximately 6 servings/day)
Sugar-sweetened beverages and fruit juice, servings/day	≥1	0
Nuts and legumes, servings/day	0	≥1
Red/processed meat, servings/day	≥1.5	0
Trans fat, % energy	≥4	≤0.5
Long chain (n-3) fats (EPA+DHA), mg/day	0	250
PUFA, % energy	≤2	≥10
Sodium, mg/day	Highest decile	Lowest decile
Alcohol, drinks/day[1]		
Women	≥2.5	0.5-1.5
Men	≥3.5	0.5-2.0
Total	0	110

Adapted from: Chiuve et al. (2012) Total score /110

1. In the design of the AHEI, authors assigned the highest score to moderate, and the worst score to heavy, alcohol consumers. The nondrinkers received a score of 2.5. One drink is 4 oz of wine, 12 oz of beer, or 1.5 oz of liquor (1 oz = 28.35 g).

Supplemental table 3: Food groups used for the reduced rank regression analysis

Food groups	Description*
Dark Green Vegetables	All dark green vegetables. One portion is equivalent to 125 ml except for leafy vegetables for which the portion size is 250 ml.
Orange Vegetables	All orange vegetables (e.g. carrots, pumpkin, squash, sweet potatoes and yam). Includes some orange fruits (apricot, cantaloupe, mango, nectarine, papaya and peach). One portion is equivalent to 125 ml except for some fruit (3 apricots, ½ papaya, 1 medium nectarine or peach).
Other Vegetables	Vegetables that are not included in Dark Green and Orange Vegetables. One portion is equivalent to 125 ml except for leafy vegetables for which the portion size is 250 ml.
Whole Fruit	All fruit except orange fruit included in the Orange Vegetables. Fruit juices are excluded. One portion defined as 125 ml or the equivalent.
Fruit Juice	All 100% fruit juices. One portion defined as 125 ml.
Whole Grains	Grain product for which the first ingredient is a whole grain product. One portion defined as 125 ml of cooked grain or the equivalent of 30 g of processed grain.
Refined Grains	All grain products except those included in the Whole grains group. One portion defined as 125 ml of cooked grains or the equivalent of 30 g of processed grain.
Yogurt	All yogurt and kefir. One portion defined as 175 g except for yogurt drink for which the portion is 200 ml.
Milk	All types of milk excluding fortified soy beverages. One portion defined as 250 ml.
Other Dairy Products and Alternatives	All other milk and alternative excepted milk, yogurt and kefir. Includes fortified soy beverages. One portion defined as 250 ml for milk and 50 g for cheese.
Nuts and Legumes	Includes all types of nuts, legumes and soy product beside fortified soy milk. One portion is defined as 35 g for nuts and nut butter, 120 g for legumes, 150 g for soy products.
Fish and Seafood	All types of fish and seafood. One portion defined as 75 g.
Poultry	All types of poultry. One portion defined as 75 g.
Eggs	One portion defined as two eggs or 100 g.
Red and Processed Meat	Includes beef, pork, veal, lamb, game meat, horse and giblets. Processed meat includes cold cuts and sausages. One portion defined as 75 g.

Sugar-Sweetened Beverages	Portions defined as 227 g (8 oz of 28.35 g). Included fruit-flavoured drinks, soft drinks, sports drinks, energy drinks, sugar-sweetened coffee and tea. Excludes 100% fruit juices and flavoured milks.
Other Foods	Includes food items with very high content in fat, sugar and/or salt and not included in Canadian food guide groups. Excludes sugar-sweetened beverages. As there is no defined portion for most of the food in this group, one portion is defined as 1 kcal.

* Portions are measured in volume according to the Canadian Food Guide guidelines. Conversion from volume to weight with the Canadian Nutrient File.

Supplemental table 4: Response variables used to derive the dietary patterns across quintiles (Q) of the selected dietary pattern (DP) (N=998).

	Quintiles of DP										P for trend
	Q1		Q2		Q3		Q4		Q5		
	Means	SD	**Means**	SD	**Means**	SD	**Means**	SD	**Means**	SD	
HDL-cholesterol (mmol/L)	**1.5**	0.5	**1.5**	0.5	**1.4**	0.4	**1.4**	0.4	**1.3**	0.4	<0.001
Triglycerides (mmol/L)	**1.1**	0.6	**1.3**	0.8	**1.4**	0.7	**1.4**	1.0	**1.6**	1.4	<0.001
HOMA-IR	**3.5**	2.7	**3.8**	3.2	**4.1**	4.3	**3.8**	2.5	**4.4**	3.2	0.06
Waist circumference (cm)	**85.5**	14.6	**88.7**	13.5	**93.0**	17.3	**93.1**	15.5	**99.7**	16.9	<0.001
Mean blood pressure (mmHg)	**85.2**	11.0	**86.9**	10.3	**88.8**	10.9	**89.3**	10.5	**91.1**	10.5	<0.001

Supplemental table 5: Prevalence ratio of the metabolic syndrome components across quintiles of adherence (5th vs 1st quintiles) of Healthy Eating Index (C-HEI 2007), Alternate Heathy Eating Index 2010 (AHEI), the selected dietary pattern (DP) and the Modified Healthy Eating Index 2007 (Modified C-HEI) (N=998).

		Prevalence ratio (95% CI)[1]			
	% of cases	C-HEI 2007	AHEI	DP	Modified C-HEI
Blood pressure (≥130/85)	19.0	**0.58*** (0.37, 0.92)	**0.42***** (0.27, 0.67)	**0.50**** (0.33, 0.78)	**0.42**** (0.26, 0.68)
Fasting blood glucose (≥5.6 mmol/L)	20.3	**0.72** (0.50, 1.01)	**0.90** (0.59, 1.36)	**0.69** (0.45, 1.06)	**0.65*** (0.44, 0.97)
Triglycerides (≥1.7 mmol/L)	29.9	**0.60***** (0.45, 0.80)	**0.50***** (0.36, 0.70)	**0.44***** (0.31, 0.62)	**0.46***** (0.34, 0.63)
HDL-cholesterol (women: <1.3 mmol/L; men: <1.0 mmol/L)	25.5	**1.00** (0.72, 1.39)	**0.50**** (0.34, 0.74)	**0.90** (0.61, 1.32)	**0.75** (0.53, 1.06)
Waist circumference (women: ≥88 cm; men: ≥102 cm)	37.9	**0.78** (0.60, 1.01)	**0.48***** (0.36, 0.64)	**0.55***** (0.42, 0.73)	**0.60***** (0.45, 0.78)

Binomial regression adjusted for age (continuous), physical activity (continuous), energy (continuous), smoking status (2 categories), sex (2 categories), ethnicity (2 categories), marital status (2 categories) and education (3 categories)

P for linear trend across prevalence ratio* P<0.05, **P<0.01, ***P<0.001

1. Reference is the 5th quintile (strongest adherence and lowest diet quality) for DP and the 1st quintile (lowest adherence and lowest diet quality) for C-HEI 2007, AHEI and Modified C-HEI.

Chapitre 8 – Development and validation of a Brief Diet Quality Assessment Tool in the French-speaking adults from Quebec.

Résumé

L'objectif de cette étude était de développer et de valider un questionnaire court, auto-administré visant à évaluer la qualité alimentaire dans un milieu clinique en utilisant le score Alternative Healthy Eating (AHEI) comme référence. L'outil bref d'évaluation de la qualité alimentaire a été développé en utilisant la méthode d'arbre de classification et de régression (*Classification And Regression Tree*; CART). Les individus classés comme ayant une diète de qualité plus élevée étaient significativement plus âgés, avaient un IMC, un pourcentage de gras et un tour de taille plus faible ainsi qu'une pression artérielle, des triglycérides sanguins, un ratio cholestérol/HDL et un taux d'insuline à jeun plus faible en plus d'avoir un taux de cholestérol-HDL plus élevé (tous $P<0,05$). En somme, la méthode CART a permis de développer un outil simple et rapide pour identifier les individus à risque d'avoir une faible qualité alimentaire.

Title page

Title : Development and validation of a Brief Diet Quality Assessment Tool in the French-speaking adults from Quebec.

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Keywords: Diet quality, classification and regression tree, alternative healthy eating index, Brief Diet Quality Assessment Tool

Background

One of the cornerstones of chronic disease prevention is to persuade the population to adhere to dietary guidelines (1). For years, clinical guidelines have been largely focused on the concept of primary prevention, which aims to alleviate the impact of risk factors on chronic diseases. More recently, the notion of primordial prevention has emerged as a potentially more efficient public health strategy. Primordial prevention, for which optimizing diet is key, aims to avoid the development of risk factors in the first place (2). However, physicians rarely inform their patients about the importance of healthy eating. In a Canadian study (3), family practitioners reported discussing diet with only 32% of their patients with type 2 diabetes and with less than 10% of their non-diabetic patients. One of the major challenges to implementing dietary counseling in a primary care setting is the lack of valid tools that assess diet quality, rapidly and accurately. In that regard, assessing global diet quality rather than relying on a few single nutrients of concern such as sodium and sugar is essential. A comprehensive approach to assessing diet quality, which takes into consideration food choices as well as interactions among foods and nutrients is more promising. Several complex dietary scores based on mathematical algorithms have been developed to describe the quality of the diet. The Alternative Healthy Eating Index (AHEI), which has been revised over the years to reflect current scientific literature, is well established (4). It is based on extensive research on the association between foods and chronic disease risk (4,5). However, as with many other diet quality scoring systems (6–8), computing the AHEI score requires in-depth data collection and analyses of food and nutrient intakes, which is very difficult in clinical settings.

Food frequency questionnaires, which survey a list of foods and beverages consumed over a specific period, hence providing information on habitual food intake, are an important tool in nutrition research (9). Although most of these questionnaires range from 80 to 120 questions and take up to 60 minutes to complete (10), shorter versions have been developed as screening tools of diet quality (11–16). Some screening tools have been developed to identify foods that contribute the most to the intake of specific nutrients such as saturated fat or sodium (13,17). Previously published data indicated that a diet quality score derived from such short questionnaires is weakly but significantly correlated with a diet quality score assessed using data from full dietary assessment questionnaires (18). However, to the best of our knowledge, no Brief Diet Quality Assessment Tool has yet been developed specifically to predict a global diet quality score such as the AHEI.

The objective of this study was to develop and validate a short, simple and cost-effective Diet Quality Assessment Tool in French-speaking adults from the Province of Quebec, in Canada. The classification and regression tree (CART) approach was used for that purpose. We hypothesized that the CART approach yields a predictive model of diet quality that is simple and easy to use, and hence potentially transferable and useful in clinical settings.

Methods

Participants

This study is based on data from two main samples of participants, from which subsamples have been created for specific analyses, as detailed below. As shown in Figure 1, the first sample (development sample) included 1643 healthy participants involved in 11 studies previously conducted at the Institute of Nutrition and Functional Food (INAF) over the years. All data were taken at the baseline of each study, prior to initiating any treatment or intervention, hence reflecting usual habits. The external validation sample comprised 3344 participants taking part in a longitudinal occupational study on cardiovascular health (19). This external validation sample comprised older individuals, which is relevant to the screening of diet quality since behavioural factors including diet are important predictors of morbidity and mortality in aging populations (20). Moreover, individuals aged 65 and older are the most frequent users of primary care, therefore a key target population for dietary screening in such settings (21). All participants lived in the Province of Quebec at the time of the study and spoke French as their primary language. All participants provided consent in written form to have their data included in a database for use in research other than the main project in which they participated. The protocol of each of these studies was in accordance with the declaration of Helsinki. Data used in this project are part of a data management framework approved by the Laval University Ethics Committee (2008-279 CG A-1 R-2).

Assessment of cardiometabolic risk factors

Each participant visited the INAF or one of the affiliated research centers for at least one in-person data collection session. Height and weight were measured by trained staff. A sub-sample of 940 individuals from the development sample, referred to as the predictive validation sample, provided a 12-h fasting blood sample and had their blood pressure, body composition and waist circumference measured. Blood samples were immediately centrifuged at 17°C for 10 min at 1100 × g to obtain serum samples, which were stored at -80°C until processed. Serum total cholesterol, triglycerides, and HDL-cholesterol concentrations were assessed with the use of a Roche Modular P system (Roche Diagnostics, Mannheim, Germany). LDL-cholesterol was calculated using the Friedewald equation (22). Fasting blood glucose concentrations were measured by colorimetry (Hexokinase Method, Roche Modular P System), whereas insulin concentrations were measured with the use of electrochemiluminescence (Cobas 6000, Roche Diagnostics). Systolic and diastolic blood pressures were determined from the means of 3 consecutive measurements that were taken 3 min apart in a sitting position after a 10-minute rest with the use of an automated blood pressure monitor (Digital BPM HEM-907XL model; Omron). Percent body fat was determined by the body composition analyzer BC-418 (Tanita, Arlington Heights, Il). Waist circumference measurements were taken at the end of a normal expiration with a tape placed horizontally directly on the skin at mid-distance between the last rib and the top of the iliac crest. Waist circumference was determined as the mean of three measurements at the nearest 0.1 cm.

Dietary Assessment

All participants from the development sample and the external validation sample completed the same validated web-based food frequency questionnaire (webFFQ) (23) at home, from which the AHEI was calculated as proposed by Chuive et al. (4). The scoring method is presented in Table 1. All questions from the webFFQ are structured similarly. Frequency of consumption is first assessed based on up to 8 predetermined answers. Participants then provide information on portion size using up to 6 image options. This sequence is cognitively easier for respondents (24).

Among participants in the development sample, self-reported energy intake (rEI) was estimated using dietary intake data derived from the webFFQ and estimated basal metabolic rate (eBMR) was calculated using the Mifflin-St Jeor equation (25). We considered, based on the Goldberg cut off (26), that participants with a ratio of rEI:eBMR ranging from 1.2 to 2.4 were plausible reporters. Data from non-plausible reporters based on these criteria in the development sample were excluded from the model development analysis because using potentially invalid data from individuals with over or underreporting food intake to develop the Brief Diet Quality Assessment Tool may have yielded spurious associations between food intake and diet quality. However, all plausible and non-plausible reporters were included in the external validation sample in order to test the validity of the Brief Diet Quality Assessment Tool in a context that more closely reflect real life conditions, where the risk of over or underreporting is not assessed and therefore unknown.

Development of the Brief Diet Quality Assessment Tool

The CART approach was used to develop the Brief Diet Quality Assessment Tool in the development sample. CART is a statistical approach of supervised learning that draws food patterns and identifies best predictors of an outcome among a list of variables (4). This type of algorithm is used to split a sample of independent variables in mutually exclusive subgroups based on common traits (20). By design, the tool identifies individuals at risk of having a diet of low quality, so that they may receive adequate guidance. By default, all remaining individuals who do not fall into this category have a high probability of having adequate dietary habits. The AHEI was considered the outcome variable, while answers to individual questions in the webFFQ as well as food groups were used as predictors. Overall diet quality was arbitrarily categorized as high (AHEI ≥65/110) or low (AHEI<65/110) to develop the Brief Diet Quality Assessment Tool. This cut-off was chosen based on the observation that individuals with a score of 65/110 and above are at a lower risk of major chronic disease compared with those with a lower score (4). Information from the webFFQ was converted into equivalent of servings per day for the analysis using standard references in Canada. Of the 136 questions of the webFFQ, 117 were included in the analysis.

As the webFFQ measures food intake with a high degree of specificity for some foods, it was decided to exclude right from the beginning questions that were considered too specific or irrelevant for use in a Brief Diet Quality Assessment Tool. For example, questions from the webFFQ that did not specifically indicate the type of foods consumed (e.g. "How often do you eat other types of bread?") were not considered in the developing the CART. A total of 27 categories were created to generate meaningful food groups based on the categorization proposed in Canada's Food Guide (27) as well as through consensus within the research team. Specifically, a subgroup was created for the different forms of cow milk (low, regular fat), and for all types of milk (including plant-based milks), of yogurt, and of cheese. Subgroups were also created for processed meats (including cold cuts, nuggets, bacon, terrines and sausages) and the different types of fish, breads, cereals, rice, pasta, chocolate and peanut butter were also grouped each in single food categories. Other subgroups were created for processed foods such as muffins, pancakes, pizza, sub sandwiches, cookies, cakes, pies, as well as for soft drinks, tea and coffee, desserts as well as nutritional supplements. Finally, food subgroups reflecting added sugar (in tea or coffee) and added fat were also created. Although most of the questions from the webFFQ are related to specific food items, some refer to a series of foods that have similar nutritional composition (e.g. “How often do you eat broccoli, green and yellow beans, Brussels sprouts, turnips, beets, asparagus, cabbage, mushrooms and mixed vegetables).

Age and sex, which are known to influence diet quality, were also considered as covariates in the models (28,29). The complete list of variables used to develop the Brief Diet Quality Assessment Tool is available in the Supplemental File. Overfitting was controlled using tenfold Monte Carlo cross-validation (30). The CART modeling was performed using the statistical program R and the package Rpart with version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

Statistical analysis

In plausible reporters from the development sample, accuracy of the Brief Diet Quality Assessment Tool was assessed by calculating sensitivity (the probability of being classified by the tool as having a diet of low quality among those with an AHEI <65/110), specificity (the probability of being classified by the tool as having a diet of high quality among those with an AHEI ≥65/110), agreement (proportion of respondents adequately categorized by the tool), positive predictive value (PPV; the probability of an AHEI <65/110 in those classified by the tool as having a diet of low quality), negative predictive value (NPV; the probability of an AHEI ≥65/100 in those classified by the tool as having a diet of low quality) and the area under the Receiving Operating Characteristic (ROC) curve.

Predictive validation

In the predictive validation sample, Student's paired t-tests were used to compare the cardiometabolic risk profile of participants classified by the Brief Diet Quality Assessment Tool as having a low or high-quality diet and between true positives (individuals with an AHEI <65 correctly classified as having a low-quality diet) and false negatives (individuals with an AHEI <65 incorrectly classified as having a high-quality diet).

External validation

External validation of the Brief Diet Quality Assessment Tool was undertaken using data from the external validation sample and the accuracy metrics described above (ie. sensitivity, specificity, agreement, PPV, NPV and area under the ROC curve) with the AHEI as reference.

XLSTAT 2017 (Addinsoft, Paris, France) was used to assess accuracy of the Brief Diet Quality Assessment Tool while SAS version 9.4 (SAS Institute Inc., NC, USA) was used for all other statistical analyses.

Results

Characteristics of all plausible reporters from the development sample (N=1040) and all participants from the external validation sample (N=3344) are presented in Table 2. Participants in the external validation sample were older, had slightly but significantly lower body mass index (BMI, P=0.01) and higher AHEI score (P<0.001) compared with those in the development sample.

Figure 2 presents the output of the decision tree produced by the CART in the plausible reporters from the development sample. Each split represents the question of the webFFQ that best differentiates the dietary outcome (i.e. diet of low vs. high quality). The cut-offs, expressed in servings per day, are determined by the model itself. The exact same model with the same cut-offs were used for the validation process. Color coded terminal leaves classify the respondents as having a low or a high-quality diet according to the AHEI cut-off of 65/110. Most of the 16 variables included in the final model are directly related to individual components of the AHEI. The first split corresponds to the intake of processed meat, which comprised questions on cold cuts, nuggets, bacon, terrines and sausages. Questions related to the intake of vegetables (broccoli, onion and salad), fruit (apples, which referred to the question: "how often are you eating apples, tangerines, oranges, pears, nectarines or peaches?"), whole grains (whole-grain bread), sugar-sweetened beverages and fruit juice (soft drinks and fruit juice), nuts and legumes (nuts, hummus and peanut butter), long chain (n-3) fatty acids (fish), sodium (French fries and processed meat) are also integral part of the AHEI calculation. Three questions that yielded a decisive split in the CART model were not directly associated with components of the AHEI, namely, 2% M.F. milk, pasta and the grouping of tea and coffee.

Accuracy of the Brief Diet Quality Assessment Tool to identify individuals with a low diet quality (AHEI <65) in the development sample is presented in Table 3. The Brief Diet Quality Assessment Tool had a high area under the ROC curve (0.92) and PPV (0.90). Other metrics were generally consistent with high accuracy (range 0.84-0.88). Comparative analysis of the cardiometabolic risk profile of individuals with a predicted low and high diet quality in the predictive validation sample is shown in Table 4. As expected, both men and women classified by the Brief Diet Quality Assessment Tool as having a low-quality diet had a significantly lower AHEI score than those classified as having a high-quality diet. Furthermore, individuals classified as having a low-quality diet by the Brief Diet Quality Assessment Tool were younger, had a higher BMI and waist circumference and, globally, a deteriorated cardiometabolic profile compared to those classified as having a high-quality diet. False negatives (individuals with an AHEI <65 incorrectly classified as having a high-quality diet by the Brief Diet Quality Assessment Tool) had a higher AHEI score and a more favourable cardiometabolic profile than true positives (individuals with an AHEI <65 correctly classified as having a low-quality diet, Table 5). Finally, Table 6 presents accuracy metrics of the Brief Diet Quality Assessment Tool in the external validation sample. All metrics were significantly lower in the external validation sample than in the development sample (sensitivity, specificity and agreement values of 73.0%, 69.0% and 71.3%, respectively).

Discussion

The objective of this study was to develop and validate a short and simple questionnaire to assess diet quality for potential use in a clinical and primary care setting. Using the CART modeling approach, the analysis yielded a Brief Diet

Quality Assessment Tool that comprises a maximum of six questions, with acceptable accuracy metrics to identify individuals likely to have a diet of low quality. Predictive validation of the Brief Diet Quality Assessment Tool using cardiometabolic risk factors provided further evidence of adequate performance to identify individuals at risk of having a low diet quality. External validation analyses in a sample of older adults also showed relatively good predictive values, although the model was overall less accurate than in the sample in which it was developed. Therefore, this suggests that Brief Diet Quality Assessment Tool has interesting potential for use in a primary care setting, as it identifies individuals at risk of having a low-quality diet and hence with the greatest needs in terms of nutritional support and guidance.

We are unaware of other studies where screening tools of global diet quality have been developed using detailed dietary assessment methods such as the AHEI as reference. Cook et al. (31) have developed three questionnaires of one and five questions to predict fruit and vegetable consumption. Although more than 80% of high fruit consumers were correctly identified by the single question questionnaire, only 56% of the individual identified as high fruit consumers were true positives. For vegetables, the sensitivity of different options of the model ranged from 36% to 70% and the PPV from 26% to 39%. Similarly, Teal et al. (14) created a screening tool for excessive fat consumption that could reasonably identify high fat consumers (PPV of 81%) but not those with a lower fat intake (NPV of 39%). Screening tools developed with supervised learning approaches appear to yield higher accuracy metrics. Indeed, using stepwise multiple logistic regression, Glümer et al. (32) developed and validated a screening tool for type 2 diabetes in the Danish population that demonstrated good sensitivity (73%) and specificity (74%). Using the CART approach, Xie et al. (33) developed a diabetes screening tool that was more sensitive and specific in women than in men (61% vs. 59% and 71% vs. 63%, respectively). In the present study, the Brief Diet Quality Assessment Tool presented adequate accuracy metrics. Sensitivity was high with 88% of individuals with AHEI <65 adequately correctly classified as having a low-quality diet. Specificity, reflecting the capacity of the Brief Diet Quality Assessment Tool to correctly identify individuals not at risk of having a poor diet, was also high at 85%. The area under the ROC curve was 0.92, indicating that the AHEI cut-off of 65/110 was optimal to generate a maximal proportion of true positives over false positives.

A higher AHEI score has been associated with higher HDL-cholesterol concentrations (34) and lower waist circumference (35), blood pressure and triglyceride levels (36) in different populations. Our data are consistent with these observations by showing significant differences in cardiometabolic risk between participant categorized with the Brief Diet Quality Assessment Tool as having a high or a low-quality diet for almost all variables tested. Even if the Brief Diet Quality Assessment Tool did not correctly classify all participants, individuals with an AHEI <65 who were misclassified as having a high-quality diet (false negative) had a more favorable cardiometabolic risk profile when compared with true positive individuals. Indeed, in addition to presenting a higher AHEI, false negatives had lower BMI, waist circumference, blood pressure, serum TG, insulin and cholesterol/HDL-cholesterol ratio compared with true positives. This observation alleviates the consequences of misclassifying someone with a low diet quality.

In the external validation sample, accuracy metrics of the Brief Diet Quality Assessment Tool were lower than in the development sample. This was anticipated as the CART algorithm was specifically built based on data from the development sample. However, the Brief Diet Quality Assessment Tool performed reasonably well in this independent sample with sensitivity and specificity values of 73% and 69%, respectively. Other investigators have also observed lower metrics of accuracy of the predictive model when testing its external validity (32).
The accuracy metrics yielded by the Brief Diet Quality Assessment Tool needs to be contextualized for its potential use in a clinical primary care setting and according to the consequences of false positive or negative classifications. In a clinical setting, individuals classified as having low-quality diet based on the Brief

Diet Quality Assessment Tool may be offered to meet with a dietician, who will inevitably assess dietary habits using more comprehensive dietary assessment methods and confirm their status. False positives, i.e. those presumably at risk of having a low-quality diet but who in fact have an AHEI ≥ 65, would unnecessarily use dietary counseling resources until their true dietary status is confirmed by more comprehensive assessment methods. Meanwhile, false negatives, i.e. individuals incorrectly classified as having a high-quality diet, will most likely maintain suboptimal dietary habits until further assessment. However, our data indicated that false negative individuals had a less deteriorated cardiometabolic risk profile than true positive individuals. This suggests a higher degree of "tolerance" before actions can be formally implemented to address the issues of diet quality in these patients. Finally, health practitioners need to acknowledge that this Brief Diet Quality Assessment Tool is not intended to be a precise screening tool. The primary function of this new tool is to bring the topic of diet quality to the discussion and potentially awaken consciences of both patients and physicians about this key aspect of preventive medicine.

Strengths and limitations

The use of the CART approach in this study is highly original and can be considered an important strength. This type of algorithm is used to split a sample of independent variables in mutually exclusive subgroups based on common traits (37). The end product is visually meaningful and can be easily interpreted by non-statisticians (38). Other supervised learning methods and regression analysis have been used in the past with slightly better accuracy, but their translation into visually attractive tools is challenging (39,40). Each CART is also inherently representative of the population in which it was developed. This ensures the generalizability at a local level, which is not guaranteed with tools validated elsewhere (41). Consequently, this approach has a limited reproducibility in populations other than French-speaking adults of Quebec, in which food habits could be different. The CART approach has also been shown to be prone to classification errors (39). Such errors apparently did not materially affect the performance of the model predicting diet quality in the development sample. The main advantage of this supervised learning strategy is to maximize specificity while limiting the number of questions by grouping the respondents in subgroups. Indeed, unlike calculating the AHEI using detailed and comprehensive dietary assessment methods, the Brief Diet Quality Assessment Tool can be self-administered within few minutes and interpreted without diet analyzing software. As indicated above, screening tools cannot substitute more comprehensive methods when detailed results are needed for counseling. Finally, even if the final model may be deceptive to some because of the small number of questions it comprises, it is important to highlight that the CART approach identified, from a broad series of foods, those that most closely predict an objective diet quality score, the AHEI, while ignoring other foods that did not statistically contribute to predicting this outcome (42).

There are limitations associated with the use of an FFQ to assess dietary intake, including a certain degree of misreporting (43), despite thorough validation (23). However, the AHEI has been developed using dietary intake data from FFQs (4). The Brief Diet Quality Assessment Tool was developed in a sample that excluded individuals with non plausible energy intake. Meanwhile, external validation was undertaken in a sample of individuals that did not exclude non plausible reports. The external validation sample in the present study was composed of older adults than individuals included in the development sample. While this may have attenuated the external validity of the tool to identify those with a low-quality diet, this approach more closely reflects real-life contexts, in which reporting status is unknown when screening for diet quality. We also acknowledge that the development sample may be biased as it includes participants involved in previous nutrition-related studies who might have a pre-existing interest in nutrition, thereby potentially influencing food choices and behaviors. Nevertheless, our analysis demonstrated that the Brief Diet Quality Assessment Tool may be useful in groups of adults with various characteristics.

Conclusion

We have developed and validated an easy-to-use Brief Diet Quality Assessment Tool that classifies individuals according to their risk of having a diet of low quality. Individuals classified as having a diet of low quality had a deteriorated cardiometabolic risk profile compared with those classified as having a diet of better quality, a strong predictive validation demonstration. This Brief Diet Quality Assessment Tool could easily be implemented in a primary care setting, where dietary assessment is highly challenging due to limited resources and expertise. Future research includes extensive testing of a web-based version of the Brief Diet Quality Assessment Tool with different health professionals and populations in primary care settings. Testing the external validity of the tool in other populations is also imperative before it can be recommended for use.

List of abbreviations:

AHEI: Alternative healthy eating index
CART: Classification and regression tree
INAF: Institute of nutrition and functional food
NPV: Negative predictive value
PPV: Positive predictive value
ROC: Receiving Operating Characteristic
webFFQ: web-based food frequency questionnaire

Declarations

<u>Ethics approval and consent to participate</u>

All participants provided consent in written form to have their data included in a database for use in research other than the main project in which they participated. The protocol of each of these studies was in accordance with the declaration of Helsinki. Data used in this project are part of a data management framework approved by the Laval University Ethics Committee (2008-279 CG A-1 R-2).

Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on a reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

JL, SL and BL designed the study. DL, CB, PC and BL collected the data and conducted the studies constituting the database used for this project. JL, SH and DT build the statistical model and analyzed the data. JL interpreted the data and wrote the manuscript. All authors critically revised and approved the final version of the manuscript.

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Tables and figures

Figure 1: Flow diagram of the data collected, and statistical analyses performed within each sample and sub-sample for the development and the validation of the Brief Diet Quality Assessment Tool.

Figure 2: Classification and regression tree for the prediction of diet quality (N=1040). Each box represents a split of the sample according to a specific food item predicting the diet quality outcome. The percentage of the total sample used at each split is shown in parentheses. Cut-offs of binary division are selected by the model to create the two most distinctive subgroups based on the diet quality outcome to predict (low vs. high). Cut-offs in servings/day are presented for each split under the box. Each sequence of questions yields the predicted diet quality (low or high).

Figure 1

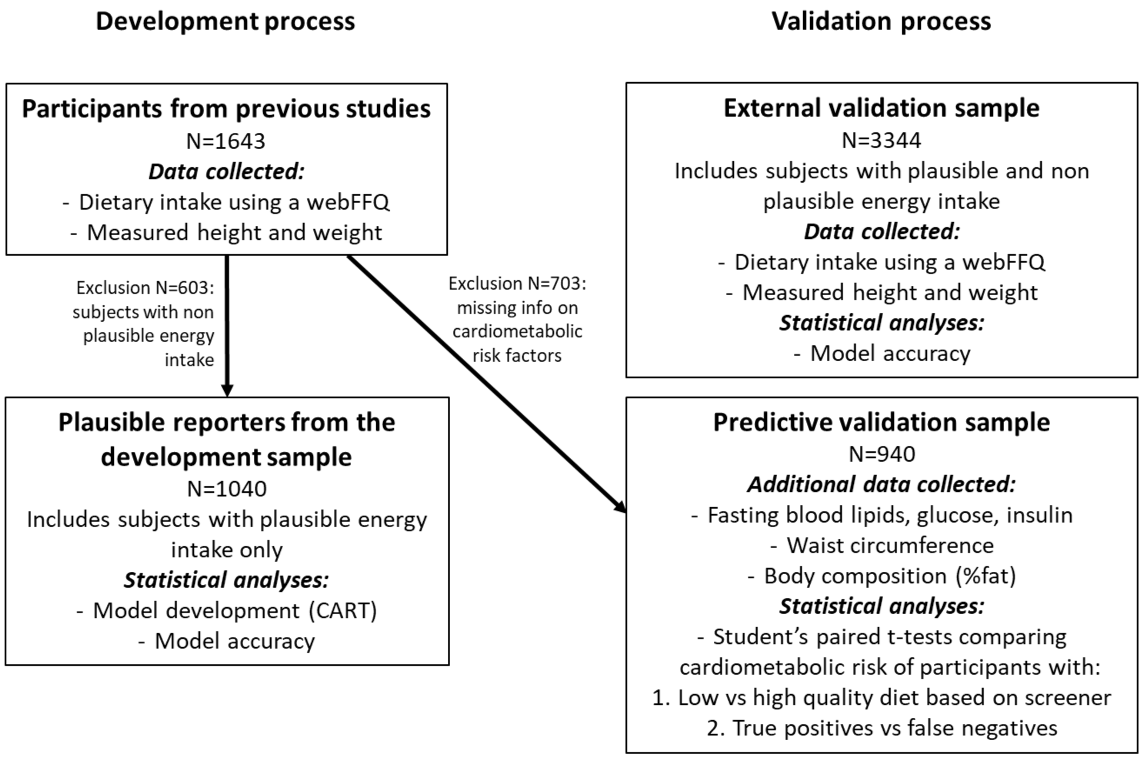
Development process
Validation process
Participants from previous studies
N=1643
Data collected:
- Dietary intake using a webFFQ
- Measured height and weight
Exclusion N=603: subjects with non plausible energy intake
Exclusion N=703: missing info on cardiometabolic risk factors
Plausible reporters from the development sample
N=1040
Includes subjects with plausible energy intake only
Statistical analyses:
- Model development (CART)
- Model accuracy
External validation sample
N=3344
Includes subjects with plausible and non plausible energy intake
Data collected:
- Dietary intake using a webFFQ
- Measured height and weight
Statistical analyses:
- Model accuracy
Predictive validation sample
N=940
Additional data collected:
- Fasting blood lipids, glucose, insulin
- Waist circumference
- Body composition (%fat)
Statistical analyses:
- Student's paired t-tests comparing cardiometabolic risk of participants with:
1. Low vs high quality diet based on screener
2. True positives vs false negatives

Figure 2

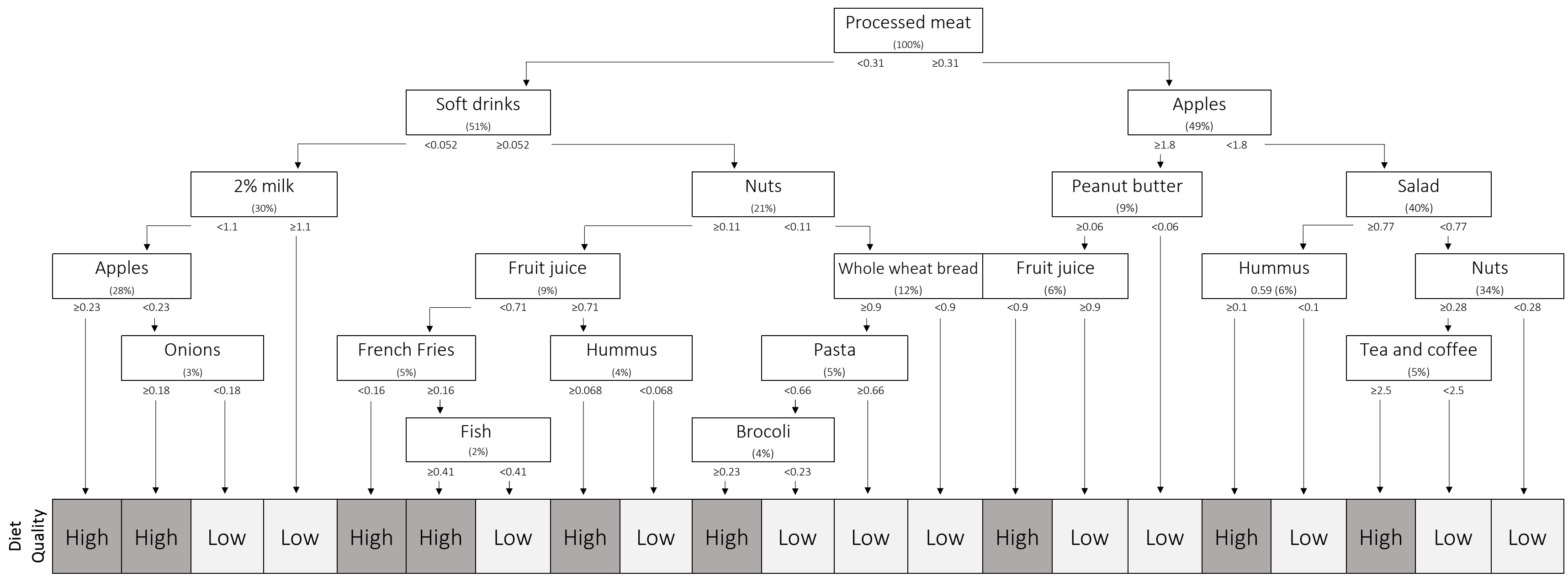
Processed meat
(100%)
<0.31
≥0.31
Soft drinks
(51%)
<0.052
≥0.052
Apples
(49%)
≥1.8
<1.8
2% milk
(30%)
<1.1
≥1.1
Nuts
(21%)
≥0.11
<0.11
Peanut butter
(9%)
≥0.06
<0.06
Salad
(40%)
≥0.77
<0.77
Apples
(28%)
≥0.23
<0.23
Fruit juice
(9%)
<0.71
≥0.71
Whole wheat bread
(12%)
≥0.9
<0.9
Fruit juice
(6%)
<0.9
≥0.9
Hummus
0.59 (6%)
≥0.1
<0.1
Nuts
(34%)
≥0.28
<0.28
Onions
(3%)
≥0.18
<0.18
French Fries
(5%)
<0.16
≥0.16
Hummus
(4%)
≥0.068
<0.068
Pasta
(5%)
<0.66
≥0.66
Tea and coffee
(5%)
≥2.5
<2.5
Fish
(2%)
≥0.41
<0.41
Brocoli
(4%)
≥0.23
<0.23
Diet Quality
High
High
Low
Low
High
High
Low
High
Low
High
Low
Low
Low
High
Low
Low
High
Low
High
Low
Low

Table 1: Alternative Healthy Eating Index (AHEI)-2010 scoring method

Components	**Criteria for minimum score (0)**	**Criteria for maximum score (10)**
Vegetables, servings/ day	0	≥5
Fruit, servings/day	0	≥4
Whole grains, g/day	0	
Women		75 (approximately 5 servings/day)
Men		90 (approximately 6 servings/day)
Sugar-sweetened beverages and fruit juice, servings/day	≥1	0
Nuts and legumes, servings/day	0	≥1
Red/processed meat, servings/day	≥1.5	0
Trans fat, % energy	≥4	≤0.5
Long chain (n-3) fats (EPA+DHA), mg/day	0	250
PUFA, % energy	≤2	≥10
Sodium, mg/day	Highest decile	Lowest decile
Alcohol, drinks/day[1]		
Women	≥2.5	0.5-1.5
Men	≥3.5	0.5-2.0
Total	0	110

1. In the design of the AHEI, authors assigned the highest score to moderate, and the lowest score to heavy, alcohol consumers. The nondrinkers received a score of 2.5. One drink is 4 oz of wine, 12 oz of beer, or 1.5 oz of liquor (1 oz = 28.35 g).
Adapted from Chiuve et al. (2012)

Table 2: Participants' characteristics in the plausible reporters from the development sample and external validation samples.

	Plausible reporters from the development sample (n=1040)			**External validation sample (n=3344)**		
	All participants (n=1040)	Women (n=536)	Men (n=504)	All participants (n=3344)	Women (n=1614)	Men (n=1730)
AHEI score	61.9 (14.1) [18.9-99.0]	65.2 (13.2) [29.2-99.0]	58.4 (14.3) [18.9-91.4]	63.4 (12.9) [22.9-100.8]	65.8 (12.6) [26.6-100.8]	61.3 (12.8) [22.9-99.8]
Age (years)	45.4 (14.2) [18.0-72.0]	45.3 (14.4) [18.0-70.0]	45.5 (14.0) [18.0-72.0]	66.5 (6.4) [47.0-91.0]	64.8 (5.9) [47.0-87.0]	68.2 (6.4) [47.0-91.0]
BMI (kg/m^2)	27.7 (5.3) [16.3-54.7]	26.9 (5.5) [16.3-54.7]	25.5 (5.0) [17.2-48.2]	27.1 (4.8) [13.6-56.1]	26.7 (5.4) [13.6-56.1]	27.5 (4.18) [14.7-48.0]

Values are presented as mean (standard deviation) and range [minimum-maximum]
AHEI= Alternate Healthy Eating Index, BMI= Body mass index

Table 3: Accuracy of the Brief Diet Quality Assessment Tool to predict low diet quality in the plausible reporters from the development sample (N=1040)

Accuracy metrics (95% CI)	
Sensitivity	0.88 (0.86-0.91)
Specificity	0.85 (0.86-0.88)
Agreement	0.87 (0.85-0.89)
Positive predictive value	0.90 (0.87-0.92)
Negative predictive value	0.84 (0.80-0.87)
AUC of the ROC	0.92 (0.90-0.94)

AUC of the ROC = Area under the receiver operating characteristic curve

Table 4: Cardiometabolic risk profile by categories of diet quality predicted by the Brief Diet Quality Assessment Tool in the predictive validation sample (N=940) *

	Diet quality according to Brief Diet Quality Assessment Tool					
	All		Women		Men	
	High (N=373)	**Low (N=567)**	**High (N=227)**	**Low (N=251)**	**High (N=146)**	**Low (N=316)**
AHEI score (/110)	71.5 (11.4)	53.1 (11.2) [c]	72.3 (11.5)	55.2 (10.2) [c]	70.2 (11.1)	51.4 (11.6) [c]
Age (years)	46.2 (13.5)	42.5 (13.1) [c]	45.9 (13.4)	41.7 (13.2) [c]	46.5 (13.5)	43.1 (13.0) [b]
BMI (kg/m^2)	25.9 (5.2)	28.6 (6.5) [c]	25.3 (5.2)	28.9 (7.3) [c]	26.8 (5.1)	28.5 (5.8) [b]
Waist circumference (cm)	87.3 (14.6)	96.0 (16.6) [c]	83.0 (13.1)	92.1 (16.7) [c]	93.9 (14.4)	99.1 (15.8) [c]
Percent fat (%)	28.9 (9.1)	30.2 (10.4) [a]	33.0 (7.5)	37.3 (8.7) [c]	22.6 (7.6)	24.6 (7.9) [b]
Blood pressure (mmHg)						
Systolic	114.9 (14.6)	119.9 (13.6) [c]	110.8 (14.2)	115.2 (13.8) [c]	121.3 (12.6)	123.6 (12.3)
Diastolic	71.3 (9.9)	75.3 (10.1) [c]	69.8 (10.0)	74.1 (10.1) [c]	73.6 (9.3)	76.3 (10.0) [b]
Lipids (mmol/L)						
TG	1.2 (0.7)	1.5 (1.1) [c]	1.2 (0.7)	1.4 (1.0) [a]	1.2 (0.7)	1.5 (1.1) [c]
LDL-cholesterol	2.8 (0.9)	2.9 (0.9)	2.8 (1.0)	2.9 (0.9)	2.8 (0.8)	2.9 (0.9)
HDL-cholesterol	1.5 (0.5)	1.4 (0.4) [c]	1.6 (0.5)	1.5 (0.4) [c]	1.4 (0.4)	1.3 (0.4) [b]
Chol/HDL-Cholesterol	3.4 (1.1)	3.8 (1.4) [c]	3.3 (1.2)	3.7 (1.4) [b]	3.6 (1.1)	4.0 (1.3) [b]
Glucose (mmol/L)	5.1 (0.7)	5.3 (1.0) [a]	5.1 (0.7)	5.1 (0.8)	5.3 (0.7)	5.4 (1.3)
Insulin (pmol/L)	88.1 (49.8)	107.0 (77.6) [c]	86.1 (54.6)	103.6 (60.4) [c]	91.3 (41.0)	109.7 (88.9) [b]

Variables are presented as mean (standard deviation)
AHEI= Alternate Healthy Eating Index, BMI= Body mass index
[a] P<0.05, [b] P<0.01, [c] P<0.001, from the Student's t-test for the difference between participants classified as having a high diet quality or a low diet quality.
*Only men and women from the development sample among whom cardiometabolic risk factors were measured were included in this analysis. This is why the number of participants (total N=940) is lower than in the entire development sample (N=1643).

Table 5: Cardiometabolic risk profile of participants with an AHEI <65/110 from the predictive validation sample, classified as true positive and false negative based on the Brief Diet Quality Assessment Tool (N=592) *

	All participants with AHEI <65		
	True positives (N=500)	**False negative (N=92)**	**P[1]**
AHEI score (/110)	50.7 (9.4)	56.3 (7.0)	<0.001
Age (years)	42.0 (13.2)	42.5 (12.9)	0.77
BMI (kg/m^2)	28.8 (6.6)	26.6 (5.2)	<0.001
Waist circumference (cm)	96.4 (17.0)	90.0 (14.4)	<0.001
Percent fat (%)	30.2 (10.4)	29.6 (9.0)	0.60
Blood pressure (mmHg)			
Systolic	120.1 (13.7)	115.5 (13.5)	0.003
Diastolic	75.6 (10.1)	72.6 (9.1)	0.01
Lipids (mmol/L)			
TG	1.5 (1.1)	1.2 (0.7)	<0.001
LDL-cholesterol	2.9 (0.9)	2.8 (0.8)	0.42
HDL-cholesterol	1.4 (0.4)	1.5 (0.5)	0.06
Chol/HDL-cholesterol	3.9 (1.4)	3.5 (1.1)	0.006
Glucose (mmol/L)	5.3 (1.2)	5.2 (0.8)	0.42
Insulin (pmol/L)	109.2 (80.3)	91.0 (42.8)	0.002

Variables are presented as mean (standard deviation)
AHEI= Alternate Healthy Eating Index, BMI= Body mass index
1. P value of the Student's t-test for the difference between participants classified true positive (AHEI<65 and classification as low diet quality with the Brief Diet Quality Assessment Tool) and false negative (AHEI<65 and classification as high diet quality with the Brief Diet Quality Assessment Tool).
*This analysis included only individuals from the predictive validation sample among whom the AHEI was < 65 (total N=592).

Table 6: Accuracy of the Brief Diet Quality Assessment Tool to predict low diet quality in the external validation sample (N=3344)

Accuracy metrics (95% CI)	
Sensitivity	0.73 (0.71-0.75)
Specificity	0.69 (0.67-0.71)
Agreement	0.71 (0.70-0.73)
Positive predictive value	0.77 (0.75-0.79)
Negative predictive value	0.64 (0.62-0.67)
AUC of the ROC	0.79 (0.77-0.80)

AUC of the ROC = Area under the receiver operating characteristic curve.

Conclusion générale

L'objectif de ce projet de thèse était de développer et de valider deux nouveaux outils destinés aux chercheurs en nutrition ainsi qu'aux professionnels de la santé afin d'améliorer l'évaluation alimentaire des habitants du Québec. Les travaux réalisés se détaillent en six articles révisés par les pairs et publiés dans des journaux scientifiques. Tout d'abord, les deux premiers s'attardent à tester globalement la validité du R24W pour évaluer les apports alimentaires moyens puis les trois articles subséquents s'intéressent plus précisément à la description et la mesure de la qualité alimentaire. Dans ces articles, des méthodes complémentaires ont été utilisées afin d'établir une preuve de validité convergente soit la validité absolue en contexte d'étude d'alimentation contrôlée, la validité relative au journal alimentaire, la validité relative à un biomarqueur de l'apport en légumes et en fruits et finalement la validité relative à des marqueurs de la santé métabolique.

Enfin, le dernier article décrit le développement et la validation d'un deuxième outil, un questionnaire court de dépistage nutritionnel. Il a été développé grâce à une méthode d'apprentissage automatique et sa validité interne (cohorte de développement) et externe (cohorte de validation) a été évaluée. La **figure 1** illustre schématiquement les six sections de cette thèse.

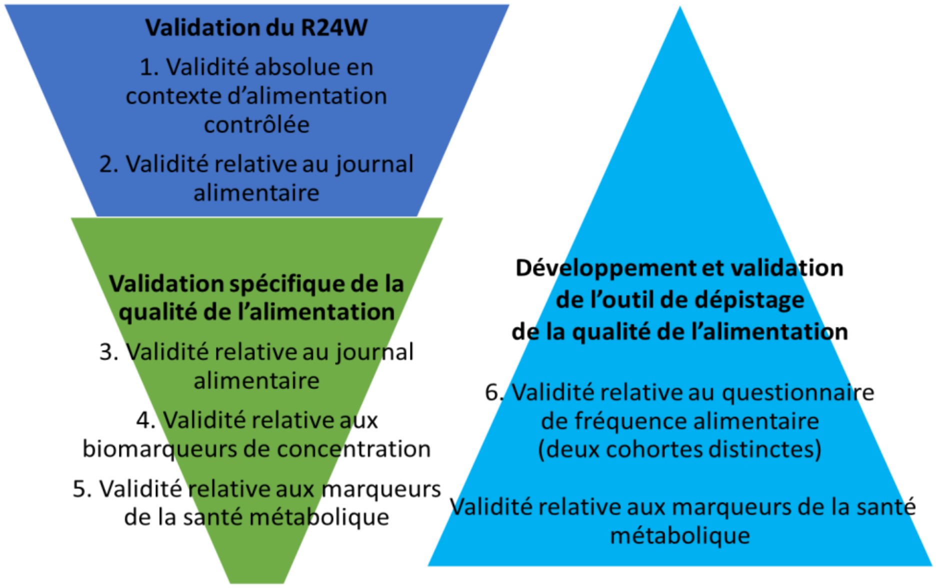

Figure 1 Plan de validation des deux outils d'évaluation de la qualité alimentaire

Tel que décrit au chapitre 1, le rappel de 24 heures permet de mesurer les apports moyens de manière adéquate surtout si quelques journées sélectionnées de manière aléatoire sont utilisées (61). Ces journées ne doivent cependant pas être trop étalées dans le temps sachant que les habitudes alimentaires tendent à varier à travers les saisons. Une méta-analyse publiée par Stelmach-Mardas illustre justement que les apports en énergie augmentent durant l'hiver et que les saisons sont des déterminants importants des apports en légumes, fruits, céréales, œufs, viande et alcool (137). Shahar et al. ont par ailleurs démontré que la modification des apports alimentaires entre l'été et l'hiver était associée à des changements dans l'indice de masse corporelle, la pression artérielle et le taux de cholestérol sanguin (138). Toutefois, bien que les apports en certains groupes alimentaires varient à travers l'année, certaines études suggèrent que la mesure globale de la qualité alimentaire demeure assez stable dans le temps (139,140). Nous avons donc tenté, au moyen d'études aux méthodologies variées, de démontrer que la mesure de l'alimentation avec trois jours de rappel de 24 heures sur une période de moins d'un mois permettait de tracer un portrait assez juste des apports moyens de cette période de l'année ainsi que de la qualité de l'alimentation des répondants.

Il est toutefois important de mentionner que les projets inclus dans cette thèse se sont limités à valider deux outils d'évaluation alimentaires et ne visaient pas à faire l'analyse critique des apports usuels des adultes québécois. En effet, comme les apports en aliments et en nutriments varient beaucoup d'un jour à l'autre, il est impossible d'obtenir une estimation précise de la distribution des apports dans la population (141). Ainsi, la moyenne de quelques jours aléatoires permet de tracer un portrait des apports alimentaires des individus. Cependant, la proportion de grands et petits consommateurs sera probablement inadéquate. Pour obtenir un estimer des apports usuels, il faut appliquer un ajustement statistique sur les données qui tient compte de la variation intra-individuelle. Plusieurs méthodes ont été développées (142), notamment celle de l'Institut national sur le cancer américain (143). Cette méthode permet d'estimer la distribution des données dans la mesure où deux journées de rappels de 24 heures sont disponibles pour au moins une partie de l'échantillon analysé. On utilise cette méthode pour rendre compte des enquêtes nationales de santé (144), mais il est aussi recommandé de s'en servir lorsque l'on s'intéresse à l'effet de la diète ou de ses composantes sur une autre variable dépendante (comme l'incidence de maladie par exemple) (145). Des études portant sur les prédicteurs de la saine alimentation ainsi que sur les habitudes alimentaires des Québécois dans lesquelles le R24W a servi d'outil de collecte de données ont déjà été publiées et plusieurs autres suivront prochainement (81,146,146,147).

Les études présentées aux chapitres 3 et 4 illustrent que le R24W a une validité et une précision acceptable pour mesurer ce que les utilisateurs ont consommé ainsi que leurs apports moyens en énergie et en nutriments. En effet, dans un contexte de recherche où tous les apports alimentaires étaient connus, les répondants ont réussi à estimer la taille des portions consommées avec une marge de 3,2g ou 9,3%. De plus, les répondants ont adéquatement rapporté 89% des aliments qui leur avaient été offerts (145). Dans un contexte où l'usage de la mémoire est nécessaire, une erreur d'estimation moyenne de moins de 10% peut être considérée comme acceptable (148). Ceci démontre que les fonctions de recherche du R24W sont suffisamment faciles à maitriser pour permettre aux utilisateurs de bien identifier les aliments qu'ils ont consommés et que les outils visuels intégrés au R24W ne semblent pas induire d'erreurs systématiques. Lorsque les apports moyens de près de 150 adultes évalués au moyen de trois jours de rappels sur le logiciel R24W ont été comparés à ceux relevés au moyen d'un journal alimentaire de trois jours, des apports comparables ont été observés pour l'énergie et 21 des 24 nutriments testés (149). Sachant que des journées différentes ont été analysées avec chacun des deux outils, il est prévisible qu'une certaine variabilité dans les apports soit notée. Nous avons toutefois tenté de valider l'hypothèse que l'évaluation des apports moyens avec trois journées de rappels de 24 heures pouvait limiter les erreurs aléatoires liées à la variabilité des apports d'un jour à l'autre. Étant donné que les apports réels des volontaires sont impossibles à authentifier dans un contexte où l'alimentation n'est pas contrôlée par l'équipe de recherche, nous avons utilisé le journal alimentaire de trois jours comme outil de référence. Ce dernier ne fait pas appel à la mémoire puisqu'il peut être complété au fur et à mesure et son format non structuré permet l'ajout de beaucoup de détails (48). Malgré ces atouts, des erreurs aléatoires attribuables aux répondants (informations incomplètes, apports significativement différents des apports usuels, modification des apports dans le contexte de la recherche) ou à l'équipe de recherche (erreur lors de l'entrée des données, codification dans les tables de valeurs nutritives incorrectes) pourraient avoir entraîné une évaluation imparfaite des apports moyens. C'est pourquoi plusieurs tests ont été utilisés pour mesurer la validité relative du R24W tel que suggéré par Lombard et al. (2) et qu'il n'est pas possible de conclure formellement de sa validité. Les données obtenues suggèrent que le R24W pourrait fournir des données inadéquates pour les apports en niacine, zinc et vitamine C étant donné que la lecture de ses trois nutriments variait à plusieurs égards par rapport à celle fournie par le journal alimentaire de trois jours. Des analyses plus poussées seront à compléter pour éclaircir cette question. Il est possible que certains aliments présentés dans la base de données du R24W soient liés à un code de la table de valeur nutritive qui surestime ou sousestime certains nutriments ou encore que des images présentées portent à rapporter une portion inadéquate. Une étude actuellement réalisée par notre équipe de recherche évalue la relation entre les apports alimentaires et les biomarqueurs de l'énergie, des protéines, du sodium et du potassium. Cette étude pourra valider la mesure de ces nutriments et proposer des hypothèses quant aux sources de variation entre les mesures du R24W et celles du journal alimentaire. Si des erreurs systématiques sont détectées, elles pourront être corrigées afin d'améliorer la validité de l'outil. Les stratégies envisageables pour corriger les potentielles erreurs systématiques incluent l'ajout d'aliments au profil nutritionnel particulier dans la base de données du R24W ou encore la modification des codes liant certains aliments à la valeur nutritive inscrite dans le fichier canadien sur les éléments nutritifs afin qu'ils soient plus représentatifs des choix alimentaires des utilisateurs. Outre ces trois nutriments pour lesquels un doute plane toujours, il semble adéquat d'affirmer que les apports moyens peuvent être mesurés avec confiance au moyen de trois jours de rappel de 24 heures via la plateforme R24W. En effet, la concordance des apports relevés au moyen de différents outils (concordance inter-observateurs) et lors de différentes journées (concordance dans le temps) est bonne tout comme la précision dans l'estimation de la taille des portions.

Les études présentées aux chapitres 5, 6 et 7 s'intéressent la mesure de la qualité alimentaire. Sachant que ce concept est difficile à définir, différentes méthodes ont été utilisées pour tenter d'en cerner les éléments-clés. Dans un premier temps, la mesure du score C-HEI 2007 au moyen du R24W fut comparée à celle issue du journal alimentaire. Encore une fois, des jours différents ont été utilisés pour le calcul du score avec chacun des deux outils. Nous posions l'hypothèse que trois jours de rappels de 24 heures permettaient de tracer un portrait assez juste de la qualité alimentaire. Nous avons observé que la concordance entre le R24W et le journal alimentaire pour la mesure du score C-HEI 2007 était supérieure à celle observée pour l'énergie et tous les nutriments testés précédemment dans la même cohorte. En effet, plus de 90% des répondants ont été classés dans le même quartile de score C-HEI 2007 ou dans un quartile adjacent lorsque ce dernier était mesuré avec le R24W ou avec le journal alimentaire alors qu'en moyenne, cette proportion n'était que de 80% lorsqu'il était question des apports en nutriments (150). Le score HEI permet de décrire des habitudes alimentaires de manière plus globales ce qui peut expliquer que sa mesure soit moins affectée par les variations quotidiennes dans la prise alimentaire (83). Par ailleurs, bien que les mesures aient été conduites dans un échantillon relativement homogène d'adultes québécois et francophones, nous avons aussi observé que les femmes ont obtenu en moyenne un score plus élevé que les hommes tout comme les répondants plus âgés par rapport aux plus jeunes. Ces observations ont été rapportées par d'autres chercheurs dans le cadre d'études de validation de scores de la qualité alimentaire (151,152). Ceci constitue donc un élément de validité externe pour la mesure du score C-HEI 2007 au moyen du R24W. Cette analyse a aussi soulevé certaines questions par rapport à la concordance interne du score lui-même. En effet, le score C-HEI 2007 est obtenu par l'addition des scores indépendants de 11 sous-échelles valant de 5 à 20 points chacune (voir **Tableau 1** au chapitre 1). Cependant, nous avons observé que les sous-scores attribués pour les échelles « Laits et substituts » ainsi que « Viandes et substituts » n'étaient pas significativement associés au score C-HEI 2007 total dans cette cohorte. Au sein de 998 participants de l'étude transversale PREDISE (chapitre 7), une analyse similaire de concordance interne a démontré que l'échelle « Laits et substituts » n'était, une fois de plus, pas associée au score total alors que l'échelle « Sodium » y était négativement associée (153). Cependant, dans les deux études ainsi que dans plusieurs autres où des analyses de validité interne du score HEI ont été conduites au sein de populations canadiennes et américaines (103,152,154), les échelles associées aux apports en légumes et en fruits étaient très fortement associées au score total. Les apports en légumes et en fruits sont par ailleurs associés à la santé métabolique et l'espérance de vie dans plusieurs grandes études (155,156). Il s'agit donc d'un bon indicateur de la qualité alimentaire. Dans l'étude présentée au chapitre 6, nous avons cherché à établir la validité du R24W pour mesurer les apports en légumes et en fruits en utilisant le dosage des caroténoïdes sériques comme biomarqueurs. Plusieurs chercheurs ont validé des outils d'évaluation alimentaire au moyen de ce biomarqueur tel que rapporté dans deux revues systématiques publiées par Burrows et al. (42,43). Nos analyses ont révélé des associations d'une envergure similaire à celles présentées dans ces revues entre les apports alimentaires en caroténoïdes et les dosages sériques de caroténoïdes (157). Ces résultats soutiennent que les apports en légumes et fruits relevés au moyen du R24W sont représentatifs des apports moyens pour la période testée étant donné que le dosage des caroténoïdes sériques a été réalisé 15 à 30 jours avant la mesure des apports en légumes et en fruits. Il semble donc approprié de conclure que le R24W permet de faire une lecture assez juste des apports en légumes et en fruits pour distinguer les plus grands consommateurs des plus faibles ce qui constitue un indicateur important de la qualité de leur alimentation habituelle. Les deux études précédentes ont donc permis d'établir que le R24W pouvait mesurer de manière adéquate le score C-HEI 2007 ainsi que les apports moyens en légumes et en fruits. Pour la dernière étude portant sur cet outil, nous avons utilisé les données issues de l'étude transversale PREDISE qui regroupait des adultes issus de cinq grandes régions métropolitaines du Québec afin d'avoir un échantillon plus représentatif de la population de la province en matière d'apports alimentaires ainsi qu'en matière de profils de santé métabolique. Dans ces analyses, les composantes du syndrome métabolique (la circonférence de taille, la pression artérielle, les triglycérides sanguins, le HDL-cholestérol et la glycémie à jeun) (158) ont été utilisées comme élément de comparaison pour mesurer la qualité alimentaire. En effet, sachant qu'une alimentation de qualité vise à réduire l'incidence de maladies métaboliques, ces marqueurs de santé peuvent servir à tester la validité externe d'un outil de mesure de l'alimentation (159). Cette étude se démarque des précédentes quant à sa méthode. En effet, nous avons d'abord cherché à tester si le score C-HEI 2007 calculé automatiquement au moyen du R24W pouvait prédire la prévalence du syndrome métabolique dans une cohorte représentative de la population québécoise. Sachant que le C-HEI 2007 visait avant tout à mesurer l'adhésion aux recommandations du GAC 2007 (où l'atteinte d'apports adéquats en nutriments est prioritaire par rapport à l'amélioration de la santé métabolique (95)), nous avons aussi tenté de déterminer si le score AHEI qui a été élaboré à partir des recommandations entourant la santé métabolique performait mieux pour prédire la prévalence du syndrome métabolique (115). Enfin, nous avons utilisé l'approche RRR pour déterminer les principaux facteurs alimentaires prédicteurs de la santé métabolique dans notre cohorte (121). Cette étude a révélé, dans un premier temps, que les répondants ayant un score C-HEI 2007 supérieur tel que calculé automatiquement avec le R24W ne présentaient pas une plus faible prévalence du syndrome métabolique que ceux ayant un score plus faible (153). Le score AHEI permettait toutefois d'établir cette distinction. Ceci suggère que le R24W peut faire une lecture valide de la qualité de l'alimentation des répondants telle que définie comme une alimentation favorisant la santé métabolique, mais que le score C-HEI 2007 n'est probablement pas l'outil le plus approprié pour y arriver. L'analyse du patron alimentaire obtenu avec la méthode RRR a révélé que les individus présentant une meilleure santé métabolique étaient ceux rapportant consommer plus de légumes, de fruits, de grains entiers et de protéines végétales tout en rapportant consommer moins de viandes rouges et transformées, de grains raffinés, de boissons sucrées et d'aliments transformés riches en gras saturés, en sucres et en sel. Ces observations corroborent toutes les recommandations issues de la version la plus récente du GAC 2019 (92). Il est donc logique de croire qu'en utilisant le R24W ainsi qu'une version modifiée du score C-HEI 2007 tenant compte des recommandations du GAC 2019 nous pourrions obtenir une lecture plus juste de la qualité de l'alimentation des adultes québécois.

Toutes ces analyses visaient principalement à tester la validité interne du R24W. En effet, toutes les études ont été conduites dans des cohortes d'adultes québécois dont la première langue est le français. Bien que les groupes de participants inclus dans les études présentées aux chapitres trois à sept présentaient des caractéristiques variées en termes de sexe, d'âge et de situation socio-démographique, il est donc important de mentionner que les conclusions des différentes analyses présentées dans cette thèse ne peuvent pas être généralisées à d’autres populations. D’ailleurs, une étude de validation réalisée dans une cohorte de femmes enceintes a récemment été publiée (160) et une autre est en cours dans une population d’adolescents.

Finalement, l’article présenté au chapitre 8 fait état du développement et de la validation d’un tout autre outil, un questionnaire de dépistage de la qualité alimentaire. Bien que différent des articles précédents dans ses objectifs et ses méthodes, cet article s’inspire de plusieurs des constats émis lors de la validation du R24W. Tout d’abord, les premières études de cette thèse ont démontré que même avec un outil facile à maitriser comme le R24W, un répondant doit disposer de temps et de volonté pour fournir un portrait détaillé de ses habitudes alimentaires. Nous nous sommes donc basés sur une méthode issue de l’intelligence artificielle pour identifier les éléments-clés à cibler de manière à obtenir un maximum d’information avec un minimum de questions (135). Ensuite, les études portant sur la qualité alimentaire ont illustré à quel point il est important de bien définir ce concept afin de s’assurer d’en faire une bonne lecture. En effet, nous avons constaté que bien que les différentes versions du score HEI aient été mises en relation avec la santé dans plusieurs études (161), le C-HEI 2007 n’était pas le meilleur indicateur de la santé métabolique. C’est pourquoi nous avons choisi de développer un outil de dépistage basé sur le score AHEI et nous avons inclus une étape de validation externe où plusieurs paramètres associés à la santé métabolique ont été analysés. De plus, une étape additionnelle de validation a été complétée au sein d’une cohorte indépendante. Parmi les répondants de ce deuxième groupe, l’outil de dépistage élaboré au moyen de la méthode CART a permis d’identifier environ 70% des adultes ayant une alimentation sous-optimale. De plus, les répondants classés comme ayant une alimentation de meilleure qualité avaient aussi, en moyenne, des paramètres de santé métabolique associés à un risque réduit (162).

Ce projet de thèse permet de prendre la mesure de l’impact de la validation des outils de mesure de l’alimentation dans l’interprétation de toutes les études en nutrition. Beaucoup d'outils ont servi à produire des données nutritionnelles sans faire l'objet d'un processus de validation détaillé. En révisant les études publiées au cours des dernières décennies, on constate que les données issues d'outils imparfaits utilisés au sein de très grandes cohortes de manière longitudinale ont permis d'identifier les patrons alimentaires qui constituent encore aujourd'hui l'essence de nos recommandations nutritionnelles. En effet, on a pu démontrer dans plusieurs types d'études robustes que la consommation d'aliments végétaux peu transformés était associée à une meilleure espérance de vie en santé (87,87). Cependant, d'autres associations plus pointues liant la consommation de certains aliments et le développement de maladie semblent être plus fortement influencées par l'outil d'évaluation alimentaire employé par les chercheurs (53). C'est pourquoi des efforts constants sont déployés pour améliorer la validité des outils, mais aussi pour arrimer les données obtenues issues d'anciens outils à celles qui seront produites par des outils présentant un meilleur niveau de validité.

Les données cumulées dans les articles présentées dans cette thèse tendent à démontrer que le R24W a un niveau de validité adéquat pour évaluer les apports moyens en nutriments et la qualité alimentaire des Québécois francophones. Dans le plan initial de ce projet, nous avions prévu ajouter des analyses de calibration afin d'améliorer l'acuité du R24W pour mesurer l'énergie et certaines caractéristiques de l'alimentation telle que les apports en légumes et en fruits (61,163). Nous avons finalement révisé notre plan étant donné que nous disposions principalement de données de validation relative qui ne permettaient pas de faire ce type d'analyses. Toutefois, les différentes études présentées dans cette thèse nous ont fait prendre conscience de la grande hétérogénéité dans les sources d'erreurs lors de l'évaluation alimentaire. Ainsi, même si nous disposions de mesures de biomarqueurs permettant de faire des analyses de calibration pour certains nutriments (164) il ne serait toujours pas possible de décrire toutes les facettes de l'alimentation avec précision. Il est donc essentiel, tel que suggéré par les experts du groupe STROBE-nut, de toujours interpréter les données de recherche en tenant compte des forces et faiblesses de l'outil de mesure de l'alimentation sélectionné (6).

Il a été mentionné à plusieurs reprises dans cette thèse que le R24W a été développé afin de mesurer l'adhésion aux recommandations nutritionnelles et la qualité alimentaire. Les travaux réalisés ont toutefois mis en lumière la nature équivoque de ce construit. En effet, les recommandations nutritionnelles sont vouées à évoluer avec la recherche en nutrition. Un nouveau guide alimentaire a d'ailleurs été publié pendant la complétion de cette thèse. La façon même de présenter les recommandations a été modifiée. Il n'est plus question de consommer un certain nombre de portions de certains aliments, mais bien d'adopter des comportements alimentaires favorisant la saine alimentation comme manger en famille et cuisiner davantage. La mesure de l'adhésion à ces recommandations exigera des outils permettant d'illustrer l'alimentation de manière plus globale. On peut aussi s'attendre à ce que des outils de dépistage basés sur les comportements et non sur les choix alimentaires voient le jour. D'un point de vue clinique, cette approche est certainement bénéfique puisqu'elle valorise l'importance de changements concrets que les patients peuvent facilement comprendre et s'approprier. Pour les chercheurs, elle pose beaucoup de défis techniques de standardisation des mesures, mais conduira certainement à l'amélioration des méthodes d'évaluation alimentaire à long terme.

Le R24W a pris une place importante dans le développement des projets de recherche à l'Institut sur la nutrition et les aliments fonctionnels (INAF) ainsi que dans d'autres centres affiliés. Il a servi à la collecte des données du projet PREDISE visant à identifier les déterminants individuels, sociaux et environnementaux de l'adhésion aux recommandations nutritionnelles (146,165). Il est aussi actuellement mis à l'œuvre pour collecter les données du projet NutriQuébec dont l'objectif est de suivre l'évolution des habitudes alimentaires des Québécois pour plusieurs années (166,167). Sa plateforme web ainsi que l'automatisation de l'analyse nutritionnelle permet d'épargner beaucoup de temps en collecte de données et de le faire évoluer avec les besoins des chercheurs. Il est réaliste d'imaginer qu'il servira à inspirer les futures plateformes d'évaluation nutritionnelle qui serviront à faire des enquêtes nationales de santé. Le R24W est aussi utilisé par certaines nutritionnistes cliniciennes collaborant avec notre institut de recherche. En effet, les outils sur plateforme-web permettent d'améliorer l'efficacité de la collecte et de l'analyse de données alimentaires. Les nutritionnistes peuvent donc se consacrer davantage aux stratégies de changements de comportement (168).

Quant à l'outil de dépistage de la qualité alimentaire, il n'a pas encore été adapté pour être utilisé à grande échelle. L'algorithme validé a toutefois été utilisé dans le cadre de certains projets de recherche en cours afin d'établir le profil de risque nutritionnel des participants. Des études d'interventions en milieux de soins permettront de guider les dernières étapes de configuration. À terme, il pourrait faciliter le travail des intervenants de première ligne et faciliter le référencement en nutrition ce qui pourra contribuer à améliorer les habitudes alimentaires d'une plus grande part de la population.

Dans une étude controversée publiée en 2015, au tout début de mon parcours doctoral, le docteur Edward Archer stipulait au moyen de plusieurs exemples détaillés que les chercheurs devraient abandonner l'utilisation d'outils d'évaluation alimentaire basés sur la mémoire. Il illustrait que ces derniers étaient tellement biaisés que leurs mesures devraient être considérées comme de la pseudoscience (1). Cet article a beaucoup influencé l'orientation de mes projets ainsi que ma vision de l'évaluation nutritionnelle. Bien que plusieurs de ses arguments aient été statistiquement démontés par d'autres auteurs (169–171), certaines questions de nature philosophique demeurent. Il est bien entendu qu'en 2020 il est toujours impossible d'obtenir un portrait exact des apports alimentaires des individus. Plusieurs outils sont en développement, notamment des logiciels permettant de reconnaitre les aliments et d'estimer les portions à partir de photographies ainsi que de nouveaux biomarqueurs. Ces outils pourront aider à confirmer ou remettre en question les observations obtenues avec les outils dont nous disposons actuellement. Cela pourrait permettre d'éclairer le lien entre certains aliments, certains patrons alimentaires et certaines maladies ou encore de mieux cibler les interventions pour optimiser les apports en nutriments. Malgré tout, il est difficile de croire que des outils technologiques pourront permettre une lecture exacte de la prise alimentaire réelle à grande échelle. Tout d'abord, cela pourrait provoquer de réels enjeux éthiques. En effet, les choix alimentaires sont grandement imbriqués dans un contexte psychologique et social. Il est donc indispensable que les individus puissent choisir ce qu'ils veulent partager ou non avec les chercheurs, ce qui laisse sans doute place à des zones grises. Ensuite, même les outils les plus performants ne permettent pas de lire les intentions derrière les comportements alimentaires. La science de la nutrition devra donc continuer d'évoluer en utilisant des données parfois incomplètes et imprécises des apports alimentaires et intégrer des expertises biochimiques, statistiques, psychologiques et sociologiques pour arriver à éclaircir les liens entre l'alimentation et la santé. C'est la somme de toutes ces expertises qui permet à long terme de mieux comprendre les comportements alimentaires, d'effectuer une surveillance adéquate des apports populationnels et de développer des programmes pertinents à grande échelle pour optimiser la santé des citoyens. C'est justement ce qui contribue à rendre cette discipline innovante et fascinante, et c'est pourquoi cette dernière doit demeurer une priorité nationale en matière de recherche et de politique.

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Annexe 1 - Les caroténoïdes sériques comme biomarqueurs: une stratégie pour améliorer la validité de l’évaluation alimentaire.

Résumé

La marge d’erreur dans l’évaluation de la prise alimentaire au moyen des outils traditionnels comme le rappel de 24 heures, le questionnaire de fréquence et le journal alimentaire est grande et peut conduire à l’interprétation erronée de résultats de recherche. Le développement de biomarqueurs associés à la consommation de légumes et de fruits a le potentiel d’améliorer sensiblement la validité de la mesure de la prise alimentaire ainsi que la mesure des associations entre la qualité alimentaire et la santé. Les caroténoïdes, des pigments issus presque exclusivement du monde végétal, présentent un intérêt grandissant dans ce domaine. Les caractéristiques des caroténoïdes ainsi que les avantages et les défis que pose leur utilisation dans l’évaluation nutritionnelle seront développés dans la présente revue.

Page titre

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Mots-clés : Caroténoïdes, évaluation alimentaire, biomarqueurs, fruits et légumes.

Les caroténoïdes sériques comme biomarqueurs: une stratégie pour améliorer la validité de l'évaluation alimentaire.

Introduction

En tant que professionnels de la santé, nous basons notre jugement clinique sur les données probantes issues de recherches publiées. Le processus de révision par les pairs ainsi que les standards des journaux scientifiques nous rassurent sur la validité de ces données. Il n'est toutefois pas rare, dans le domaine de la nutrition, que deux études aux protocoles rigoureux démontrent des conclusions divergentes quant aux impacts de la consommation de certains nutriments, aliments ou diètes sur la santé. Une grande part de la variation entre les études en nutrition serait attribuable à la technique utilisée pour évaluer la prise alimentaire. Les chercheurs utilisent le plus souvent le rappel de 24 heures, le questionnaire de fréquence alimentaire ou le journal alimentaire pour détailler l'apport en énergie et en nutriments des sujets de leurs études. Bien que ces outils possèdent certaines forces, il est démontré qu'ils permettent difficilement de représenter la prise alimentaire réelle avec le niveau de précision désiré (1).

Limites de l'évaluation alimentaire

Il est connu que les techniques rapportées ci-haut sous-estiment l'apport alimentaire attendu en partie car les sujets tendent à omettre de rapporter certains aliments, mais aussi parce qu'ils changent leurs habitudes lorsqu'ils prennent part à une étude (2). Selon certaines analyses, les données recueillies dans le cadre du National Health and Nutrition Examination Survey (NHANES) aux États-Unis présenteraient plus de 50% de données d'apports énergétiques physiologiquement irréalistes (3). La sous-déclaration des apports alimentaires s'observe de manière très variable d'une personne à l'autre. En effet, les individus présentant un statut pondéral plus élevé, un niveau socio-économique plus faible ainsi qu'un degré de restriction cognitive et de désirabilité sociale supérieur tendent à sous-déclarer davantage (4,5). De plus, la marge d'erreur n'est pas équivalente pour tous les nutriments. Les collations et les condiments étant plus fréquemment oubliés que les mets principaux (6), certains nutriments typiques de ces aliments se retrouvent donc sous-représentés. Il est d'ailleurs reconnu que les protéines sont rapportées de manière plus exact que l'énergie ce qui laisse croire que les lipides et glucides sont particulièrement sous rapportés (1,7,8). L'impact de cette distorsion dans l'évaluation des macronutriments pourrait être majeur dans l'évaluation du risque relatif reliant l'alimentation à des indicateurs de santé. Par exemple, Prentice et al. (9) ont déterminé qu'après ajustements pour la sous-déclaration et l'erreur de mesure, le risque relatif associé à la consommation de lipides (10e par rapport au 90e percentile de consommation telle qu'évaluée par un questionnaire de fréquence) sur le développement du cancer du sein chez les femmes après la ménopause chutait de 4.00 à 1.42.

En plus des études nationales canadiennes et américaines sur la nutrition, plusieurs grandes études longitudinales telles que la Nurses' Health Study (10) et la Women Health Initivative (11) ont eu un impact majeur sur le développement des lignes directrices en matière de nutrition. Celles-ci se basent toutefois aussi sur des observations nutritionnelles découlant de l'utilisation d'outils tels que des questionnaires de fréquence et des rappels de 24 heures qui sont sujets à plusieurs biais. Bien que ces données ne soient pas totalement erronées, à la lumière des observations précédentes, elles méritent d'être analysées avec précaution.

Afin d'aborder ce problème, plusieurs groupes de chercheurs travaillent à revoir complètement les stratégies de validation des outils de mesure de la prise alimentaire. La découverte de plusieurs biomarqueurs nutritionnels est au cœur de ce changement de perceptive. En effet, il est désormais possible de mesurer objectivement la dépense énergétique grâce à la technique de l'eau doublement marquée (12) et l'apport en protéines grâce au dosage de l'azote urinaire (13). Plusieurs autres biomarqueurs sont présentement à l'étude.

Les caroténoïdes

Il existe plus de 600 formes de caroténoïdes dans la nature et de ce nombre, une soixantaine est détectable dans les aliments. Les six plus fréquemment observées et étudiées sont le lycopène, le β-carotène, l'α-carotène, le β-cryptoxanthine, la lutéine et la zéaxanthine (14). Les caroténoïdes sont des antioxydants qui piègent les radicaux libres en agissant comme immunomodulateur (15). Certains caroténoïdes ont aussi le potentiel d'agir comme précurseur de la vitamine A.

Les taux sériques de caroténoïdes chez des hommes et des femmes adultes en santé oscillent entre 0.08 et 0.47 nmol/litre, le lycopène, le β-carotène et la lutéine étant ceux présents en plus grande quantité (16). Les caroténoïdes se retrouvent presqu'exclusivement dans le règne végétal, principalement dans les légumes et les fruits, mais dans des proportions très différentes d'un aliment à l'autre (voir Tableau 1) (17–19).

Absorption et métabolisme des caroténoïdes

L'interprétation des dosages plasmatiques de caroténoïdes chez l'humain doit tenir compte de plusieurs facteurs. D'abord, les recherches démontrent de manière soutenue que l'ajout de lipides améliore la biodisponibilité des caroténoïdes (20–23). La consommation simultanée de fibres limite toutefois l'accès des caroténoïdes aux sites d'absorption (24). Enfin, l'ingestion de différents caroténoïdes, au moyen de suppléments, a été associée à une réduction de l'absorption par compétition pour les sites d'absorption. Une chute de la biodisponibilité de la lutéine a entre autre été observée suite à la consommation d'un supplément de β-carotène (25). Ces facteurs expliquent la variabilité observée dans les taux d'absorption des caroténoïdes. En effet, Reboul et al. (26), a établi des ratios (apport/taux sérique) de biodisponibilité assez larges pour l'α-carotène (1.6-14.5%), le β-carotène (0.1-17.5%), le lycopène (0.1-1.6%) et la lutéine (37.6-59.4%).

Association entre les dosages plasmatiques en caroténoïdes et les apports en fruits et légumes

Malgré les taux de biodisponibilité variables, plusieurs chercheurs ont observé des corrélations significatives entre les dosages sériques de caroténoïdes et les apports en fruits et légumes (18,27). Certaines études ont aussi utilisé les dosages sériques de caroténoïdes comme indicateurs de l'adhésion aux recommandations nutritionnelles visant l'augmentation de la consommation de fruits et de légumes. Le Marchand et al. (28) ont noté une hausse du taux sérique de caroténoïdes totaux de 29% chez les participants ayant réussi à augmenter leurs apports en fruits et légumes de 4.2 à 9.5 portions/ jours grâce au counseling nutritionnel.

De plus, dans certaines études contrôlées où des légumes en particulier étaient offerts, des variations significatives ont été observées dans les taux de caroténoïdes. Dans une étude de Micozzi et al. (29), les participants consommant une diète standard enrichie en brocoli ont vu leur taux plasmatique de lutéine augmenter; chez ceux recevant une diète riche en carottes ont a noté une augmentation de leurs taux d'α-carotène et de β-carotène alors que ceux qui ont reçu une diète additionnée de tomates ont vu leur taux de lycopène augmenter. De manière similaire, en comparant différents groupes, Van het hof et al (30) ont observé que la consommation d'une diète riche en brocoli pouvait engendrer une augmentation du taux de lutéine de 150% ainsi qu'une augmentation du taux de β-carotène de 26% par rapport à une diète contrôle pauvre en légumes. Dans une revue systématique menée en 2011 (31), les auteurs ont observé que dans 35 des 36 études où des fruits et des légumes étaient fournis aux sujets (généralement l'équivalent de 5 portions/jour) une augmentation de certains caroténoïdes était observable. Enfin, en faisant l'analyse des taux sériques de caroténoïdes de plus de 300 individus ayant pris part à des études d'alimentation contrôlée, des chercheurs de notre équipe ont observé des corrélations significatives entre la nombre de portions de légumes et fruits des diètes et les taux sériques de lutéine et de B-Cryptoxanthine (32).

Conclusion : le développement de biomarqueurs à partir des caroténoïdes sériques

La section précédente démontre que les caroténoïdes plasmatiques représentent dans une certaine mesure les apports en fruits et en légumes et peuvent être utilisés comme biomarqueurs de consommation. Cependant, plusieurs facteurs additionnels doivent certainement être pris en considération afin de caractériser l'apport en fruits et légumes d'un individu en fonction de son taux circulant de caroténoïdes (33).

D'abord, certains caroténoïdes, tel que le β-crytpoxanthine, la lutéine et l'α-carotène ont démontré les meilleures corrélations avec les apports en fruits et légumes (18,27), mais les résultats varient beaucoup d'une étude à l'autre. Cela peut s'expliquer par le fait que tous ces pigments sont présents dans les types de fruits et de légumes dans des proportions différentes. Les habitudes alimentaires globales du groupe étudié peuvent donc grandement influencer l'association entre certains caroténoïdes et la consommation de fruits et légumes. L'évaluation combinée de plusieurs caroténoïdes pourrait permettre de développer un biomarqueur applicable à plusieurs types de patrons alimentaires (31). La biodisponibilité des caroténoïdes est aussi très variable d'un aliment à l'autre et tributaire des processus de transformation. En effet, lorsque les aliments sont hachés finement ou réduits en purée, les pigments sont libérés de leur compartiment cellulaire et absorbés en beaucoup plus grande quantité (34,35). De plus, la lutéine et la zéaxanthine, par leur polarité réduite démontrent une absorption supérieure à l'α-carotène et au β-carotène (26,36). Enfin, la sélection des caroténoïdes utilisés comme biomarqueur doit tenir compte de la bioconversion des précurseurs de vitamine A qui peut altérer la transposition sérique des caroténoïdes ingérés (37). Le β-carotène, l'α-carotène et le β-cryptoxanthine ont le potentiel d'être convertis en vitamine A dans des proportions variant selon les apports et le statut nutritionnel du sujet (38).

Dans la plupart des études, les valeurs brutes de caroténoïdes plasmatiques sont corrélées à l'apport alimentaire en fruits et en légumes. Cependant, en tenant compte de ces facteurs, il semblerait pertinent d'évaluer le potentiel biomarqueur des différents caroténoïdes en ajustant les corrélations en fonction du degré de transformation des aliments consommés (34), de l'apport concomitant en lipides (20), en fibres (24) et en suppléments nutritionnels riches en caroténoïdes. De plus, sachant que les caroténoïdes sont principalement entreposés dans le tissu adipeux et que ce dernier est négativement associé aux taux circulants de certains caroténoïdes (39) il serait pertinent de mesurer l'impact de cette variable sur l'association entre l'apport en fruits et légumes et les caroténoïdes sériques.

Pertinence pour la pratique

Le dosage sérique des caroténoïdes pourrait permettre de mieux caractériser l'apport en fruits et en légumes des individus et de calibrer les outils de mesures de la prise alimentaire afin qu'ils représentent plus adéquatement la qualité globale de l'alimentation (40). Cette nouvelle technologie représente un outil intéressant pour les cliniciens de par sa complémentarité avec l'entrevue nutritionnelle. En effet, bien que le dosage de caroténoïdes sériques puisse aider à objectiver l'évaluation de l'apport en fruits et légumes, aucun test sanguin ne peut caractériser le choix des fruits et légumes, le format sous lequel ils sont consommés ainsi que tous les autres facteurs socio-culturels qui influencent la prise alimentaire. Il reste aussi du travail pour standardiser les mesures afin qu'elles reflètent adéquatement une variété de patrons alimentaires et pour rendre ces mesures accessibles aux cliniciens. La recherche sur les biomarqueurs aura sans aucun doute une grande influence sur l'avancement des connaissances en nutrition. Elle permettra de jeter un nouvel éclairage sur plusieurs constats d'études antérieures réalisées avec des mesures auto-rapportées.

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Tableau

Tableau 1 : Sources alimentaires des principaux caroténoïdes sériques

Caroténoïdes	Sources alimentaires
Lutéine	Épinards, brocoli, maïs, abricots et nectarine
Zéaxanthine	Épinards, brocoli, maïs, abricots et nectarine
B-Cryptoxanthine	Oranges, papayes, nectarines
A-Carotène	Légumes et fruits orangés, légumes vert foncé tels que les épinards, les pois, les haricots
B-Carotène	Légumes et fruits orangés, légumes vert foncé tels que les épinards, les pois, les haricots
Lycopène	Tomates et produits dérivés

Tiré de Breithaupt et al. (2001), Jansen et al. (2004), Rodriguez-Amaya (2010)