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Quantitative approaches to nutrient density for public health nutrition

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Abstract

Nutrient density, the vitamin or mineral content of a food or diet per unit energy, has long been a useful concept in the nutritional sciences. However, few nutritionists have applied the idea in quantitative, population-based nutrition planning and assessment. This paper discusses the conceptual issues related to the calculation of a nutrient density value that, if consumed, should meet the nutrient needs of most individuals in a population or sub-population, and outlines several methods for estimating this value. The paper also discusses the potential influence on the estimate's validity of factors such as skewed distributions and correlated energy intake and nutrient requirement.

Keywords
Nutrient density
Nutrition planning
Probability approach

Nutrient density, the vitamin or mineral content of a food or diet per unit energy, has long been a useful concept in the nutritional sciences. Increased risk of micronutrient malnutrition among infants, for example, is often viewed as a function of high nutrient requirements in comparison to relatively low energy need. Indeed, one argument in favour of the delayed introduction of weaning foods in the developing countries is the relatively low nutrient density of weaning foods in comparison to breast milk[1,2]. In the elderly, declining energy intake with age has been identified as a potential contributor to micronutrient malnutrition[3,4].

Despite long use of the nutrient density concept in a qualitative sense, few nutritionists have applied the idea in quantitative, population-based nutrition planning and assessment. The present paper discusses the conceptual issues related to the calculation of a nutrient density value that, if consumed, should meet the nutrient needs of most individuals in a population or sub-population. The paper also outlines several methods for estimating this value and discusses the potential influence on the estimate of factors such as skewed distributions and correlated energy intake and nutrient requirement.

The importance of nutrient density

The concept of nutrient density recognises the close relationship between energy intake and consumption of other nutrients. Vitamins and minerals are almost always consumed together with significant amounts of energy; therefore, intakes of energy and micronutrients are often strongly correlated[5]. Because energy intake, unlike vitamin and mineral consumption, is actively regulated by appetite and satiety, energy needs may be satisfied well before requirements for vitamins and minerals are met. The result is increased risk of malnutrition. When energy intakes are adequate, food-based strategies for improving the nutritional status of individuals and groups must increase the nutrient density of the diet. In many cases, a target nutrient density may be useful for planning and assessment purposes. For example, a recent Institute of Medicine (IOM) report used an energy density approach to establish technical specifications for an emergency relief product for use in nutrition emergencies[6].

The joint distribution of energy intake and nutrient requirement

Analogous to the Recommended Dietary Allowance (RDA), a *Recommended Nutrient Density* (RND) might be defined as the nutrient content of a diet that would ensure that 97.5% of a population or sub-population meets their nutrient requirements when individuals consume their usual energy intake. As with the RDA, selection of 97.5% as the target value is arbitrary, and a lower (or higher) percentile value might be more appropriate depending on the requirements of the assessment and/or intervention.

In 1974, Beaton and Swiss[7], who expanded on earlier work by Lorstad[8], outlined the conceptual issues related to nutrient density in an article about protein–energy ratios. Together with Fieller's Theorem[9], the Beaton–Swiss article

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became the basis for the estimation of 'safe PE (protein–energy) ratios' as endorsed in the 1985 Food and Agriculture (FAO)/World Health Organization (WHO)/United Nations University (UNU) report on energy and protein requirements[10]. As noted by Beaton in 1994, the conceptual issues with respect to PE ratios are directly applicable to the concept of an RND as applied to vitamins and minerals[11]. Underlying the Beaton–Swiss approach was the recognition that safe PE ratios are a function of the joint distribution of protein and energy requirements in a population. Similarly, an RND is dependent on the joint distribution of nutrient requirement and usual daily energy intake.

Ideally, an RND value would be based on information concerning the nutrient requirements and energy intakes of *individuals* from a large, representative sample of the population in question. From this information, the distribution of individual ratios of nutrient requirement to usual energy intake (defined as mean energy intake within individuals) could easily be obtained and the 97.5th percentile identified. Unfortunately, individual requirements for vitamins and minerals cannot be measured precisely, and average energy intakes are difficult and expensive to measure without considerable error. Therefore, alternative approaches must be used to estimate an RND.

In the absence of specific information on individual energy intake and nutrient requirement, an RND value can be estimated if the joint distribution of usual energy intake and nutrient requirement can be characterised for the *group*. In much the same way, the prevalence of inadequate nutrient intake can be estimated (using the 'probability approach') if the joint distribution of nutrient requirement and nutrient intake can be specified[12,13].

Estimation of a valid RND requires accurate information on the joint distribution of energy intake and nutrient requirement, which can be viewed as a function of (1) the distribution of nutrient requirement, (2) the distribution of usual energy intake and (3) the relationship of energy intake to nutrient requirement. Information on each of these parameters, although often fairly speculative, is available from a range of sources. The North American Dietary Reference Intake (DRI) and FAO/WHO reports provide information about the distributions of nutrient requirements[14–19]. The distribution of usual energy intakes, although often unavailable for a specific population, can be estimated by using data and formulae from a variety of sources[10,20]. Finally, the relationship of energy intake and nutrient requirement for any given age–sex category is likely to be weak: although positive correlations have been hypothesised between energy intake and requirement for some B vitamins, 'the DRI report on the recommended intakes of B vitamins . . . notes that no studies were found that examined the effect of energy intake on the requirements of thiamin, riboflavin or niacin'[13].

A hypothetical joint distribution of folate requirement and energy intake

For illustration purposes, Fig. 1 shows a hypothetical joint distribution of folate requirement and usual energy intake for 3000 non-pregnant, non-lactating women aged 19–30 years. The bivariate normal distribution was created by a computer simulation that used the following parameters:

- usual energy intake is normally distributed with a mean of 2200 kcal day^{-1} (9.21 MJ day^{-1}) and a coefficient of variation (CV) of 20% (values that were taken from the 1989 *Recommended Dietary Allowances*[21]);
- folate requirement is normally distributed with an Estimated Average Requirement (EAR) of 320 μg day^{-1} and a CV of 10% (values that were used in the recent DRI report on B vitamins to derive the folate RDA for non-pregnant, non-lactating women aged 19–30 years[16]); and
- folate requirement and energy intake are uncorrelated (independent).

All three assumptions are almost certainly flawed to some extent, but the resulting hypothetical distribution provides

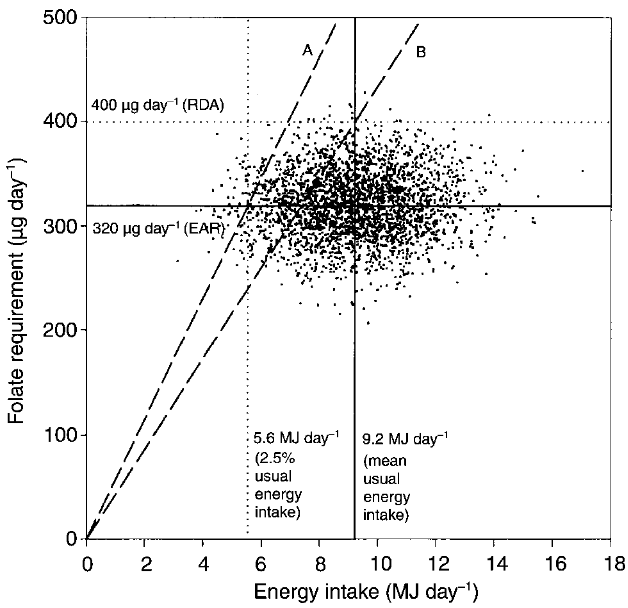

Fig. 1 A hypothetical joint distribution of usual energy intake and folate requirement for 3000 non-pregnant, non-lactating women aged 19–30 years. Line A shows the set of points at which the folate requirement/energy intake ratio is equal to 58.8 μg MJ^{-1}; this value is the slope of line A. To the left of line A is ~2.5% of the population – those with the highest folate requirement/energy intake ratios (or densities). Notice that line A nearly (but not exactly) passes through the point of intersection between the folate Estimated Average Requirement (EAR) and the 2.5th percentile of usual energy intake. Line B has a slope that is equal to the Recommended Dietary Allowance (RDA) (400 μg day^{-1}) divided by the mean energy intake (9.2 MJ day^{-1}), and passes through the point of intersection between the RDA for folate and mean usual energy intake. To the left of line B is the ~17% of the population with the highest folate requirement/energy intake ratios

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a useful focus for considering the issues related to the derivation of an RND value.

Each 'individual' in Fig. 1 has a unique ratio of folate requirement to usual energy intake ($\mu g\,MJ^{-1}$). Individuals with high folate requirements relative to energy intake are disproportionately located in the upper left quadrant of the distribution, while those with the lowest folate/energy ratios tend to be in the lower right quadrant. To establish an RND, one needs to find a means of identifying the top 2.5% of the folate/energy distribution.

Approaches to calculating an RND value

Several different methods may be used to estimate the RND, and selection of a particular approach will depend on the presumed joint distribution of energy intake and nutrient requirement, and practical issues such as computational resources. The different estimation methods are described below. A subsequent section describes the influence of violations of assumptions on the validity of the RND estimate.

Direct calculation

An RND estimate can be calculated directly if simplifying assumptions are be made concerning the joint distribution of usual energy intake and nutrient requirement. As Beaton[11] noted in 1994, the FAO/WHO/UNU equations for estimating 'safe PE (protein–energy) ratios' will yield very close approximations of the RND if usual energy intake and nutrient requirement can be assumed to be normally distributed (and estimates exist of the mean and standard deviation of nutrient requirement and usual energy intake) (see Appendix A). The Beaton approach does *not* assume the independence of energy intake and nutrient requirement because the modified FAO/WHO/UNU equations contain a term for the Pearson correlation between energy intake and nutrient requirement. However, the validity of the Beaton estimates will be influenced by 'irregularities' such as skewed distributions, heteroscedasticity and non-linear relationships.

For the folate scenario, the Beaton approach yields an RND value of 58.8 μg folate MJ^{-1}. Line A shows the set of points where the folate requirement/energy intake ratio is equal to 58.8 μg folate MJ^{-1} (Fig. 1). To the left of line A is the ~2.5% of the 'population' with the highest folate requirement/energy intake ratios.

The 'geometric approach' is a second technique for the direct calculation of an RND. This approach, like the Beaton approach, assumes that energy intake and nutrient requirement are normally distributed (see Appendix B). Additionally, the geometric approach assumes that energy intake and nutrient requirement are uncorrelated (i.e. Pearson's $r = 0.00$). Like the Beaton approach, the geometric approach yields an RND value of 58.8 $\mu g\,MJ^{-1}$ for the folate scenario. Indeed, when usual energy intake and nutrient requirement are uncorrelated ($r = 0.00$), the Beaton and geometric approaches yield identical values over a very broad range of plausible and implausible energy and nutrient values (not shown). Although computationally different, the two techniques appear to be mathematically equivalent for all positive energy intake and nutrient requirement values.

Compared with the Beaton approach, the only advantage of the geometric approach is computational. The geometric approach can be used to calculate standardised (unitless) nutrient densities that can easily be converted to the desired RND in usual units (e.g. $\mu g\,MJ^{-1}$) using a hand calculator. Table 1 provides standardised nutrient densities for a range of plausible %CVs of usual energy intake and nutrient requirement.

RDA approach

One tempting (but incorrect) method of calculating the RND value is to divide the RDA by the group's average, usual energy intake. Although this approach considers variability in nutrient requirement, the RDA approach does not adjust for variability in usual energy intake and is seriously flawed. Dividing the folate RDA (400 $\mu g\,day^{-1}$) by mean usual energy intake (9.21 $MJ\,day^{-1}$) yields a value of 43.4 $\mu g\,MJ^{-1}$. Line B in Fig. 1 shows the set of points where the folate requirement/energy intake ratio is equal to 43.4 $\mu g\,MJ^{-1}$. (Note: line B passes through the point at which the RDA and mean usual energy intake lines meet.) Above line B is the ~17% of the population whose folate requirements would not be met by the nutrient density value obtained by the RDA approach. The RDA-based estimate underestimates the 'true' RND value by 26.2% because the RDA approach ignores those individuals with lower than average energy intakes.

Monte Carlo simulation

Monte Carlo simulation can be used to obtain an approximation of the RND (much as the simulation used to create Fig. 1). The goal of Monte Carlo simulation is to obtain a robust estimate of the parameter of interest by creating a large number of 'samples', each of which is comprised of a large number of 'cases'. For our folate scenario, 3000 'samples' of 5000 'cases' each were generated for a total of 15 million cases (see Appendix C).

Table 1 Standardised slopes for different values of the coefficient of variation (%CV) of nutrient requirement and energy intake. Recommended Nutrient Density in usual units (e.g. $\mu g\,MJ^{-1}$) can be obtained by multiplying the standardised slope by the standard deviation of the nutrient requirement and dividing this by the standard deviation of usual energy intake (see Appendix B)

	Energy intake (%CV)					
Nutrient requirement (%CV)	15	16	17	18	19	20
10	2.214	2.422	2.641	2.873	3.120	3.383
15	1.540	1.680	1.827	1.984	2.150	2.326
20	1.212	1.319	1.432	1.551	1.677	1.811

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Nutrient requirement/energy intake ratios were then calculated for each 'case' by dividing the individual nutrient requirement by usual individual energy intake. The 97.5th percentile of the resulting nutrient density distribution was then identified for each 'sample', and the mean of these 3000 values was calculated. The resulting estimate was 58.7 μg MJ^{-1}, which is a very close to 58.8 μg MJ^{-1}, the directly calculated RND estimate for this scenario (see Direct calculation, above).

The Monte Carlo approach has the great advantage of being 'distribution-free'. If the desired distribution can be programmed, then valid RND estimates can be obtained regardless of deviations from bivariate normal, moderate correlations between energy intake and nutrient requirement, or heteroscedasticity. However, the simulation approach requires access to programming expertise. Additionally, the Monte Carlo approach may be intellectually unsettling to some because the precise value of the RND is never actually calculated. Nevertheless, when deviations from bivariate normal occur, Monte Carlo simulation will offer the most accurate solutions *if* the joint distribution of usual energy intake and nutrient requirement can be specified accurately.

Cut-point approach

In 1994, Beaton proposed the 'EAR cut-point method' for estimating the prevalence of inadequate nutrient intake in a population[11]. As discussed in *Dietary Reference Intakes: Applications in Dietary Assessment*[13], the EAR cut-point method 'is very straightforward, and surprisingly, can sometimes be as accurate as the probability approach' for estimating the prevalence of inadequate intakes. However, the EAR cut-point method performs best if: (1) energy intake and nutrient requirement are independent (uncorrelated), (2) the distribution of requirement is symmetric and (3) the variability in nutrient requirement is small relative to that nutrient intake[22].

A variant of the EAR cut-point method can be used to estimate the RND by dividing the EAR by the 2.5th percentile of energy intake ($Z = -1.96$). In our folate scenario, dividing the folate EAR (320 μg day^{-1}) by 5.60 MJ day^{-1} (the 2.5th percentile of energy intake) yields an RND value of 57.2 μg folate MJ^{-1}, which underestimates the Beaton RND value (58.8 μg MJ^{-1}) by -2.8%. Figure 1 illustrates this approach: line A very nearly (but not exactly) includes the point of intersection between the folate EAR and the 2.5th percentile of usual energy. Monte Carlo simulation (3000 'samples' of 5000 'cases' each) shows that the cut-point estimate would be expected to 'miss' ~0.5% of the population (27 of 5000 individuals) (see Monte Carlo simulation, above).

Figure 2 shows that the cut-point approach works because it 'substitutes' individuals in triangle B (individuals with nutrient densities below the 97.5th percentile, but who have low energy intake and low nutrient requirement) for an approximately equal number of individuals in triangle A (individuals with nutrient densities above the 97.5th percentile and who have low energy intake and high nutrient requirement). If the distribution of energy intakes is normal (or symmetric), then a somewhat larger number of individuals can be expected to be in triangle A than in triangle B because triangle A is closer to the centre of the distribution of usual energy intake. And, the substitution A for B should usually yield a slightly lower RND estimate than the value that would be obtained using the Beaton or Monte Carlo approaches.

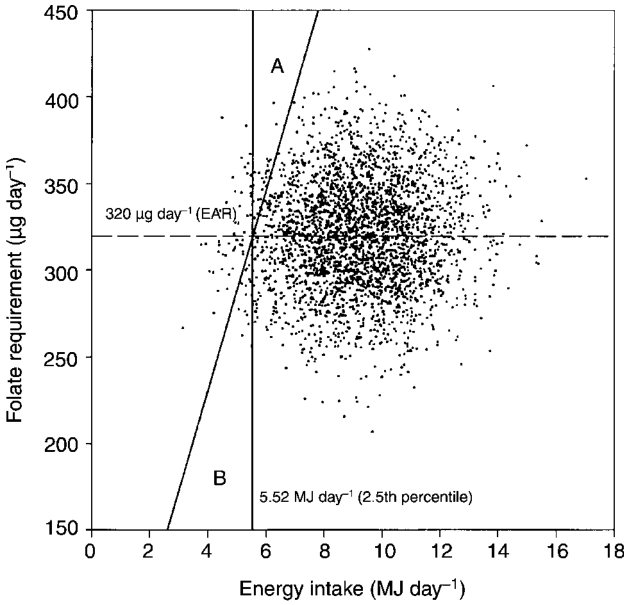

Fig. 2 The 'cut-point' method works by substituting individuals in triangle B (people who have nutrient densities below the 97.5th percentile, and who have low energy intakes and low nutrient requirements) for an approximately equal number of individuals in triangle A (people who have nutrient densities above the 97.5th percentile, and who have high nutrient requirements and low energy intakes). EAR – Estimated Average Requirement

Table 2 shows the effect of different %CVs of usual energy intake and nutrient requirement on the validity of the cut-point estimate. Percentages show the extent to which the cut-point method underestimates the Beaton value. Numbers in parentheses are the expected number of missed 'cases' in a sample of 5000 persons. The greatest underestimates of the RND occur when variability in energy intake is low and variability in nutrient requirement is large.

Factors that influence the validity of the RND estimate

The validity of an RND estimate will depend on the estimation approach and accurate specification of the joint distribution of energy intake and nutrient requirement. Misspecification of the joint distribution of energy intake and nutrient requirement may potentially occur with respect to (1) the distribution of nutrient requirement,

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Table 2 Percentages are the extent to which the cut-point estimate (using the 2.5th percentile of usual energy intake, or $Z = -1.96$) is lower than the Recommended Nutrient Density value obtained using the Beaton approach. The numbers of persons 'missed' by the cut-point approach (in a population of 5000) are presented in parentheses. The latter values were obtained by Monte Carlo simulation (see Appendix C). Note that cut-point estimates are constant across the range of coefficient of variation (%CV) of nutrient requirement because these are obtained by dividing the Estimated Average Requirement by the 2.5th percentile of usual energy intake

	%CV of energy intake		
	15.0	20.0	25.0
Cut-point (μg MJ^{-1})	49.2	57.2	68.1
%CV of nutrient requirement			
5.0	−1.1% (−16)	−0.7% (−7)	−0.5% (−2)
10.0	−4.0% (−66)	−2.8% (−27)	−1.9% (−12)
15.0	−8.0% (−148)	−5.7% (−61)	−4.1% (−27)

(2) the distribution of energy intake and (3) the relationship of energy intake to nutrient requirement.

Correlation between energy intake and nutrient requirement

The effect of correlation on the RND estimate can be investigated via the Beaton (FAO/WHO/UNU) equations (assuming energy intake and nutrient requirement have normal distributions). In the folate scenario, a perfect positive correlation ($r = +1.0$) between energy intake and folate requirement would reduce the RND by 21.8% (from 58.8 μg MJ^{-1} to 46.0 μg MJ^{-1}). A more physiologically reasonable correlation of $r = +0.30$ would result in an RND of 55.5 μg MJ^{-1} (5.6% below the geometric value and 3.0% lower than the cut-point estimate of 57.2 μg MJ^{-1}). In summary, when an unidentified positive correlation between energy intake and nutrient requirement exists, the cut-point, geometric and Beaton (assuming $r = 0.00$) approaches will yield conservative estimates of the RND, overestimating the nutrient density value needed to meet the needs of 97.5% of a population.

The influence of skewed distributions

Skewed distributions of either usual energy intake or nutrient requirement will also influence the RND. Table 3 shows RND values for normal and skewed distributions of folate requirement and energy intake. The median folate requirement is 320 μg day^{-1} with a CV of 10%; and the median usual energy intake is 9.21 MJ day^{-1} with a CV of 20%. The RND values were calculated using Monte Carlo simulations with 3000 replications of 5000-'person' populations. The right-skewed distributions (with a disproportionate number of high values) are log normal, while the left-skewed distributions are the 'mirror image' of the corresponding right-skewed distributions (the median was subtracted from each case and the resulting 'residual' value was then subtracted from the median).

Table 3 shows that the RND is more greatly influenced by skew in usual energy intake than skew in nutrient requirement (when variability in energy intake is great relative to nutrient requirement – as is likely to be the case for any given age–sex category). (When variability in the two parameters is approximately equal, the disparate influence of skew in energy intake remains, but is much reduced (not shown).)

Right skew in nutrient requirement (for example, as seen with iron and menstruating women) leads to a somewhat higher RND than if the requirement were normally distributed. In the three right-skewed (log normal) folate scenarios, the RND values are ~1.1% higher than would be the case if folate were normally distributed (Table 3). However, the number of missed 'persons' (if the 'normal' folate scenario was used to derive the RND) would be relatively small (10–17 per 5000 or <0.4% of the population). In contrast, left skew in usual energy intake, if unidentified, would lead to much greater underestimates of the 'true' RND value. In the three left-skewed energy scenarios, the RND estimates are 8–9% higher than those obtained assuming a normal distribution, and ~1.5% of the population (~76 people in a population of 5000) would be missed if the flawed, 'normal' RND estimate were employed. In summary, skew in usual energy intake will have a greater effect on the validity of the RND estimate than skew in nutrient requirement *if* the skews are of equivalent magnitude *and* the variability in energy intake is great relative to that in nutrient requirement.

Because the cut-point method is based on the 2.5th percentile of energy intake, this approach might be expected to be resistant to the effects of skewed energy

Table 3 Influence of skewed distributions on Recommended Nutrient Density (RND) estimates (μg of folate/MJ). For all scenarios, the median folate requirement is 320 μg day^{-1} with a coefficient of variation (CV) of 10%, and the median usual energy intake is 9.21 MJ day^{-1} with a CV of 20%. Right-skewed variables are log normal, while left-skewed variables are the 'mirror' image of the corresponding log normal variable. Values in parentheses are the percentage that the 'true' RND value is higher or lower than the bivariate normal RND estimate. The cut-point estimates are based on the assumption that the 2.5th percentile of usual energy intake is measured accurately

	Folate requirement			
Usual energy intake	Left-skewed	Normal	Right-skewed	Cut-point estimate
Left-skewed	64.4 (+9.5%)	65.1 (+10.7%)	65.8 (+11.9%)	64.0
Normal	58.1 (−1.2%)	58.8 (0.0%)	59.4 (+1.0%)	57.2
Right-skewed	52.9 (−10.0%)	53.5 (−9.0%)	54.1 (−8.0%)	51.4

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intake. Indeed, the cut-point approach (Table 3) provides substantially better RND estimates than those obtained using the geometric and Beaton approaches. However, the 'true' RND values, as obtained using Monte Carlo modelling, consistently exceed the cut-point estimates. In the left-skewed energy intake scenarios, the cut-point approach underestimated the 'true' RND by -0.6 to -2.7%. In the right-skewed scenarios, the extent of the underestimate was greater (-2.8 to -5.0%).

Discussion

The intellectual foundations for quantitative application of the nutrient density concept can be traced to the early work of Beaton and Swiss[8], who viewed a 'safe' protein–energy density as a function of the joint distribution of energy and protein requirement. Similarly, a Recommended Nutrient Density (RND), a nutrient density that would meet the nutrient requirements of most individuals in a population or sub-population, is dependent on the joint distribution of usual energy intake and nutrient requirement[11].

Because data on *individual* nutrient requirements are unavailable, the identification of an RND is dependent on specifying the joint distribution of energy intake and nutrient requirement using *group* information on (1) the distribution of usual energy intake, (2) the distribution of nutrient requirement and (3) the relationship between energy intake and nutrient requirement. In many cases, the latter two parameters will be poorly characterised. For example, theory suggests a positive correlation between thiamin and energy intake, but this is presently unsupported by research[16]. And variability in nutrient requirement is often known imprecisely, even when EAR values can be estimated. Although a lack of basic information will necessarily lead to error in the estimated RND value, flawed estimates obtained using imperfect data and conceptually correct methods will be superior to those obtained by use of the same imperfect information and conceptually flawed models.

All approaches to estimating an RND are based on explicit (or implicit) assumptions concerning the joint distribution of energy intake and nutrient requirement. Both the Beaton and the geometric approaches assume normal distributions of nutrient requirement and energy intake, despite the potential that requirements for many nutrients may be right-skewed (as is known to be the case with iron and menstruating women)[14]. Fortunately, simulations based on physiologically plausible models of usual energy intake and folate requirement show that skewed nutrient requirements will have limited effects on the validity of the RND estimate. In contrast, skewed usual energy intake will have much stronger effects on the RND.

Several approaches to RND estimation assume independence between energy intake and nutrient requirement. Fortunately, when an unidentified positive correlation between energy intake and nutrient requirement exists, the cut-point and geometric and Beaton (assuming $r = 0.00$) approaches will yield conservative estimates of the RND, overestimating the nutrient density value needed to meet the needs of 97.5% of a population.

The cut-point approach, in which the EAR is divided by the 2.5th percentile of usual energy intake, is attractive because of its simplicity. The method will be most accurate when: (1) variability in usual energy intake is great in comparison to nutrient requirement, (2) usual energy intake is left-skewed and (3) nutrient requirement and usual energy intake are uncorrelated, or nearly so. Even under the most physiologically plausible scenarios, the cut-point approach tends to underestimate the 'true' RND. A lower cut-point (such as $Z = -2.0$) might be used to compensate for this deficiency, but this adjustment would often fail completely to eliminate bias due to the cut-point approach. Additionally, the 2.5th percentile of energy intake will often be estimated from group information on usual energy intake (i.e. central tendency and variability), rather than from individual-level data. In the former situation, the Monte Carlo approach should yield more accurate RND estimates than the cut-point approach.

Despite its limitations, the cut-point approach highlights the extent to which the validity of an RND estimate is highly dependent on (1) an accurate estimate of the average nutrient requirement (the EAR) and (2) the lowest intakes of energy. As a result, low energy intakes must be characterised accurately, which will depend on accurate measurement of both average energy intake and variability in energy intake. Therefore, if energy values are based on individual-level dietary intake data, then these will require adjustment using the National Research Council's method or some similar approach to accurately characterise the distribution of energy intakes in the population[13,21,23]. With respect to average nutrient requirement, the bases for the EAR values (including the 'criteria of adequacy') and their appropriateness for the desired application should be considered. For example, the current EAR for vitamin C in males aged 19–50 years (75 mg day^{-1}) is based on 'intakes sufficient to maintain near-maximal neutrophil concentrations with minimal urinary loss'[15]. A lower or higher EAR based on a different criterion of adequacy might be more appropriate for some applications.

Nutritionists should avoid use of an Adequate Intake (AI) value as a substitute for the EAR. As defined by the DRI committees, the AI is 'an informed judgement about what seems to be an adequate intake'[21], but does not indicate levels of required nutrient intake. Because 'the AI would not be consistently related to the EAR and its RDA even if they could be established, AI values cannot be used to estimate the prevalence of inadequate nutrient intakes in a group'[21] or to estimate an RND value.

This paper, although written because the nutrient density concept can be useful for planning purposes, has not explicitly addressed the application of the RND for

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planning interventions. When the RND is to be used as a tool for planning, the analytical problem becomes how to alter the distribution of individual usual nutrient intakes so that all (or nearly all) individuals in the population consume a nutrient density that exceeds the RND. When a single food provides all of the energy and nutrient that is consumed (as in the case of an emergency food ration), then application of the RND is straightforward because nutrient intake is a direct function of energy intake. Therefore, the task is to alter the nutrient content of the food so that its nutrient density equals the RND (providing the intervention does not change energy intake)[6,24]. In the situation of multiple foods, individuals select their diets from a 'menu' of foods with differing nutrient densities, and the problem becomes much more complex. Recently, the IOM has endorsed two 'theoretical approaches' for using nutrient density to plan group diets under such conditions[24]. Both approaches build on Beaton's EAR cut-point approach for assessing the prevalence of inadequate nutrient intakes in a population. However, the IOM report does not explicitly address the issue of an RND as outlined in this paper. Although assessment of the IOM methods is beyond the scope of this paper, both approaches must yield individual nutrient densities that exceed an RND (if correctly estimated) to be judged accurate.

In summary, this paper has described several methods for estimating a Recommended Nutrient Density that should meet the nutrient requirements of 97.5% of a population or sub-population, providing individuals consume their average energy intake. Nutrient density values based on the RDA are conceptually flawed, will greatly underestimate the 'true' RND value, and so should be avoided. If the EAR can be characterised accurately, then a valid RND estimate will be highly dependent on accurate characterisation of the lowest energy intakes in the population.

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Appendix A – The Beaton approach

The Beaton approach assumes energy intakes and nutrient requirements are normally distributed[6]. The equations below are adapted from the 1985 FAO/WHO/UNU report on energy and protein requirements[8].

$$R_\alpha = \frac{E^2}{E^2 - Z_\alpha^2 S_e^2}\left(\frac{N}{E} - \frac{Z_\alpha^2 r S_n S_e}{E^2} + \frac{Z_\alpha^2}{E} Q\right) \tag{A1}$$

and

$$Q = \sqrt{S_n^2 - \frac{2rNS_e S_n}{E} + \frac{N^2 S_e^2}{E^2} - \frac{Z_\alpha^2 S_n^2 S_e^2}{E^2}(1 - r^2)}, \tag{A2}$$

where

R_α is the nutrient density value that would be expected to be exceeded by α proportion of individuals (e.g. $\alpha = 0.025$ or 2.5%);

E is the mean usual energy intake for the sub-population;

N is the Estimated Average Requirement (EAR) for the sub-population;

S_e is the standard deviation of usual energy intake;

S_n is the standard deviation of the nutrient requirement;

r is the correlation between usual energy intake and nutrient requirement among individuals of a given age–sex category; and

Z_α is the Z-score above which lies α% of the nutrient density distribution (e.g. if the RND is to be exceeded by 2.5% of the population, $Z_{0.025} = 1.96$).

Appendix B – The geometric approach

Calculating the RND

The geometric approach assumes that usual energy intakes and nutrient requirements have normal distributions and are uncorrelated. The RND can be calculated as:

$$\text{RND} = \left(\frac{y_2 - y_0}{x_2 - x_0}\right)\frac{S_n}{S_e}, \tag{B1}$$

where S_e is the standard deviation of usual energy intake and S_n is the standard deviation of nutrient requirement. x_0 and y_0 are derived from:

$$x_0 = -\frac{E}{S_e}, \quad y_0 = -\frac{N}{S_n}, \tag{B2}$$

where E is mean usual energy intake and N is the EAR. x_2 and y_2 are given by:

$$x_2 = \frac{1.96^2 x_0 + 1.96 y_0\sqrt{x_0^2 + y_0^2 - 1.96^2}}{x_0^2 + y_0^2} \tag{B3}$$

and

$$y_2 = \frac{1.96^2 y_0 - 1.96 x_0\sqrt{x_0^2 + y_0^2 - 1.96^2}}{x_0^2 + y_0^2}. \tag{B4}$$

Deriving the equations

Equations (B3) and (B4) can be derived by first transforming usual energy intake and nutrient requirement to Z-scores. The resulting standardised distributions have a mean of 0 and a standard deviation of 1. If energy and nutrition requirements are uncorrelated, then the joint standardised distribution will be bivariate normal. Figure B1 provides a schematic representation of this joint standardised distribution. The two concentric circles represent different standardised distances from the centre (point Q_1) of the distribution of energy intake and nutrient

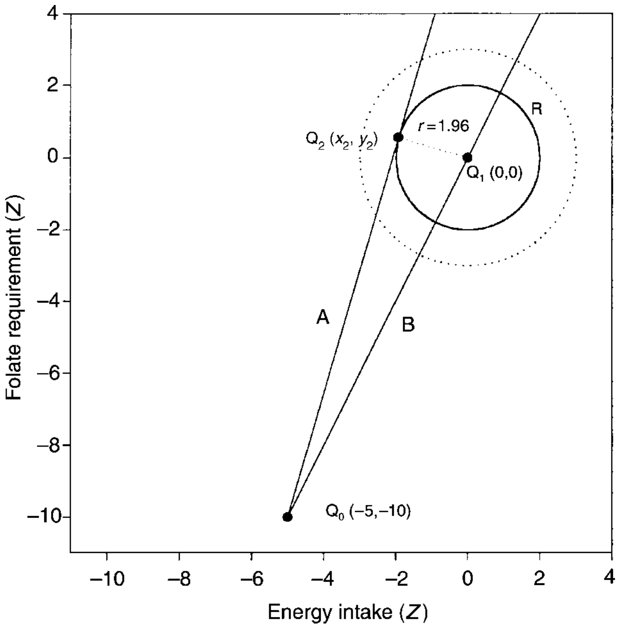

Fig. B1 Schematic drawing of the bivariate distribution of nutrient requirement and energy intake (expressed as Z-scores). Slope of line B is the standardised nutrient density needed to meet ~97.5% of the nutrient requirements of the population

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requirement. The solid circle (circle R) has a radius of 1.96 Z-scores (a Z-score of 1.96 is approximately equal to the 97.5th percentile of a normal distribution). Q_0 represents the point at which no energy is consumed and nutrient requirement is zero ($x_0 = -5$, $y_0 = -10$). Line A is tangent to circle R at the point Q_2. The slope of line A is the standardised nutrient density that meets the nutrient requirements of 97.5% of the population. This value can be calculated given the locations of points $Q_0(x_0, y_0)$ and $Q_2(x_2, y_2)$ as follows:

$$\text{Slope} = \left(\frac{y_2 - y_0}{x_2 - x_0}\right). \tag{B5}$$

The coordinates of point Q_0 are:

$$x_0 = \frac{(0 - \overline{X}_e)}{S_e} = -\frac{\overline{X}_e}{S_e}, \quad y_0 = \frac{(0 - \overline{X}_n)}{S_n} = -\frac{\overline{X}_n}{S_n}. \tag{B6}$$

The location of $Q_2(x_2, y_2)$ can be calculated using the equations for identifying points of tangency by a line drawn from a point outside a circle[1]:

$$x_2 = \frac{r^2 x_0 + r y_0 \sqrt{d^2 - r^2}}{d^2}, \qquad y_2 = \frac{r^2 y_0 - r x_0 \sqrt{d^2 - r^2}}{d^2}, \tag{B7}$$

where $r = 1.96$ (the radius of the circle) and d is the distance from point Q_0 to Q_1. Using Pythgoras Theorem:

$$d^2 = (0 - x_0)^2 + (0 - y_0)^2 = x_0^2 + y_0^2. \tag{B8}$$

Substituting this equation for d^2 in equations (B7) yields the final forms of equations (B3) and (B4).

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Appendix C – Monte Carlo simulation

The following SAS program generates 3000 bivariate normal distributions of 5000 ‘cases’ with a mean folate requirement of 320 µg day^{-1} and a mean energy intake of 9.21 MJ day^{-1}.

```
data generate;
    seed = -1;
    e_mean = 9.21;     /* mean energy intake */
    e_cv = .20;        /* CV for energy intake */
    e_std = e_mean*e_cv;
    n_mean = 320;      /* estimated average nutrient requirement */
    n_cv = .10;          /* %CV for nutrient requirement */
    n_std = n_mean*n_cv;
    do x = 1 to 5000;
        do y = 1 to 3000;
          nutrient = n_mean + n_std*rannor(seed);
          energy = e_mean + e_std*rannor(seed);
          density = (nutrient/energy);
          output;
        end;
    end;
proc sort data = generate;
      by y density;
data picks;
      set generate;
          by y;
      if first.y then n = 0;
          n + 1;
          pct = (n/5000)*100;
          if pct = 97.5;
proc means;
      var density;     /* RND estimate */
run;
```

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