Investigating dietary measurement error: A review of statistical methods

Janet A. Tooze, PhD
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Surveillance Measurement Error Working Group

Regan Bailey
Dennis Buckman
Raymond Carroll
Kevin Dodd
Laurence Freedman
Patricia Guenther
Victor Kipnis
Sharon Kirkpatrick
Susan Krebs-Smith
Douglas Midthune
Amy Subar
Fran Thompson
Janet Tooze
Outline

• Dietary Assessment: Goals and tools
• Sources and magnitudes of dietary measurement errors
• Other challenges to estimating usual dietary intake
• How the effects of measurement error and other challenges may be alleviated
• Regression Calibration
Dietary Assessment
Usual dietary intake
Average or long-run intake (*habitual intake*)
over a specific period of time

- We usually want to estimate usual intake
- Nutrients are stored in the body
- Intakes vary from day to day
- It is unnecessary and impractical to achieve nutrient and food recommendations every day
- Hypotheses about health outcomes and diet are based on dietary intakes over the long term
Food frequency questionnaire (FFQ)

- Aims to capture long-term intake
- Inexpensive to administer
- Finite food list
- Affected by recent diet
- Cognitively challenging
- Lack of Detail → Conversion to nutrient intakes cumbersome and makes assumptions
24-hour recall

• Less cognitively challenging than FFQ
• Rich detail makes conversion to nutrients easier

• Expensive to collect and code (until recently)
• Short term instrument
Recovery biomarkers

• Specific biologic product directly related to intake
• Not subject to homeostasis or substantial interindividual differences in metabolism
• Examples:
  • Doubly labeled water for energy intake
  • Urinary nitrogen for protein intake
Dietary Measurement Errors
What is measurement error?

• Difference between the true value and the value obtained from a measurement
Types of error

• Random
  • An unpredictable source of error that contributes variability
  • An instrument that is subject to only random error is unbiased, but may or may not be precise

• Systematic
  • A source of error in which measurements consistently depart from the true value in the same direction
  • An instrument that is subject to systematic error is inaccurate or biased
Measurement error

- Day to day variation
- Error in Reporting
  \[ \{ \text{Random} \]  
  \[ \{ \text{Additive Error} \]
  \[ \{ \text{Intake-related bias} \]
  \[ \{ \text{Person-specific bias} \]
- Systematic

Wake Forest School of Medicine
Implications of Measurement Error
Impact of random error

- Attenuated slope
- Loss of Power
How do we quantify measurement error?

- Use a reference measurement to estimate truth
- Calculate bias
- Calculate correlation between measure and truth
Main versus reference instrument

• Main instrument
  – The primary dietary assessment instrument

• Reference instrument
  – An instrument used to calibrate or validate the main instrument
  – Assumed to provide estimates that are closer to the underlying truth than the main instrument (alloyed gold standard)
Reference instrument: ideal properties

- Unbiased measure of individual true usual intake
- Errors uncorrelated with true usual intake
- Errors uncorrelated with errors in study instrument
Validation study

- Observing Protein and Energy Nutrition (OPEN) Study
  - Assessed measurement error structure in:
    - Interviewer-administered 24HR
    - FFQ
    - Recovery biomarkers
      - Doubly labeled water
      - Urinary nitrogen
  - Included 484 men and women aged 40-69 years and living in Montgomery County, Maryland
Attenuation

• Attenuation factor ($\lambda$):
  • the degree to which a regression coefficient is biased toward the null
  • Between 0 and 1
  • Close to 0, more attenuation
## OPEN Validation Study: FFQ (Women)

### Attenuations

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Measure of Truth</th>
<th>Attenuation $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>DLW</td>
<td>.04</td>
</tr>
<tr>
<td>Protein</td>
<td>UN</td>
<td>.14</td>
</tr>
<tr>
<td>Protein Density</td>
<td>UN/DLW</td>
<td>.32</td>
</tr>
</tbody>
</table>
If a specified increase in protein or energy intake actually increases the risk of cancer by 100%, a study using the OPEN FFQ for women would estimate the increased risk as only between 3% and 10% (25% for protein density).
Correlation

• Correlation between self report and truth ($\rho_{QT}$)
  • Related to statistical power to detect diet-health relationships.
  • Close to zero, less power
## OPEN Validation Study: FFQ (Women)

### Correlations with True Intake

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Measure of Truth</th>
<th>Correlation $\rho_{QT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>DLW</td>
<td>.10</td>
</tr>
<tr>
<td>Protein</td>
<td>UN</td>
<td>.30</td>
</tr>
<tr>
<td>Protein Density</td>
<td>UN/DLW</td>
<td>.35</td>
</tr>
</tbody>
</table>
If you are interested in the effect of energy on health, multiply the number of cases you thought you needed by 100. For protein/protein density, by about 8-10.
**OPEN findings: Structure of measurement error**

<table>
<thead>
<tr>
<th>24-hour recall (24HR)</th>
<th>Food frequency questionnaire (FFQ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Larger within-person random error</td>
<td>• Smaller within-person random error</td>
</tr>
<tr>
<td>• Smaller systematic error</td>
<td>• Larger systematic error</td>
</tr>
</tbody>
</table>
Linear Regression Calibration
What is regression calibration?

• When there is a **single** dietary exposure measured with error in a diet-health model:
  • Estimated diet-health relationship (risk) is **attenuated** (underestimated)
  • Power to detect relationship is **decreased**
  • Way of alleviating measurement error
    • Adjust the risk estimate
      • Regression calibration
Risk Model

- Risk/Health model (linear regression):
  \[ Y = \alpha_0 + \alpha_T T + \alpha_{Z1} Z_1 + \cdots + \alpha_{Zp} Z_p \]

- \( Y \) = health outcome variable
- \( T \) = true dietary intake
- \( Z_1, \ldots, Z_p \) = other variables in disease model
- \( Z = \{Z_1, \ldots, Z_p\} \)
- \( \alpha_T, \alpha_{Z1}, \ldots, \alpha_{Zp} \) = regression coefficients
Risk model

- Risk model:
  \[ Y = \alpha_0 + \alpha_T T + \alpha_{Z1} Z_1 + \cdots + \alpha_{ZP} Z_P \]

- Problem:
  
  - We are unable to measure \textbf{true} intake \( T \)
  
  - Instead, we obtain \textbf{reported} intake \( Q \) which is subject to measurement error

  - If we use \( Q \) instead of \( T \) in the risk model, the estimate of \( \alpha_T \) will be biased (attenuated)
Regression calibration

- Risk model:

\[ Y = \alpha_0 + \alpha_T X + \alpha_{Z1} Z_1 + \cdots + \alpha_{ZP} Z_P \]

- Regression calibration method:
  
  - Step 1: Calculate \( E(T|Q, Z) \) = conditional expectation of \( T \) given \( Q \) and \( Z \)

  \( E(T|Q, Z) \) is the "predicted value" of \( T \) given \( Q \) and \( Z \)

  - Step 2: Replace \( T \) with \( E(T|Q, Z) \) in risk model
How do we calculate $E(T|Q, Z)$?

- In order to predict $T$, we need to develop a “prediction equation”

- Example: **linear** prediction equation

$$E(T|Q, Z) = \lambda_0 + \lambda_Q Q + \lambda_{Z_1} Z_1 + \ldots + \lambda_{Z_p} Z_p$$

- If $T$ were observable in a sample of participants, could estimate the parameters in prediction equation by regressing $T$ on $Q$ and $Z$

- **BUT** $T$ is not observable…

- **BUT** what if we had a reference instrument?
Reference instrument: ideal properties

- Unbiased measure of individual true usual intake
- Errors uncorrelated with true usual intake
- Errors uncorrelated with errors in study instrument
Reference instrument: Use

• This means that our reference instrument $R$ gives us a measure of truth, with some noise, i.e.

$$R = T + e$$

• Under this assumption, the noise averages out

$$E(R|Q, Z) = E(T|Q, Z)$$

• Estimate prediction equation by regressing $R$ on $Q$ and $Z$ in a sample of participants

• We use 24 hour recall as $R$, even though it is not ideal
Calibration studies

• In order to regress R on Q, we have to have some people who have measures of both R and Q

• A sample collected for this purpose is called a “calibration study”
Additional Challenges of Dietary Data: Skewness

As if life wasn’t complicated enough....
Skewness

Density

Folate intake (µg/day)
Transformation and backtransformation

• Transform to deal with skewness
• Backtransform to original scale
  • Mean of transformed data $\neq$ transformation of mean on the original scale
  • With nonlinear transformation is used, the estimated mean is an integral that can be calculated/approximated in several ways
    • Taylor series approximation
    • Numerical integration
Regression Calibration with Transformation
Regression Calibration with Transformation

- We have skewed diet data
  - Incorporate transformations
    - Predictor Q
    - Outcome R
- Our goal is still to get $E(T|Q,Z)$
- We still use $E(R|Q,Z)$ to get this
- But…
  - We have to transform R
  - We have to transform Q
Regression calibration with transformation

- Assumption for reference instruments
  \[ E(R|Q, Z) = E(T|Q, Z) \]

- After transformation, this equality is only approximate
  \[ E\{g(R)|Q, Z\} \approx E\{g(T)|Q, Z\} \]

- In practice, approximation is usually assumed good enough for dietary components consumed (nearly) every day
Additional Challenges of Dietary Data: Consumption Patterns

As if life wasn’t complicated enough....
Daily vs. episodic consumption

• Consumed nearly daily by nearly all persons
  • E.g., vitamin C, total grains, total vegetables, protein foods

• Consumed episodically by most persons
  • E.g., Vitamin A, whole grains, dark green vegetables, fish
Daily consumed: Total grains

Source: EATS, men, day 1
Episodically consumed: Whole grains

Source: EATS, men, day 1
Two parts of usual intake

Usual Intake

Probability to Consume

Amount Consumed on Consumption Day
Correlation between probability and amount of whole grain intake, men.
Regression Calibration for Episodically Consumed Foods
NCI Method: Overview

Two-Part Model: for episodically-consumed constituents

• Part 1: Probability
  • Mixed model logistic regression
    • Can incorporate covariates – FFQ and others
• Part 2: Amount
  • Mixed model linear regression
    • Can incorporate covariates – FFQ and others
    • Transformed scale – accounts for skewness
• Link
  • Person-specific effects are correlated – Models correlation
  • May share covariates
Regression calibration

• Regression of R on Q, Z is a two-part model
  • Probability of consumption
  • Consumption day amount
• $E(T|Q,Z)$ comes from the product of probability and amount
Additional Challenges of Dietary Data: Energy Adjustment

As if life wasn’t complicated enough….
Energy Adjustment

• In regression models, we are not usually interested in just the effects of one variable

• We often want to adjust for other variables of interest, especially total energy

• Reasons for energy adjustment:
  – Interest in association between dietary composition and health
  – Energy-adjustment often decreases measurement error in reported intake
Regression calibration with two dietary exposures

• Outcome model:

\[
Y = \alpha_0 + \alpha_{T1}T_1 + \alpha_{T2}T_2 + \alpha_{Z1}Z_1 + \cdots + \alpha_{ZP}Z_P
\]

• Replace \(T_1\) and \(T_2\) with \(E(T_1|Q_1,Q_2,Z)\) and \(E(T_2|Q_1,Q_2,Z)\)

• \(E(T_1|Q_1,Q_2,Z)\) is the **predicted value** of \(T_1\) given reported intakes \(Q_1\) and \(Q_2\) and explanatory variables \(Z_1, \ldots, Z_p\)

• Confidence intervals for odds ratios calculated using the bootstrap method
Regression Calibration with Transformation for Episodically Consumed Foods Adjusted for Energy
Regression calibration

• Regression of R on Q, Z is a three-part model
  • Probability of consumption for food
  • Consumption day amount for food
  • Amount of energy intake
  • $E(T_F|Q_F,Q_E,Z)$ comes from the product of probability and amount for the episodically-consumed food
  • $E(T_E|Q_F,Q_E,Z)$ comes from the equation for energy
• Use both of these predictors in the disease model with bootstrap for standard errors
• Still have transformations to deal with
Conclusions
Caveats

• Assume that it is possible to regress the recall on the FFQ (and other covariates)
• Implies that FFQ has a “well behaved” distribution, at least on a transformed scale
  • May not be the case
• Need to have an adequate calibration sample size to be able to deal with the inflated variance associated with estimating the regression calibration estimate $E(T|Q,Z)$
  • Regression calibration corrects for bias, but does not restore power
Use of Regression Calibration

- Nutrients, even skewed
- Episodically-consumed foods
- Energy adjustment
- Can be used with different types of disease and health outcomes
  - Linear regression, logistic regression, Cox regression
- Not yet developed to estimate many foods/nutrients simultaneously