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TWELFTH BOYD ORR MEMORIAL LECTURE

Nutrient requirements and population data

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During his career in nutrition, Boyd Orr pursued and publicized many areas of endeavour. One of particular relevance to the present paper was his interest, as a member of The Food and Agricultural Organization of the United Nations (FAO), in the assessment of population nutrition needs and supplies. The 'correct' approach to such national assessments remains a matter of debate, sometimes of heated controversy (FAO, 1985). Attention has centred primarily on estimates of total food supply expressed as mean individual energy consumption. However, a less obvious development during the past decade has been in the approach to estimations of the distribution of observed nutrient uptake, and it is this development that is the subject of the present paper. The question of estimating intake distributions, a necessary step in the work initiated by Boyd Orr, will not be considered; instead, my remarks will refer to observed intake distributions. Thus, the assessment of energy intakes, which should be addressed quite differently (FAO/World Health Organization (WHO)/United Nations University (UNU), 1985) will not be considered; the focus will be on nutrient intakes and nutrient requirements.

The present paper describes the 'coming together' of two separate, apparently independent, lines of thought, and the consequent emergence of some innovative ideas about the future. It will draw heavily on a recent US National Academy of Sciences report (National Research Council (NRC), 1986), which has collected and identified these developments. However, credit for these conceptual developments belongs to a wide range of investigators, not all of whom are cited in the present paper. Although the underlying ideas are not new, they have only recently been drawn together. The future possibilities are tantalizing. This, then, is the story that will be presented.

The two primary areas of concern in estimating population intake may be seen as (1) the estimation of food intake and the computation of food intake, and (2) the definition and application of criteria of adequacy.

There is a voluminous and largely negative literature on each of these. In the present paper, however, the emphasis will be on the positive rather than the negative, although the starting point will be the problems and issues identified in earlier work. In keeping with the suggestion that two independent lines of thought have recently come together, the paper will consider the themes separately, and then their combination and the implications for the future.

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Estimation and description of nutrient intake distributions

In the estimation of food intake distributions, we have not suddenly found new or innovative methods of collecting information. Rather, what has emerged in the last decade is a new awareness of the nature of the information we are collecting and its implications for analysis and interpretation. In North America, beginning in the late 1970s, there has been a major interest in the within-person variability of food intake (Garn *et al.* 1978; Beaton *et al.* 1979; Houser & Bebb, 1981; McGee *et al.* 1982; Rush & Kristal, 1982; Hunt *et al.* 1983; Todd *et al.* 1983; Sempos *et al.* 1985) and the statistical error term in the estimation of 'usual intake'. In epidemiological studies, in individual assessments, and indeed in population assessments, there has been progressive realization that most of the diet–biological response relations in which we are interested really involve 'chronic' or 'usual' intake and a health-related condition. For example, in the diet–lipid–atherosclerosis hypothesis, it is the individual's 'usual' diet, his intake viewed across a period of weeks or months, that is expected to influence serum lipid levels and atherogenesis. When intake is estimated over a single 24-h period, or even over a period of a few days, a very poor estimate of the individual's usual intake is obtained. Intake is likely to vary widely from day-to-day; the single day does not provide a reliable description of the usual intake (Block, 1982). This error in the estimation of the true variable carries important implications for analyses (Liu *et al.* 1978; Beaton *et al.* 1979; Jacobs *et al.* 1979). Specifically, a large within-person variation in comparison with the between-person variation will: (1) mask a correlation between diet and an outcome variable, (2) bias a regression slope toward zero if diet is the independent variable.

The effect that worried statisticians and epidemiologists is illustrated in some simulation studies portrayed in Fig. 1. Here Beaton & Chery (1986) had simulated a situation in which there was a relation between sodium intake and blood pressure. They

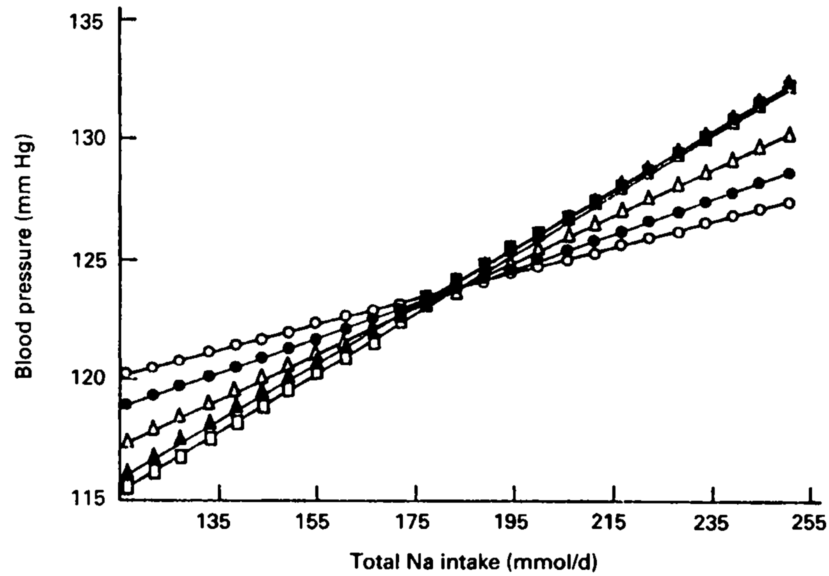

Fig. 1. Impact of food intake methodology (no. of days of observation) on regression slopes. (○), 1 d, B=0·048; (●), 3 d, B=0·072; (△), 7 d, B=0·096; (▲), 14 d, B=0·119; (□), 28 d, B=0·125. A simulation model of the relation between sodium intake and blood pressure was generated. The impact of changing food intake methodology was then simulated by adding random variance to the intake estimate in keeping with the magnitude of the expected day-to-day variability of intake. Taken from Beaton & Chery (1986).

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Table 1. *Reported ratios of intra-individual:inter-individual variance in dietary values**

Subjects . . .	Young adults	Older adults	Women 1 d recall		Men	Pregnant women
Dietary method . . .	24 h recall	3 d record	Year 1	Year 2	7 day record	24 h recall
Source† . . .	(a)	(b)	(c)	(c)	(d)	(e)
Males						
Energy	1·1	1·0			0·8	
Protein	1·5	1·2			1·4	
Carbohydrate	1·6	2·1			0·6	
Fat	1·2	1·2			1·3	
SFA	1·1	2·2			1·4	
PUFA	2·8	3·5			1·9	
Cholesterol	3·4	5·6			1·6	
Vitamin A	‡	1·6				
Vitamin C	3·5	2·3				
Thiamin	2·5	0·9				
Niacin equivalent	1·6	2·2				
Calcium	2·2	1·1				
Iron	1·7	1·8				
Females						
Energy	1·4	0·8	1·6	1·6		1·1
Protein	1·5	1·3	2·1	2·1		1·4
Carbohydrate	1·4	1·2				1·1
Fat	1·6	0·9				1·2
SFA	1·4	1·7				
PUFA	4·0	2·2				
Cholesterol	4·3	4·2				
Vitamin A	24·3	2·5	7·7	10·9		
Vitamin C	2·0	2·8	2·3	2·5		
Thiamin	4·4	1·6	3·3	3·9		
Niacin equivalent	4·0	2·5				
Ca	0·9	1·7	1·1	1·2		1·1
Fe	2·5	1·5	2·7	2·5		

SFA, saturated fatty acids; PUFA, polyunsaturated fatty acids.

*Variance estimates derived from repeated estimates of 1 d intakes using the dietary method indicated. The ratio shows the variances of 1 d intakes.

†Taken from (US) National Research Council (1986). References to original work: a, Beaton *et al.* (1979, 1983); b, Hunt *et al.* (1983); c, Sempos *et al.* (1985); d, McGee *et al.* (1982); e, Rush & Kristal (1982).

‡None of the variance could be assigned to subjects (inter-individual component).

then asked 'what is the likelihood of seeing this relation as the dietary methodology is changed?'. Fig. 1 portrays the effect, on the regression slope, of changing the number of days of intake values collected. Clearly, with values for only a few days the slope is seriously underestimated. One might well conclude that there was no relation, even though in the data set there was! This illustrates the basis of the concern that had developed about the role of dietary methodology in the false negative conclusions about diet and health. It led to a realization that many of the arguments about the relation between diet and disease have been based on inadequate dietary methodology; not

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inadequate in its technical sense of wrongly estimating intake but inadequate in the sense of estimating the wrong intake!

Interest in dietary methodology, and associated error terms and analytical effects, was rekindled among statisticians, epidemiologists and biologists. Estimates of the magnitude (and effect) of these error terms began to appear. Some are presented in Table 1. From a statistical standpoint, the larger the variance ratio, the greater is the attenuation of regressions and correlations. Clearly this varies with the nutrient and with the study (population studied and specific methodology used). The error term can be reduced by increasing the number of days of values collected and pooled (Beaton, 1982).

What does this have to do with population assessments? Surely if we have enough people we can estimate the population mean without statistical bias (Marr, 1971; Gersovitz *et al.* 1978)? Yes we can. However, except for energy, it is not the population mean that we usually want to examine (FAO/WHO/UNU, 1985). Rather, nutritional interest lies in the distribution of intakes. The issues mentioned previously affect, very directly, the apparent distribution of intakes.

Some years ago, Hegsted (1972) pointed this out by comparing the apparent distributions of iron intake obtained when values for different numbers of days were collected from the same subjects. The type of effect he reported is shown in Fig. 2. The population mean does not change as the number of days of values changes (provided there is a large sample). The apparent distribution of intake does change. This is one manifestation of the effect generally known as 'regression to the mean'. If one were to apply cut-off points to these distributions, the apparent prevalence of inadequate, or of excessive, intakes changes as the dietary methodology changes. There would be a serious bias in the estimation of the magnitude of the problem in the population! It can be demonstrated that the magnitude of the distributional effect, and hence of the bias in the prevalence estimate, is a function of the intra-individual, or day-to-day, variation in intake. More specifically, it is a function of the variance ratios portrayed in Table 1 and of the number of days of values collected.

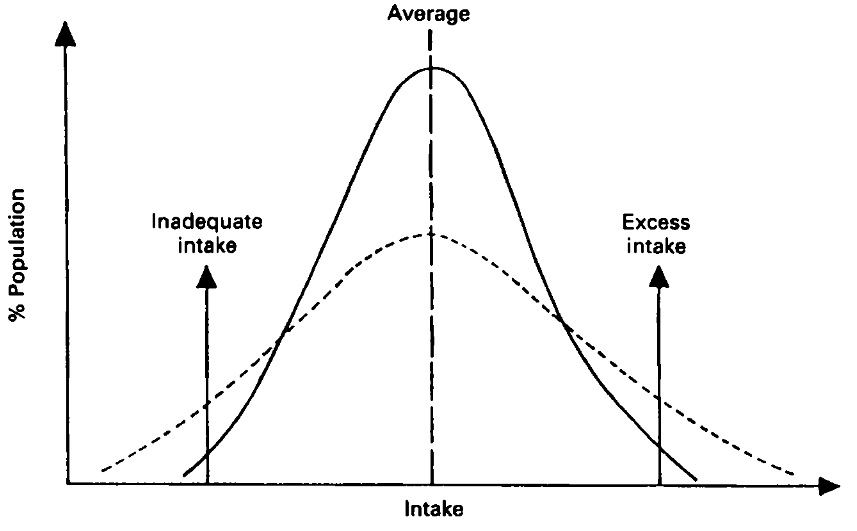

Fig. 2. Impact of day-to-day variability of intake on the observed distribution of nutrient intakes. This contrasts the distributions that might be observed with 1 d intakes (- - - - - -) and with 'usual' intakes (long observation period) (———) for the same subjects. Note that the group mean intake does not change. Note also the differences in apparent prevalence of low and high intakes that would be seen. Taken from Beaton (1982).

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Progressively it was recognized that the problem of intra-individual variation that has been worrying statisticians and epidemiologists also affected approaches to nutritional or toxicological assessment of observed dietary intakes.

What innovations have arisen from this recognition? Epidemiologists have addressed their version of the problem (attenuation of correlations and regressions) by searching out methods that would better estimate usual intake even though they sacrificed precision of the estimation. The current popularity of food-frequency methods in epidemiological studies is the direct result. Nutritionists were loathe to accept this approach since they were concerned about the imprecision of these 'qualitative' methods. The National Academy of Sciences Committee (NRC, 1986) pointed out a very simple fact. If indeed one can examine the partitioning of variance in dietary values to produce the estimates of intra- and inter-individual variation presented in Table 1, then surely one can use these estimates to adjust the observed distribution, i.e. to remove the effect of the day-to-day variation in intakes.

This approach is portrayed with actual values for dietary Fe intakes of US women, age 23–34 years, in Fig. 3. The values were collected in the US Department of Agriculture National Food Consumption Survey (NFCS) of 1977–78. Only dietary Fe, not Fe supplements, was included. The primary data base included information over 3 d for about 2400 women. Fig. 3 portrays the distribution of 1 d intakes, derived from the original survey. Also shown is an adjusted distribution of 'usual intakes', a distribution from which the effect of within-person (day-to-day) variability of reported intake has been removed.

What is needed to do this? The primary requirement is a sample of replicated estimates of intake. With these replicates, the partitioning of variance can be estimated by conventional statistical techniques. With a knowledge of the variance ratios, the observed distribution can be adjusted, point by point, to portray the estimated distribution of 'usual' intakes (NRC, 1986). The techniques are quite straightforward and well-known to statisticians. However, they have seldom been applied by nutritionists.

The real innovation in this regard, then, is not in how values are to be collected, but rather in how they should be analysed and interpreted. A serious problem of the past can

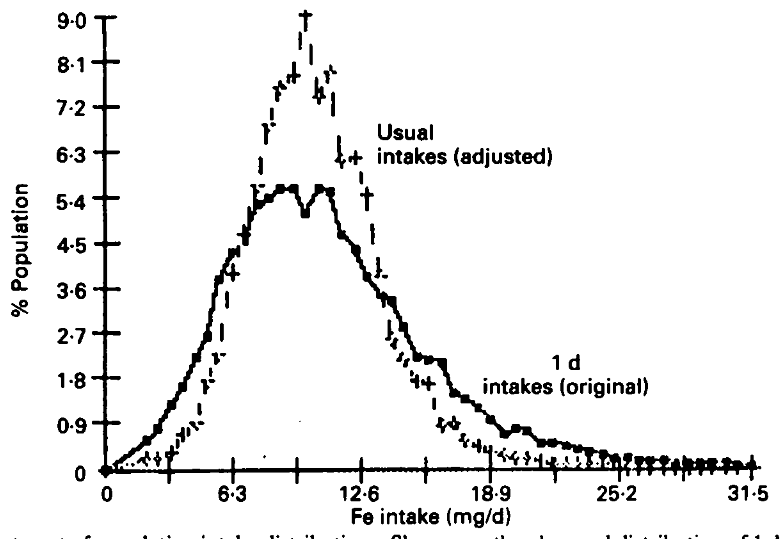

Fig. 3. Adjustment of population intake distributions. Shown are the observed distribution of 1 d iron intakes in US women and the estimated distribution of usual intakes derived in accord with procedures recommended by the National Academy of Sciences Committee (National Research Council, 1986).

be circumvented in the nutritional assessment of population intake distributions with only minimal implications for dietary methodology design: there must be a statistically adequate sample of replicated intakes (NRC, 1986).

This is one of the innovations in thought that has developed very strongly among epidemiologists and statisticians—and to a lesser extent among biologists—although it had not been applied to the problems of population nutrition assessments.

Dealing with variability of nutrient requirements

The second development that had been proceeding for a number of years was the understanding of variability of human needs and its implications. Differences of requirements between different classes of people (infants, children, adults, etc.) have always been recognized. The new interest was the variability that is known to exist between individuals who seem to be similar in outward characteristics: persons of the same age, sex, body size and activity, and consuming similar types of diets. In all biological systems, including the intact human, there appears to be individual variability. While this was intuitively recognized as applying also to nutrient requirements, there was uncertainty about what to do about it, and inconsistency in what was actually done.

Traditionally the nutrition community has addressed this variability by setting 'requirements' high enough to cover the needs of almost all individuals (FAO/WHO, 1967, 1970, 1971, 1973; NRC, 1980; Health and Welfare Canada, 1983; IUNS, 1982; FAO/WHO/UNU, 1985). When it is assumed that requirements are normally distributed, the recommended intake for nutrients has been set at the mean requirement +2 SD, theoretically enough to cover all but about 2·5% of the population. Fe illustrates the equivalent approach for a non-normal distribution. The combined distribution of menstrual Fe losses observed in Scandinavia by Hallberg *et al.* (1966) and in Scotland by Cole *et al.* (1971) is highly skewed (Beaton, 1974). Menstrual loss is thought to be the major factor influencing the distribution of Fe requirements in women. The convention that developed was to accept the 95th centile of losses as the basis of setting a recommended intake (FAO/WHO, 1970; Health and Welfare Canada, 1983).

It was a British committee (Department of Health and Social Security, 1969) that clearly identified one of the realities that many had overlooked: 'The recommended intakes of nutrients are defined as the amounts sufficient, or more than sufficient, for the nutrient needs of practically all healthy persons in a population. . . . The recommended intake of energy is equated with estimated average energy requirement and therefore does not refer to individuals, only to groups. . . . The recommended [nutrient] intakes, which are judged to be adequate for practically all individual members of a population, must of necessity be in excess of the requirements of most of them. . . .' The salient observation is that while the 'recommended intake' may be seen as conveying 'safety' to the random individual, it actually exceeds the real requirement of almost all individuals! If the recommended intake is then applied in assessing population intakes, and the question asked is 'how many people have intakes below the recommended intake?', the answer will certainly overestimate the true prevalence of 'inadequate' intakes. That is what has often been done. A result, of course, is that dietary assessments and biochemical or clinical assessments have traditionally given very disparate results, and the dietary assessments have fallen into disrepute!

This was the fundamental problem a decade ago. Much effort had been devoted to the development of estimates of a 'recommended intake'. It was becoming absolutely clear that we were misinterpreting it when we approached population assessment. What has changed? We have not addressed the problem by suddenly developing new requirement

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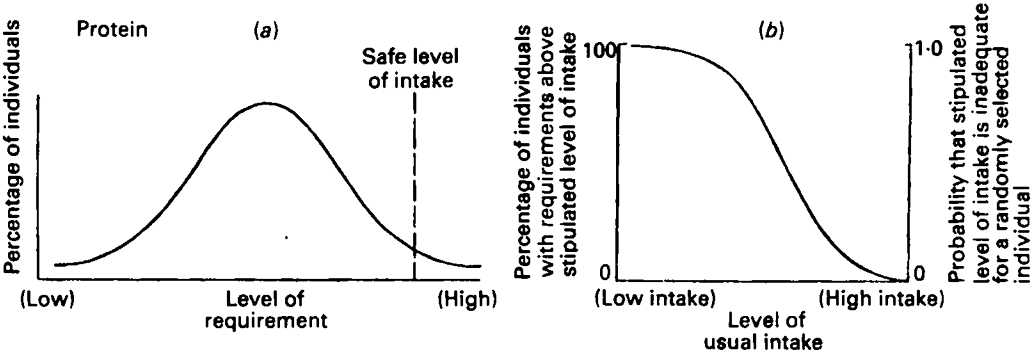

Fig. 4. The probability of inadequate intake. (*a*) The distribution of requirements of a nutrient and (*b*) this distribution plotted as a reverse cumulative distribution which describes the percentage of individuals with requirements above the selected level of intake or the probability that any particular intake level is inadequate for a randomly selected individual. Taken from Food and Agriculture Organization/World Health Organization/United Nations University (1985).

estimates but rather by applying new conceptual approaches to the interpretation of requirement distributions.

In the FAO/WHO reports beginning about 1970 (FAO/WHO, 1970, 1971, 1973; FAO/WHO/UNU, 1985), one can follow the progressive emergence of this recognition: that requirements do vary and that any approach to assessment must take this into account. Lorstad, working at FAO, published a paper providing a statistical approach to the application of requirement estimates (Lorstad, 1971). Beaton illustrated the problem and proposed a 'probability approach' to interpretation (Beaton, 1971). The most explicit statement of the principles is to be found in the recently released FAO/WHO/UNU report (FAO/WHO/UNU, 1985) in which the 'probability approach' to assessment is presented in precise terms (see Fig. 4). The NRC (1986) applied it to population data.

If one converts the usually displayed distribution of requirements to a cumulative distribution, it is readily apparent (Fig. 4) that what is portrayed is the 'risk' or 'probability' that any particular level of usual intake is inadequate for the randomly selected individual. The cumulative distribution represents the proportion of individuals with requirements above any selected level of intake. In this portrayal, the 'recommended intake' is a 'low risk' intake, a 'safe level of intake' (FAO/WHO, 1973); very few individuals would be expected to have a higher requirement. As an individual's 'usual' intake falls further and further below the recommended intake, the probability of inadequacy increases. In the case of a skewed requirement distribution like that for Fe in menstruating women, the effect is very dramatic (Fig. 5). A woman can have an intake substantially below the 'recommended intake' before the probability rises appreciably. The US recommended dietary allowance (RDA) for Fe is currently set at 18 mg/d (NRC, 1980). On the curve shown in Fig. 5, this would be adequate for all but about 2·5% of women. The Canadian recommended nutrient intake for Fe is currently set at 14 mg/d (Health and Welfare Canada, 1983). This would be adequate for all but 5% of women. What appears to be a substantial drop in intake level conveys only a small increase in risk, because of the skewing. Nevertheless, with either of the risk curves (Figs. 4 and 5) a 'probability assessment' of the observed intake can be made. Since a particular individual's actual requirement remains unknown, one can only estimate his or her position in a distribution of requirements and assess the probability that this particular intake is adequate. It is not possible to classify the intakes of particular individuals as adequate or inadequate.

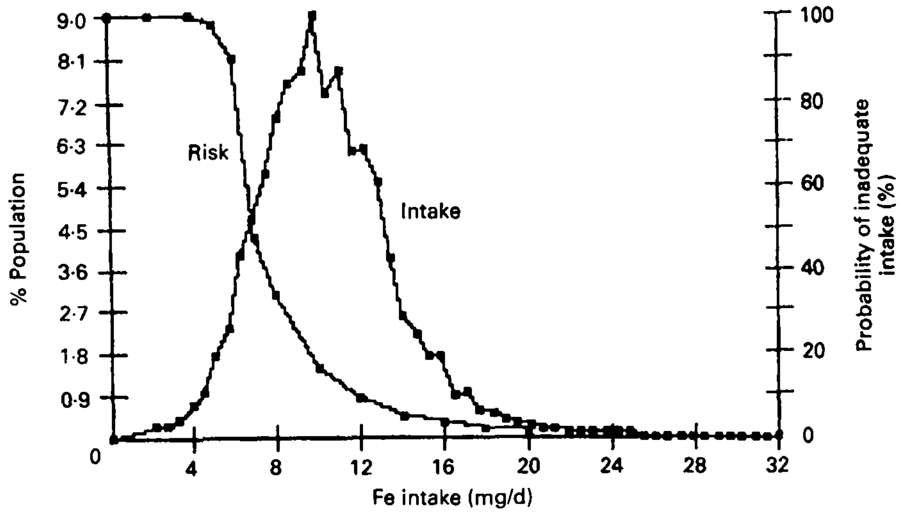

Fig. 5. Probability assessment of observed iron intake. The probability (risk) curve portrays the cumulative distribution of Fe requirements in menstruating women. The intake distribution has been adjusted as described on p. 70. For each interval of intake, a probability of inadequacy can be assigned. That probability × frequency of individuals in the intake interval, summed across the distribution of intakes, provides an estimate of prevalence of inadequate intakes. Taken from Beaton (1986).

Anderson *et al.* (1982) compared and contrasted the application of various interpretations of nutrient requirement estimates to values from a population of Canadian schoolchildren. That paper provides a dramatic illustration of the differences in inferred magnitude of the problem.

This concept of variability and of a 'probability approach' to assessment is not new. It has been presented and discussed for at least 15 years. Nevertheless, it had not gained wide understanding or acceptance. In the last 5 years, that has changed rapidly. This was the second line of thought that formed the background to the National Academy of Sciences report (NRC, 1986).

The National Academy of Sciences report: a synthesis and validation

The National Academy of Sciences Committee put the two lines of thought together in a population-assessment procedure and examined possible sources of error in the resultant prevalence estimates through a process of both empirical sensitivity testing and statistical theory. They proposed an approach which first adjusted the distribution of intakes on the basis of statistically estimated partitioning of variance (Fig. 3), and then applied the risk curve or probability curve concept (Fig. 4) to these adjusted distributions and estimated the proportion of individuals expected to have persisting or 'usual' intakes too low to meet their own, individual, requirement (NRC, 1986).

The approach is illustrated for Fe in menstruating women in Fig. 5, which shows the adjusted distribution of intakes (the estimated distribution of 'usual' intakes without the effect of day-to-day variation). Superimposed on this is the 'risk curve' for inadequacy of intake. By applying the probabilities portrayed in that curve to each interval of intake, an estimate of the prevalence of inadequate intakes can be derived for the whole population of women (Beaton, 1971; NRC, 1986). It is to be stressed that this is not a classification of individual women into 'adequate' and 'inadequate' intake categories; rather the approach estimates how many women are expected to have inadequate intakes without knowing which women have inadequate intakes.

Thus, the NRC (1986) addressed, in a positive way, two major issues that have plagued population assessments for a decade: the variability of intake within people and the variability of requirements between people.

The impact of a probability approach, in contrast to asking about the proportion of people with intakes below the recommended level, can be very dramatic. Again using the NFCS intake values for menstruating women, it would be estimated that 98% of the women had usual dietary Fe intakes below the current US RDA; 88% had intakes below the current Canadian recommended intakes; but only 23% had intakes below their actual requirements (note again that this data base did not include Fe supplements) (NRC, 1986).

The National Academy of Sciences Committee included its share of doubters! This was perhaps the most important facet of that committee for it drove the committee and the report into an exercise of examining the potential sources of error in the final prevalence estimates. It is inappropriate to review the report in detail but some of the highlights will be presented to illustrate some of the more surprising, and gratifying, findings.

The potential problems and error-sources can be divided into issues that (a) might affect the requirement criterion and (b) might affect the food intake estimate.

Consider, first, possible error-sources in the intake distribution. The approach to elimination of the effects of the day-to-day variation in intakes and the approach to adjusting the distribution have been described. What turned out to be very interesting was that this adjustment also removes the effects of some other factors that had been perceived as potential problems.

All would recognize that, at best, food composition tables present mean contents of particular foods. That is, when one consumes a particular orange, its vitamin C content is not expected to match the composition in the table. It follows that when one computes nutrient intake, there is an inherent 'error' in the estimated intake that can be traced back to the food composition tables. There was great concern that this error would defeat any approach to assessment. However, it was demonstrated (NRC, 1986) that when several food items are included in a meal, the relative error of the estimated intake decreases. The errors of the individual items are likely to be random and will tend to cancel out. The more items, the smaller the relative error. Further, this error becomes analogous to day-to-day variation in that it can be assumed to be random across days. It would be further diminished in the procedures used to adjust the intake distribution. The NRC (1986) demonstrated that quite-substantial random variation in food composition yields little appreciable effect in the final estimate of the prevalence of inadequate intakes. A major concern was set aside for this application of dietary data.

What would have an effect is any systematic bias attributable to the assay methods. Such did exist in the NFCS Fe intake values presented in the present paper since the USDA tables overestimated the Fe content of meats, an error that has since been corrected (Wolf, 1982; Exler, 1983).

A little more difficult to conceptualize is the effect of random under- or over-reporting. If this is across days, within-a-person, then it will be a part of the intra-individual variability that is factored out. However, if it is random across people (some under-report and some over-report on a consistent basis) it will have a small but not destructive effect on the final prevalence estimate. This was a very pleasant surprise! Again it is the presence of a systematic bias across all or most of the people that will cause serious problems. This could happen in substrata of the population that are separated out for particular attention, for example the overweight, a particular socio-economic group, etc. If this stratum were dominated by under- or over-reporters there would be an obvious bias in the prevalence estimate within that stratum even though it might not be a serious

Table 2. *Impact of altering the variance of nutrient requirements (mg/d) on the estimated prevalence of inadequate intakes (%) of ascorbic acid in adult males**

Requirement (mg/d)		Implied 'recommended intake'† (mg/d)	Prevalence estimate (%)
Mean	SD		
45	2	49	40·2
45	4	53	39·9
45	6	57	39·7
45	8	61	39·4
45	10	65	39·2

*Intake values taken from the US National Food Consumption Survey (1977–78). Values were adjusted to eliminate the effect of day-to-day variation and the probability approach to assessment was applied as described by the National Academy of Sciences Committee (National Research Council, 1986).

†By convention, the mean + 2SD.

problem in the whole population. The message may be that our existing methodologies for estimation of food intake may not be as limiting, for this purpose, as we have feared.

For the establishment of criteria of adequacy, a number of interesting perspectives arose (NRC, 1986). First, it turns out that the prevalence estimates are not very sensitive to the variability of the requirement distribution although they are very sensitive to the estimate of mean requirement! An example is presented in Table 2, which shows the very limited impact of changing the assumed variance of ascorbic acid requirement on the estimated prevalence of inadequate intakes in adult males. (The requirement estimate is based on the maintenance of metabolic pool sizes (NRC, 1980).) This may be compared to the major effect of the variance estimate on the recommended intake. Sensitivity testing with a series of requirement distributions, served to demonstrate that prevalence estimates are only slightly affected by alterations in the variability of requirement as long as the distribution is reasonably symmetrical; they do not have to be normal but they must be symmetrical. With a requirement distribution that is heavily skewed, such as is the case for Fe in menstruating women, distributional characteristics become important (NRC, 1986).

Recognition of the minimal impact of requirement variance on estimated prevalence has some implications for where emphasis should be placed in deriving and describing nutrient requirements. Traditionally (except for energy), the nutrition community has tended to ignore the mean requirement and put all effort into the definition of the 'recommended intake' (see Table 2). This should change. The mean intake (see Table 2) is critically important in population assessments.

Hard on the heels of this realization came recognition of the fact that we can conceptualize, and probably describe, requirements for different states of health (different definitions of adequacy). Table 3 shows the apparent prevalence of intakes that would be inadequate to sustain a metabolic pool size of ascorbic acid deemed to be desirable by a recent committee (NRC, 1980). It also gives the proportion of people who had intakes that would be predicted to be inadequate to prevent the development of clinical symptoms of deficiency (FAO/WHO, 1970). Both of these can be seen as being based on legitimate statements of 'requirement' but the requirements relate to different states of health. The National Academy of Sciences Committee pointed out that in population assessments, the duality of assessment portrayed in Table 3 would have distinct advantages, and strongly recommended the development of requirement estimates for different levels of nutriture (NRC, 1986).

Table 3. *Impact of altering the conceptual definition of requirement on the estimate of the prevalence of inadequate intakes of adult males**

Criterion of adequacy underlying nutrient requirement estimate	Estimated prevalence of inadequate intakes (%)	
	Ascorbic acid	Thiamin
Avoidance of clinically detectable malfunction	0·7	0
Maintenance of tissue levels of metabolic pools	39·6	3·4

*Intake values taken from the US National Food Consumption Survey (1977–78). Values were adjusted to eliminate the effect of day-to-day variation and the probability approach to assessment was applied as described by the National Academy of Sciences Committee (National Research Council, 1986).

A further observation, that becomes eminently sensible when one thinks about it, is that the mode of expression of requirements makes an important difference in the prevalence estimate. It is generally accepted that thiamin requirement is related to energy intake and metabolism. It is recognized also that thiamin intake relates to energy intake: the more food eaten, the more thiamin will likely be ingested. The simple probability assessment approach assumes that the correlation between intake and requirement is very low or non-existent, an assumption that is probably valid for nutrients (but not for energy). However, there is a built-in correlation between intake and requirement when we look at thiamin per day (both relate to energy intake). However, if both intake and requirement are expressed as thiamin per MJ, the spurious correlation is eliminated and the apparent prevalence of inadequate intakes in adult males (NFCS values) falls from 37% to about 3·5% (NRC, 1986). The moral is clear: where both intake and requirement depend on a third variable, this should be controlled in analysis.

Bridging consideration of both the requirement distribution and the intake distribution is the issue of nutrient availability. The customary practice is to adjust requirement estimates to take into account average availability. Some have argued that a more-correct approach would be to estimate the available nutrient in ingested foods and then compare this with the requirement for the absorbed nutrient. The concern has always been that availability for a nutrient such as Fe varies with the nature of the diet actually consumed and this varies between individuals and within the individual across meals and days.

From previous remarks the reader will be prepared for the conclusion that if availability varies randomly across the population, then the variability issue is not a major concern for this type of assessment. In this situation, the high and low availabilities will tend to cancel out, particularly in the adjusted distributions, and an average availability value can be applied to either the intake or requirement distribution. In Toronto, Beaton and colleagues (unpublished results) examined computed percentage Fe availability in relation to level of Fe intake (the values for this examination were made available by Dr Jean Sabry (Sabry & Grief, 1982)). If the two are unrelated, use of a mean availability estimate should approximate the correct distribution of available Fe. Conversely, if the availability changes with level of intake, there would be a bias in the estimate of the distribution of available Fe intakes in the population (a systematic difference between low and high intakes) and a bias in the prevalence estimate. In the limited sample of about 200 individuals, relative availability and Fe intake were unrelated! This should be confirmed in other, larger population groups. In the interim, it seems unlikely that the use of an average availability value, applied to either the intake or requirement distribution, leads to any serious bias in estimating the prevalence of inadequate Fe intakes.

The National Academy of Sciences Committee (NRC, 1986) has explored the implications of variability in the interpretation of both intake values and requirement values, in the construction of a particular type of analytical application. It has opened the door to similar explorations for other types of applications (another committee in the United States is now examining in detail the effect of dietary methodology selection on bivariate and multivariate analyses as might be used in epidemiological and other studies). The effects of variability will be quite different in different applications. One reason that application of the probability approach, preceded by intake distribution adjustment, has turned out to be much more reliable than one might have expected is that it has avoided the issue of having to estimate what each particular individual actually ingested. Individuals are not being classified as having adequate or inadequate intakes. Rather, distributions are being examined and inferences are being drawn about the proportion of people with inadequate intakes (without knowing which individuals have inadequate intakes). The distinction is important in a world where the custom has been to try to categorize each individual.

Some of these same principles hold in the interpretation of biochemical findings, particularly the issues relating to classification and development of cut-off points (Beaton, 1986). Where feasible, it may be highly advantageous to look toward distributional analyses of biochemical measurements (probability approaches) of the type adopted for dietary information by the National Academy of Sciences Committee.

The future

The innovations marked by the NRC (1986) report will not stop with that report. Fortunately there are already indications of very-encouraging future developments (and hints at even more).

The National Academy of Sciences Committee recommended that an attempt be made to define and describe different nutrient requirements for different states of nutriture. An FAO/WHO committee addressing requirements for Fe, folic acid, vitamin B_{12} and vitamin A has attempted to do just that (final report in preparation). It adopted two definitions of requirement and attempted to develop estimates of the nutrient intakes needed to meet these concepts of requirement. The definitions adopted were:

(1) *Basal requirement.* The requirement of a nutrient to prevent any clinically-demonstrable impairment of function. Individuals meeting this requirement will be well and will maintain normal growth and reproduction.

(2) *Normative storage requirement.* This refers to the requirement of a nutrient to maintain a reserve in body tissues. The reserve is seen as a supply that can be mobilized without detectable impairment of function. The amount of such reserve deemed to be appropriate and desirable is a normative judgement.

It is to be hoped that this FAO/WHO report will set in motion a new trend. At least the criterion of nutritional adequacy underlying the requirement estimate(s) must be made explicitly clear. Such clarity is desperately needed if we are ever to achieve a modicum of agreement between clinical, biochemical and dietary assessments (Beaton, 1986). Again, it is emphasized that there need not be a single definition of 'nutritional health' but there is need to agree on what the multiple levels really are. One cannot assume one standard for judging the adequacy of a diet and a different standard in laboratory assessments, at least if there is to be any hope of comparing the two. The door is opening for progress in this area. When it opens a bit more, there will be a progressive recognition that the NRC (1986) report has prepared the groundwork for the epidemiological validation of nutrient requirement estimates. If there is agreement on the definition of nutritional health, and if a statistically- and biologically-sound approach is applied in the estimation of prevalence, dietary and biochemical assessments should agree. If they don't, then there is strong reason to ask why—is the requirement estimate wrong? If the assessments agree then there is a degree of epidemiological validation of the requirement estimate (Beaton, 1974). Hopefully, future committees will have a new tool for use in estimating human nutrient needs.

The probability approach, as presented previously, does not address the question of degree of deficit. However, this is easily accomplished in population assessments. Earlier it was pointed out that the predicted prevalence of inadequate Fe intakes among menstruating women, based on the NFCS data, was about 23%. Table 4 presents a picture of the distribution of degrees of deficit in intake, and a much more informative picture of the population. This was accomplished very easily. All intakes were increased by 1 mg/d and then the probability assessment was rerun. The difference between this prevalence estimate and the former is an estimate of the proportion of women who have an intake less than 1 mg/d below their requirement. By repeating the exercise, the distribution of deficits presented in Table 4 was generated. Perhaps in the future one will see this type of portrayal of population values in addition to primary prevalence estimates.

Consider another development in the offing. The recently released FAO/WHO/UNU (1985) report on energy and protein requirements, and the Canadian report on nutritional needs (Health and Welfare Canada, 1983), both present Fig. 6 and endorse the philosophy it portrays. Traditionally, attention has focused on the implications of low intakes, and requirements have been examined in relation to prevention of deficiency. However, it is recognized that high levels of intake are also detrimental. Classic examples are vitamins A and D. The picture is much more important for the minerals and trace elements. For a number of them there is potential harm associated with both inadequate and excess intake (WHO, 1973). The early public-health concern about

Table 4. *Distribution of iron deficits among young adults*

(US National Food Consumption Survey (1977–78) intake values)

Degree of deficit in Fe intake* (mg/d)	Young adult women (%)	Young adult men (%)
<1	6·4	1·6
1–2	4·8	1·0
2–3	3·4	0·5
3–4	2·3	0·2
4–5	1·6	—
5–6	1·2	—
6–7	0·8	—
7–8	0·6	—
8	2·0	—
Total (all levels)	23·1	3·3

*'Deficit' is taken as the difference between the individual's usual intake and his or her own requirement.

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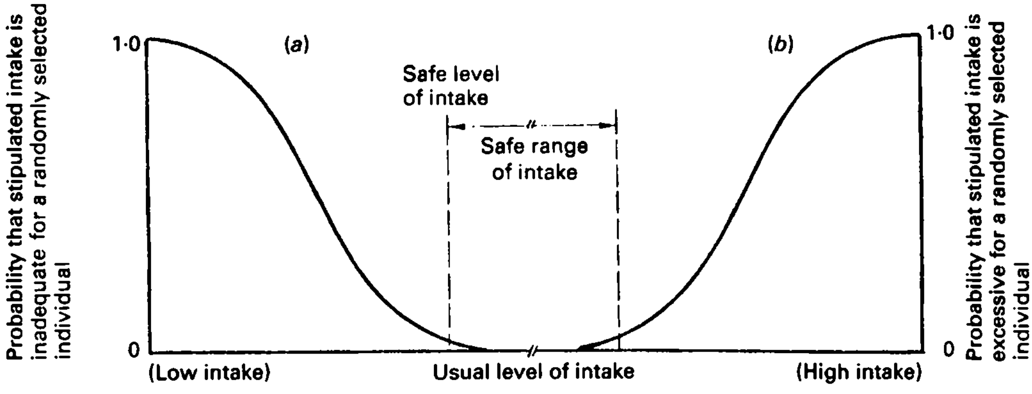

Fig. 6. The concept of a 'safe range of intakes'. (*a*) The probability of inadequacy and (*b*) the probability of detrimental effects attributable to an excess intake. Between these curves lies a range of intakes that have a very low probability of being either inadequate or excess, i.e. a 'safe range of intake'. Taken from Food and Agriculture Organization/World Health Organization/United Nations University (1985) and Health and Welfare Canada (1983).

fluoride was with regard to excess levels in public water supplies and how these could be reduced. Later the harmful effects of inadequate intakes were recognized and today the public-health objective is adjustment of water fluoride levels to a range that conveys near maximal benefit and near minimal harm. Referring to Fig. 6, the left-hand curve might be the 'decayed, missing, filled' rate and the right-hand curve the prevalence of dental mottling, both plotted against water fluoride concentration; the desirable level of fluoridation would fall between these curves (which would be closer together for fluoride) (Nikiforuk & Grainger, 1964).

Theoretically, for every nutrient there is a 'safe' or 'appropriate' or 'desirable' range of intake. At either end of this range there is an increasing risk of probability of detrimental effect. This does not imply an 'optimum' intake—nothing so glamorous. It implies only that we should be addressing both ends of this spectrum when we address nutritional needs, i.e. the definition of limits to desirable intakes.

A further implication is that as information is gained and organized, the approaches and concepts developed in the NRC (1986) report for the assessment of inadequate intake are applicable also to approaches to assessing detrimentally-high intakes!

It seems likely that there will be a major effort to operationalize the concepts portrayed in Fig. 6. Another FAO/WHO committee is in the preliminary planning phase, this time to address requirements for trace elements. That committee, like the previous trace elements committee (WHO, 1973), must be concerned with the definition of two requirement distributions: one relating to inadequacy and one relating to toxicity.

In this Boyd Orr Lecture I have attempted to relate a story of developing concepts and approaches; a story that I find exciting and challenging. I sincerely believe that as it continues to unfold it will greatly enhance our understanding of population nutrition and will begin in a very real sense to show us how to bridge the gap between experimental studies and applying the results to populations of human beings. Already we have the beginnings of approaches to the epidemiological validation of nutrient-requirement estimates based on controlled experiments. Will we soon see approaches to using epidemiological data to develop requirement estimates that can then be validated experimentally? Will we begin to apply the concepts of a 'safe range of intake' with curves of increasing risk at each end, to the study of dietary fat, where we implicitly recognize detrimental effects of both low and high intakes? It is a very exciting time; it is going to be exciting for many years to come. I can assure you that I am gratified to have played a part in these developments and I am gratified to have been given the opportunity to tell the story in the memory of one such as Boyd Orr.

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