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Commentary

For debate: problems with the DMF index pertinent to dental caries data analysis

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Abstract – The Decayed, Missing, Filled (DMF) index has been used for over 50 years and is well established as the key measure of caries experience in dental epidemiology. Despite its long history of use, there is debate about the most appropriate number of surfaces to include for a missing tooth. Assigning the maximum possible value for the 'M' component of DMFS (Surfaces) leads to overestimation of an individual's caries experience, and in any associated comparisons of in-caries experience, whereas assigning the minimum possible value for the 'M' component has the opposite effect. Alternative methods of assigning the number of caries-affected surfaces for an extracted tooth are considered. The net caries increment and adjusted caries increment (common methods of correction of the crude increment measure for reversals) are discussed, along with incidence density, a measure of caries extent. Problems exist with the adjusted caries increment, particularly among cohorts with low mean baseline caries experience. Development of an alternative method of estimating the relationship of 'true' and 'examiner' reversals is advocated, as well as greater utilization of incidence density in dental epidemiology.

Key words: adjustment for reversals; dentistry; incidence density; longitudinal study; missing teeth

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The Decayed Missing Filled Surfaces/Teeth (DMF) index has been in use for about 65 years, and is well established as the leading measure of caries experience in dental epidemiology. While there have been calls for the DMF index to be replaced (1), it remains the most commonly used epidemiological index for assessing dental caries.

The DMF index can be problematic in that, when computing DMFS, a missing tooth makes it necessary to arbitrarily allocate a number of surfaces as having been decayed (there is no such problem with the DMFT index). In the format originally proposed for the DMFS index in 1931, it was suggested that 'lost teeth are debited as deeply carious ones by adding three points to the total count of cavities', rather than the full value possible for the tooth; it was further suggested that crowns be assigned three surfaces 'as such teeth are commonly decayed on three surfaces', while those which serve as abutments for bridges may be rated lower (2). When Bödecker (3) proposed the current format of the DMF index in 1939, it was pointed out that assigning five surfaces to crowned and extracted teeth would overestimate the true caries experience of such teeth, and it was recommended that a total of three surfaces should be assigned to crowned or extracted teeth, provided that the tooth had been extracted before 35 years of age (as it was expected that older persons would have greater past caries experience at the time of tooth extraction). This was supported by a study which showed that, in a random sample of 100 extracted teeth, a mean of 3.1 surfaces were affected by caries (3). Whether all of those teeth had been extracted because of caries remains unclear.

Various methods of accounting for the 'M' component of the DMFS index have been proposed since 1939 (4). For cross-sectional studies, one of the more common methods is to ignore such surfaces, as though the affected teeth were not present at baseline (hereafter designated DM_1FS; equivalent to the DFS index). Alternatives for cross-sectional studies are to assign three surfaces for any extracted tooth ($DM_{3a}FS$, or to take the more common approach of assigning the maximum of four surfaces for an extracted anterior tooth or five for an extracted posterior tooth (DM_5FS). An examiner may also assign an arbitrary number of surfaces based upon the general status of an individual's dentition; however, this carries with it the risk of examiner bias.

Where accounting for the 'M' component of the DMFS index in a longitudinal study, it is possible to assign the same number of affected surfaces as were recorded at the most recent examination, before the tooth had been lost (DM_2FS). Alternatively, the researcher may choose to assign three surfaces for each extracted tooth, but to increase this value in cases where more than three decayed or filled surfaces had been present at the preceding examination ($DM_{3b}FS$). Another alternative would be to assign one more surface than was recorded as being affected at the preceding examination (to a maximum of four for anterior teeth and five for posterior teeth) so as to allow for a presumed worsening in-caries status of the tooth in question between the previous assessment and the extraction of the tooth (DM_4FS). In longitudinal studies, the researcher may, of course, either choose to assign '0' to extracted teeth [i.e. teeth lost because of caries can be analysed separately, so that two increments, tooth-loss and DM_1FS (or DFS), are examined], or the decision may also be made to use DM_5FS.

A further method intended for the adjustment of the MS component of DMFS among older adults (5) is based on the following formula:

$$\mathrm{DM_{adj}FS} = \mathrm{DM_6FS} = c + \left(n_{miss} * \left(\frac{c}{n_{pres}}\right) * k\right)$$

$$k = \left\{\frac{\sum_j a}{\sum_j n_{miss}}\right\} * \left\{\frac{\sum_j n_{pres}}{\sum_j c}\right\}$$

c = DFS at t_1 (follow-up), n_{miss} = no. of missing surfaces at t_1, n_{pres} = no. of tooth surfaces present at t_1, k = constant population prevalence ratio for caries in teeth that were lost vs. those that remained a = DM_1FS in teeth at t_0 that were extracted at t_1.

This method has been rarely used, possibly because of: (a) the complexity of the formula, and (b) that it gives a mathematically derived index value which is not intuitively meaningful (as it is a fractional number, rather than an integer). This method is not appropriate for use in calculation of caries increment, as it is a method for estimation of the life-long caries experience of an extracted tooth.

Incidence

The incidence of caries over a period may be computed simply as follows:

$$\text{Incidence} = \frac{\begin{array}{l}\text{Number of participants}\\ \text{experiencing a caries event} * \mathit{100}\\ \text{between two assessments}\end{array}}{\text{Total number of participants}}$$

This measure gives a somewhat broad view of the incidence of caries, as it does not distinguish between individuals who experience only one caries event and those who experience 10 (say). It is important to keep to stringent criteria for diagnosing a new incident 'case' of caries, as it is otherwise possible to observe wide variation in the percentage of individuals identified as incident cases.

'Simple' caries increment

This measure is calculated at the person (or mouth) level – rather than the tooth or the tooth-surface level – as the difference between baseline and follow-up person-level caries estimates. This is the most rudimentary of the methods discussed here; it is the quickest to calculate, but accordingly involves the most assumptions (in particular, it includes all reversals (longitudinal progression of a surface from carious or filled to sound) in the caries increment score).

$$\mathrm{SCI} = \frac{\sum_{i=1}^{n}(\mathrm{DMF}_{t_1} - \mathrm{DMF}_{t_0})}{n}$$

Crude caries increment

The crude caries increment (CCI) is a better method of identifying caries experience between two assessments, and involves comparing the baseline and follow-up status of each surface (on a surface-by-surface basis) in order to arrive at an estimate of the person-level disease increment. Thus, the researcher is able to focus upon transitions which are of particular interest. For example, using the 'simple' caries increment approach, a premolar which had been recorded as restored at baseline but orthodontically extracted before follow-up might count as a negative increment; this problem is easily solved with the CCI by not including such transitions in the calculation. The disadvantages of the CCI include: (a) that it is more difficult and time-consuming to compute; and (b) that it does not allow for reversals.

$$\mathrm{CCI} = \frac{\sum_{i=1}^{n}(\text{events where surface sound}_{it_0}\text{ but DMF}_{it_1})}{n}$$

Net caries increment

Net caries increment (NCI) is perhaps the most common method used to compensate for the effect of examiner and 'true caries reversals' upon DMFS scores. At the individual level, the number of reversals (negative increments) is subtracted from the number of positive caries increments to give the net caries increment (6).

$$\mathrm{NCI} = \frac{\sum_{i=1}^{n}(\text{events where surface sound}_{it_0}\text{butDMF}_{it_1} - \text{events where surface sound}_{it_0}\text{but sound}_{it_1})}{n}$$

Adjusted caries increment

The adjusted caries increment (ADJCI) (6) is built upon the premise that 'examiner' reversals are more common than 'true' reversals, and may be regarded as a pragmatic compromise between the NCI and CCI. It is calculated as the crude increment multiplied by the number of surfaces with caries experience at both examinations, divided by the total number of surfaces with reversals or caries at both examinations, as shown in the equation below.

$$\mathrm{ADJCI}_i = y_{2i} * 1 - \left(\frac{y_{3i}}{y_{3i} + y_{4i}}\right)$$

where ADJCI_i = adjusted caries increment for the ith participant, y_{2i} = number of surfaces with new caries (crude increment) for the ith participant, y_{3i} = number of surfaces with caries reversal for the ith participant and y_{4i} = number of surfaces with caries/restoration at both examinations for the ith participant.

The ADJCI has been previously used in epidemiological investigations of caries in older people (6–8). It has been suggested that the ADJCI should not be used when the number of reversals is <10% of the number of positive caries increments, because, if the percentage of reversals is small, the reversals might well be the result of random recording errors. In such cases, the use of the NCI is recommended (6).

Incidence density

Incidence density is a measure of the 'force of morbidity' of a disease, or a person-time incidence rate. Where a disease event (or loss from/entry into the study) occurs, it is assumed that this occurred at the halfway point between assessments. This is relevant for the calculation of the number of years of exposure. Alternative to using the halfway point between assessments it is also possible to use interval-censored survival methods, such as those summarized by Lindsey and Ryan (9), or to assume that events occurred at the end or beginning of each inter-assessment interval. The incidence density ratio and the incidence density difference may also be calculated, in order to compare the extent of disease in groups with different levels of exposure to a putative risk factor for that disease (10).

Incidence density (ID) is commonly calculated at the group level (for those exposed or unexposed), as follows:

$$\mathrm{ID} = \frac{\text{Total number of new cases of disease during study}}{\text{Total number of person-years of participation in the study}}$$

Historically, incidence density was rarely used in dental epidemiological studies (11), but it has come to be used more often since the late 1990s (12–17). For dental studies, incidence density may be calculated at the 'mouth level' rather than the participant 'group' level; so for the 'ith' participant, incidence density is calculated as follows:

$$\mathrm{ID}_{\mathrm{mouth}i} = \frac{\text{Number of new cases of disease during study}_i}{\text{Number of surface-years of participation in the study}_i}$$

The most crucial assumption required when calculating incidence density in dentistry is that any event (such as loss or eruption of a tooth or the placement of a restoration) is assumed to have occurred at the half-way point between assessments. Despite the assumptions required, incidence density is perhaps the most accurate technique of measuring the rate at which new events occur, as it accounts for caries increments relative to the number of surfaces (or teeth) present, and the time that these surfaces are at risk of caries.

Each of the methods described above for estimating 'M' and for adjusting for reversals requires a set of assumptions which may or may not be valid. There being so many techniques, it is necessary to determine their relative effectiveness. This paper will explore these issues using data from the Dunedin Multidisciplinary Health and Development Study, a longstanding cohort study. The objectives of this report are as follows: (i) to compare the effects of several methods of estimation of the 'M' component of the DMFS index upon the overall DMFS score (including their effects upon estimation of social inequalities in caries experience); (ii) to compare the effects of several methods of accounting for reversals in longitudinal studies of dental caries upon DMFS increment scores; and (iii) to stimulate discussion within the scientific literature of the appropriateness of the aforementioned modified versions of the DMF index for use in epidemiological studies of dental caries.

Method

This report is based upon an analysis of dental caries data from the Dunedin Multidisciplinary Health and Development Study assessments at ages 15, 18 and 26 years. The Dunedin Study is a longitudinal investigation of health and behaviour in a complete birth cohort. Study members were born in Dunedin, New Zealand, between April 1972 and March 1973, and 1037 persons (91% born – eligible for the study; 52% male) participated in the first follow-up at the age of 3 years; these constituted the base sample for the remainder of the study. Cohort families represented the full range of socioeconomic status (SES) in New Zealand's South Island, and were mainly white. Follow-ups were done at the ages of 5, 7, 9, 11, 13, 15, 18, 21 years, and most recently at age 26 years, when we assessed 980 (96%) of the 1019 surviving study members.

The Research Ethics Committee of the Otago Hospital Board granted ethical approval for each assessment phase. Study members gave informed consent before participation.

Estimates for $DM_{1-6}FS$ were calculated using the 15-, 18- and 26-year age data sets. Caries experience at age 26 years was calculated, as well as the SCI, CCI, NCI and ADJCI for transitions between age 15 and 26 years. Calculations were made by each of the methods of estimation of the 'M' component of the index. DM_1FS simply involved calculation of DFS at 26 years of age. DM_2FS required the number of surfaces affected by caries (DM_1FS) at age 18 years (where the tooth was extracted by age 26 years) to be added to the age 26 years DM_1FS score. If the tooth had been previously missing because of caries at age 18 years (the case for one study member), the adjustment was made according to its surface status at age 15 years. In terms of computation, $DM_{3b}FS$ was identical to DM_2FS, except that the minimum allowable number of surfaces was three per tooth extracted because of caries by age 26 years. DM_4FS was also very similar to DM_2FS; it simply required one more surface to be added to the DM_2FS value (up to a maximum of four surfaces for anterior and five surfaces for posterior teeth). DM_5FS was DMFS calculated after current practice, where four surfaces were assigned for all extracted anterior teeth and five for all posterior teeth. DM_6FS was calculated as for the $DM_{adj}FS$ formula described above (5). Incidence density was calculated using the caries data from all three ages.

In order to examine the effects of the different methods, the association between caries experience and SES was examined. The SES of the study members' families was measured on the basis of their parents' self-reported occupational status, according to the Elley–Irving index (18, 19). The variable 'childhood SES' (the average of the highest SES level of either parent, assessed repeatedly between the study members' birth and age 15 years) were also obtained from the Dunedin Study database. These scores were then trichotomised into three separate SES categories (low, medium and high). Bivariate analyses were restricted to comparisons of the measures of caries experience and incidence by this SES variable.

Results

The participation rates for the DMHDS assessments at the ages of 15, 18 and 26 years are presented in Table 1. The overall participation rate in the study was approximately 95% from age 15 to 26 years; however, participation in the dental examinations was considerably lower at ages 15 and 18 years. A total of 739 study members (72.5% of the study members living at age 26 years) were dentally examined at 15, 18 and 26 years. All subsequent analyses are limited to these 739 indi-

Table 1. Participation in the Dunedin Study at ages 15, 18 and 26 years

Year	Assessment birthday	Number eligible[a]	Number seen	Percent seen	Number dentally examined	Percent dentally examined
1987–1988	15	1029	976	94.8	781	75.9
1990–1991	18	1027	993	96.7	867	84.4
1998–1999	26	1019	980	96.2	930	91.3

[a]Number study members surviving (of the original 1037).

viduals. As this is a methodological study, it was not necessary to perform an attrition analysis to determine how, if at all, excluded study members differ from those who were included.

Most study members (668 or 90.4%) experienced at least one restoration or caries-affected surface between the ages of 15 and 26 years, and 200 (27.1%) experienced at least 11 new DM_5FS from ages 15 to 26 years. Summary caries data from ages 15, 18 and 26 years are presented in Table 2. No study member had lost any teeth because of caries by age 15 years, while one had by age 18 years, and 70 (9.5%) had by age 26 years. The proportion of erupted teeth that were decayed, missing, or filled nearly doubled between ages 15 and 26 years.

Summary data on the modified DMFS indices are presented in Table 3. Of the five methods used to calculate the cross-sectional score at age 26 years and increment scores from 15 to 26 years of age, DM_1FS produced the lowest score, while DM_5FS produced the highest score. $DM_{3b}FS$ produced a greater score than either of DM_2FS or DM_4FS. $DM_{3a}FS$ produced scores that were extremely close to $DM_{3b}FS$ (the difference was negligible and is obscured by rounding to 1 decimal place). The CCI, NCI and ADJCI are also presented in Table 3. Adjustment for reversals by the ADJCI produced lower mean caries increment scores than did the NCI. Differences in DM_2FS, $DM_{3b}FS$, and DM_4FS scores according to whether the adjustment for past caries of an extracted tooth extracted because of caries at age 26 years was made by the 15- or 18-year age data are presented in Table 4 (note that, for the one study member who had lost a tooth because of caries by age 18 years, this adjustment was made by the 15-year age data for those teeth). Similar comparisons are not made by the DM_1FS, $DM_{3a}FS$, or DM_5FS methods, as these adjustments are made independent of data from previous assessments.

Table 2. Summary data for DM_1FS (DFS), DM_5FS, and DMFT in the Dunedin Study at ages 15, 18, and 26 years

	Age 15 years	Age 18 years	Age 26 years
Mean DM_1FS (SD)	4.8 (4.9)	6.9 (6.9)	12.0 (10.2)
Mean DM_5FS (SD)	4.8 (4.9)	6.9 (6.9)	12.8 (11.5)
Mean DMFT (SD)	3.6 (3.1)	4.9 (3.9)	7.7 (5.1)

The crude incidence density for DM_5FS was 0.762% (SD 0.858%), which means that 0.76% of sound surfaces experienced a caries-related event every year of exposure between the age of 15 and 26 years. The same measure for DM_1FS was 0.702% (SD 0.761%).

Crude caries increment scores by SES categories are presented in Fig. 1 (where error bars represent the 95% CI of the mean). For the high-SES group, no differences existed according to method of estimation of the 'M' component of CCI. For the low-SES group, significant differences existed in mean CCI according to method of estimation of CCI (similar, but less profound, differences existed in the medium-SES group). The difference between mean high-SES CCI and low-SES CCI ranged from 2.1 to 3.7 surfaces, depending upon the method used to calculate 'M'.

Discussion

The DMF index is not a perfect epidemiological tool. Many approaches have been put forward to address these problems, and each has very real effects upon estimates of dental caries experience obtained at both the individual and population-group levels. None of the solutions we have described are ideal; we discuss their advantages and disadvantages below.

Calculation of 'M'

There are problems which are peculiar to the 'M' component of the DMF index. First, the study participant must recall the reason for extraction, whether due to caries, a large broken restoration, or 'some other reason'. This introduces all the problems of recall bias to what is, in essence, a clinical measure. Secondly, it is extremely unlikely that any

Table 3. Caries experience by $DM_{1-6}FS$ score at 26 years and $DM_{1-5}FS$ increment from 15 to 26 years of age; methods of calculation of 'M' component of DMFS and techniques of adjustment for reversals (decrements)

		DMFS increment 15 to 26 years		
	DMFS score at 26 years	CCI	NCI	ADJCI
DM_1FS [mean (SD)]	12.0 (10.2)	8.0 (8.0)	7.3 (7.7)	6.9 (7.2)
'M_1' = 0				
DM_2FS [mean (SD)]	12.2 (10.6)	8.2 (8.4)	7.5 (8.0)	7.1 (7.5)
'M_2' = Σ_i surfaces that were carious at age 18 years				
$DM_{3a}FS$ [mean (SD)]	12.5 (10.9)	8.5 (8.8)	7.8 (8.5)	7.4 (8.0)
'M_{3a}' = 3				
$DM_{3b}FS$ [mean (SD)]	12.5 (10.9)	8.5 (8.8)	7.8 (8.5)	7.4 (8.0)
'M_{3b}' = as method 2, but minimum of three surfaces assigned				
DM_4FS [mean (SD)]	12.3 (10.8)	8.4 (8.6)	7.7 (8.3)	7.3 (7.8)
'M_4' = $\sum_i$ surfaces that were carious at age 18 + 1 years surface per tooth (maximum = four anteriors; five posteriors)				
DM_5FS [mean (SD)]	12.8 (11.5)	8.9 (9.4)	8.2 (9.1)	7.8 (8.6)
'M_5' = 4 (anterior teeth); 'M' = 5 (posterior teeth)				
DM_6FS [mean (SD)]	12.4 (10.9)	–	–	–
'M_6' = (n_{miss} *(c/n_{pres}) *k), where $k = \sum_i a / \sum_i n_{miss} * \sum_i n_{pres} / \sum_i c$				

Table 4. Differences in DM_2FS, $DM_{3b}FS$, and DM_4FS at age 26 years by age used to adjust for previous caries experience of teeth extracted because of caries

	Age 15-year adjustment used	Age 18-year adjustment used
DM_2FS [mean (SD)]	12.1 (10.4)	12.2 (10.5)
$DM_{3b}FS$ [mean (SD)]	12.5 (10.9)	12.5 (10.9)
DM_4FS [mean (SD)]	12.2 (10.6)	12.3 (10.8)

study participant could tell a researcher the number of surfaces of the extracted tooth that had been affected by caries at the time of extraction. Thirdly, it appears that it is a particular group of individuals who undergo dental extractions as a form of treatment. As demonstrated in Fig. 1, estimates of inequalities in dental caries experience vary considerably according to whether DM_1FS (DFS) or DM_5FS (generally accepted DMFS) is used. As presented above, the difference was 2.1 surfaces with DM_1FS and 3.7 surfaces with DM_5FS. This range is too wide for either DM_1FS or DM_5FS to be taken as a estimate of the true inequality in caries experience. Results within and between studies should not be regarded as comparable just because they use the same DM_nFS definition.

Previously, a common alternative, and that used in previous reports from the Dunedin Study, has been to use a 'dual DFS (DM_1FS) and tooth-loss-due-to-caries' approach, with the reporting of each separately. However, this gives two measures of inequality – one a partial measure of disease experience, and the other at least partially a

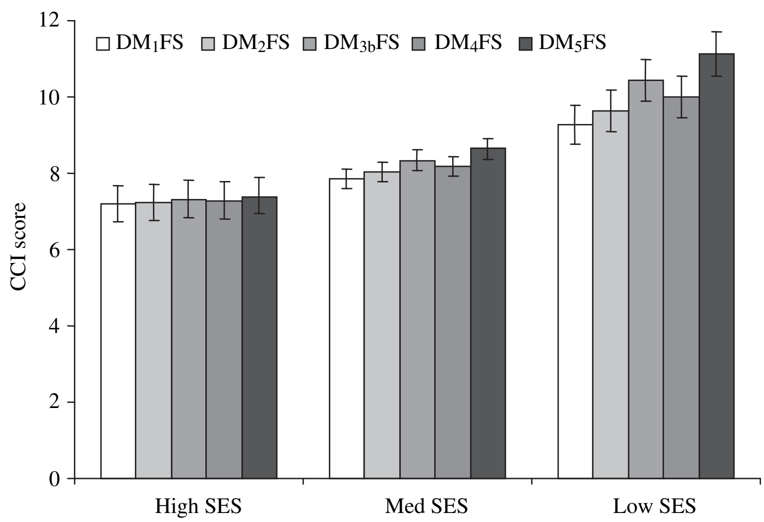

Fig. 1. Methods of calculation of the 'M' component of CCI by SES category (error bars represent 95% CI for the mean). 'M_1' = 0; 'M_2' = $\sum_i$ surfaces that were carious at age 18 years; 'M_{3b}' = as M_2, but minimum of three surfaces assigned; 'M_4' = $\sum_i$ surfaces that were carious at age 18 + 1 years per tooth (maximum = four anteriors; five posteriors); 'M_5' = 4 (anterior teeth); 'M' = 5 (posterior teeth).

treatment choice. The benefits of the alternative approaches for estimation of the true 'M' component (as outlined in this paper) are that they allow a more accurate estimate of true disease experience, and permit the use of a single variable.

Given that caries in epidemiological studies is nearly always underestimated (as, for example, radiographs are rarely taken), we should not then overestimate caries experience in the teeth that were extracted, as this would lead to bias in any analyses involving these teeth. Neither does it seem appropriate to assign non-integer adjusted DM_6FS values to individuals. We suggest that cross-sectional studies should use the $DM_{3a}FS$ approach, as the number of surfaces truly affected by caries (though unknown) would likely be closest to 3, as originally suggested by Bödecker (3). It is further suggested that longitudinal studies with relatively short recall periods should use DM_2FS, while $DM_{3b}FS$ or DM_4FS would probably be more appropriate for studies (such as the Dunedin Study) with long recall periods. However, we also advocate the conducting of research to determine the mean number of tooth surfaces affected by caries at the time of extraction as a much-needed update to the work described by Bödecker. In any such study, it would be vital to take participant age into consideration, as it is likely that older persons would have more surfaces affected by caries at the time of extraction of the tooth. It is also possible that males and persons of low SES would also have, on average, more surfaces affected by caries at the time of tooth extraction, as they may have waited longer to have the problem dealt with. Furthermore, tooth type should also be considered, as molars, premolars, and anterior teeth may have differing mean numbers of surfaces affected by caries at the time of extraction.

It might be argued that although $DM_{3a}FS$ is theoretically less accurate, it gives very similar results to $DM_{3b}FS$ so it should not matter which is used. This may be true at the summary level, but at the individual level the $DM_{3b}FS$ involves fewer assumptions. We suggest that, where data from previous assessments are available, that the $DM_{3b}FS$ be used as it is more theoretically sound. As $DM_{3a}FS$ appears to give virtually the same results as $DM_{3b}FS$, where previous data are not available $DM_{3a}FS$ may be utilized, and it should be possible to make comparisons with the results of studies where the $DM_{3b}FS$ was used with a high degree of confidence.

A problem with DM_6FS is that, for some individuals, this method will result in a value of less than DM_2FS, because of 'cross-sectional adjustment reversals'. For example, at age 26 years, one study member in our database had a DM_1FS of 18 and a DM_5FS of 28 (the MS was 10 surfaces). The DM_2FS was 26 (so eight of the 10 surfaces missing because of caries had been decayed or filled at age 18 years), but the DM_6FS was 21.45. This represents a 'cross-sectional adjustment reversal', as these surfaces were known to have been decayed at 18 years of age. Although the DM_6FS gives good estimates of caries experience at the summary level, the individual statistics may vary widely because of the use of a population-wide '*k*' value.

An alternative is for the researcher to make the judgement of how many surfaces of a missing tooth should be assigned as carious at the time of the examination (where previous data are not available). This could be estimated according to the state of the teeth remaining in the mouth. Of course, this approach would carry with it a major risk of examiner bias.

Adjustment for reversals

The transition of a surface from 'filled' to 'filled and decayed' is normally considered to be a positive increment in longitudinal studies of dental caries. In terms of the ADJCI, however, this surface transition must be included in the y_2 value and the y_4 value. Although there is new-formed caries, the old restoration is 'confirmed' to have existed previously and appears in the formula twice. By way of example, one study member in the Dunedin Study database had a crude increment of seven surfaces from age 15 to 26 years: this comprised six surfaces with new caries/restorations ($y_2 = 6$), and one surface with an increment from 'filled' to 'filled and decayed' ($y_5 = 1$). One reversal occurred between those ages ($y_3 = 1$), and one surface was affected (carious, filled, or carious and filled) at both ages ($y_4 = 1$). The study member had only two restorations at age 15 years – one of these 'disappeared' (the reversal), and the other was coded as 'filled and decayed' at age 26 years. This individual's ADJCI is computed as:

$$
\begin{aligned}
\mathrm{ADJCI}_i &= (y_{2i} + y_{5i}) * \left(1 - \frac{y_{3i}}{y_{3i} + y_{4i}}\right). \\
&= (6 + 1) * \left(1 - \frac{1}{1 + 1}\right) \\
&= 7 * (1 - 0.50) \\
&= 3.50
\end{aligned}
$$

The reader will have noticed that, although the ADJCI is intended to give a mean caries increment score which is between the CCI ($y_{2i} + y_{5i} = 7$) and NCI ($y_{2i} + y_{5i} - y_{3i} = 6$), it did not in this case: upon putting the numbers into the formula, an estimate of 'true' caries experience was gained which was more severe than the net caries increment (which was six surfaces). The problem in this case is the low number of surfaces which were filled or decayed at baseline (as implied by Tables 2 and 4, approximately two-thirds of the study members' caries experience occurred between the ages of 15 and 26 years). A less severe estimate would be obtained where there was a high baseline caries experience to make the denominator ($y_{3i} + y_{4i}$) large, thus reducing the reversals. Previous reports involving the calculation of ADJCI have all been in longitudinal studies of older people, who have much greater baseline caries experience than the participants in the Dunedin Study; hence, at the summary level, the ADJCI has always previously been reported as a value which is intermediate between the NCI and CCI.

Beck et al. (6) gave the example: 'If a subject with 20 teeth and a baseline root DFS of 21 (t_0) is recalled for a second examination (t_1) after a time interval, and 7 of those 21 decayed or filled root surfaces are recorded as ''sound'', what would be the incidence of root caries considering that new decay or fillings appeared on 5 surfaces? (20 teeth or 20 * 4 = 80 root surfaces).'

Transitions:
Sound to sound = y_1 = 54
Sound to carious/filled = y_2 = 5 (crude increment)
Carious/filled to sound = y_3 = 7 (reversal)
Carious/filled to carious/filled = y_4 = 14

$$\mathrm{CCI} = y_2 = 5$$

$$\mathrm{NCI} = y_2 - y_3 = -2$$

$$\mathrm{ADJCI} = y_2 * \left(1 - \frac{y_3}{y_3 + y_4}\right) = 5 * \left(1 - \frac{7}{21}\right) = 3.33$$

They made the point that, from the example above, it is evident that the traditional NCI is too severe, because 14 surfaces at baseline examination (y_4) were still confirmed as carious at follow-up. The penalty imposed by the net adjustment (−2) suggests that there are now only 12 DF surfaces, whereas 14 have been confirmed at the second examination. However, what happens if the parameters of the example are changed slightly so that there is only one reversal, and two surfaces that were decayed or filled at baseline that were 'confirmed' at follow-up?

Sound to sound = y_1 = 72
Sound to carious/filled = y_2 = 5 (crude increment)
Carious/filled to sound = y_3 = 1 (reversal)
Carious/filled to carious/filled = y_4 = 2

In this case, the ADJCI gives an identical estimate to the example provided by Beck et al., but it appears that the ADJCI adjustment has given a more severe estimate for reversals than the NCI.

$$\mathrm{CCI} = y_2 = 5$$

$$\mathrm{NCI} = y_2 - y_3 = 4$$

$$\mathrm{ADJCI} = y_2 * \left(1 - \frac{y_3}{y_3 + y_4}\right) = 5 * \left(1 - \frac{1}{3}\right) = 3.33$$

For a more extreme example, if the parameters were one reversal, but no surfaces that were decayed or filled at baseline that were 'confirmed' at follow-up:

Sound to sound = y_1 = 74
Sound to carious/filled = y_2 = 5 (crude increment)
Carious/filled to sound = y_3 = 1 (reversal)
Carious/filled to carious/filled = y_4 = 0

Here, the operand [1 − (y_3/(y_3 + y_4)] equals zero, and the ADJCI cannot be calculated. In keeping with the case where Study members were caries-free at baseline [y_3 = 0, 0% of caries detected at baseline reversed, so ADJCI = 100% of CCI = NCI = ADJCI = y_2 as discussed by Beck et al. (13)], where 100% of the caries detected at baseline had reversed by follow-up, the ADJCI should equal 0% of the CCI (zero). It is clear that the ADJCI is much too extreme in this case.

$$\mathrm{CCI} = y_2 = 5$$

$$\mathrm{NCI} = y_2 - y_3 = 4$$

$$\mathrm{ADJCI} = y_2 * \left(1 - \frac{y_3}{y_3 + y_4}\right) = 5 * \left(1 - \frac{1}{1+0}\right) = \mathrm{NULL} = 0$$

Perhaps the indication that ADJCI should not be used when reversals are <10% of the baseline carious lesions detected is too lenient an exclusion criterion, and that we should look instead to the baseline caries experience. Maybe the ADJCI should not be calculated where baseline caries is low relative to increment (and decrement). Noting that y_4 consists of those surfaces that were 'confirmed' as carious/filled at follow-up, perhaps those surfaces that were *sound* at both baseline and 'confirmed' sound at follow-up could be incorporated into y_4. This would solve the problem caused by low baseline caries, but the reversal adjustment would no longer be a function of those caries-affected surfaces that were 'confirmed' at follow-up.

Conclusions

The DMF index is perhaps the most valuable measure we have in dental epidemiology. However, it has inherent problems. Researchers should consider carefully how many surfaces to categorise as being previously decayed for an extracted tooth, particularly in research involving oral health inequalities. Assigning the maximum value is likely to give an overestimate of inequalities, while ignoring the 'M' component would leave out what is perhaps the most important component of inequalities.

The ADJCI should perhaps be avoided, as it is inappropriate for certain situations and its interpretation can be difficult. The NCI is tried and true – although this approach does not take into consideration whether a reversal is 'true' or is an 'examiner' reversal. Development of a valid approach to this problem is required.

Unlike other areas of health research, incidence density is rarely used in dental epidemiological studies. Great value could be gained from the more frequent use of incidence density in analyses involving dental caries. However, that would require a greater investment in longitudinal dental epidemiological research, which (we argue) would be no bad thing.

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References

1. Spencer AJ. Skewed distributions – new outcome measures. Community Dent Oral Epidemiol 1997; 25:52–9.
2. Bödecker CF, Bödecker HWC. A practical index of the varying susceptibility to dental caries in man. Dent Cosmos 1931;77:707–16.
3. Bödecker CF. The modified dental caries index. J Am Dent Assoc 1939;26:1453–60.
4. Doyle J, Horowitz HS. Influence of extracted teeth on DMF surface increments in clinical trials of caries preventives. J Dent Res 1970;49(Suppl 14):17–22.
5. Lawrence HP, Beck JD, Hunt RJ, Koch GG. Adjustment of the M-component of the DMFS index for prevalence studies of older adults. Community Dent Oral Epidemiol 1996;24:322–31.
6. Beck JD, Lawrence HP, Koch GG. A method for adjusting caries increments for reversals due to examiner misclassification. Community Dent Oral Epidemiol 1995;23:321–30.
7. Thomson WM, Spencer AJ, Slade GD, Chalmers JM. Is medication a risk factor for dental caries among older people? Community Dent Oral Epidemiol 2002;30:224–32.
8. Chalmers JM, Carter KD, Spencer AJ. Caries incidence and increments in community-living older adults with and without dementia. Gerodontology 2002;19:80–94.
9. Lindsey JC, Ryan LM. Tutorial in biostatistics methods for interval-censored data. Stat Med 1998;17:219–38 [erratum appears in Stat Med 1999 Apr 15; 18(7):890].
10. Barrow SY, Xionan X, LeGeros AR, Mijares DQ, LeGeros RZ, Galvis DL, et al. Dental caries prevalence among a sample of African American adults in New York City. Dent Clin North Am 2003;47:57–65.
11. Niehoff JU, Lehmann A, Behrbohm G, Schrader RR. Die Messung epidemiologischer Sachverhalte im Anwendungsfall der Stomatologie. Deutsche Stomatologie 1990;40:360–2.
12. Lawrence HP, Hunt RJ, Beck JD, Davies GM. Five-year incidence rates and intraoral distribution of root caries among community-dwelling older adults. Caries Res 1996;30:169–79.
13. Beck JD, Lawrence HP, Koch GG. Analytic approaches to longitudinal caries data in adults. Community Dent Oral Epidemiol 1997;25:42–51.
14. Caplan DJ, Slade GD, Biesbrock AR, Bartizek RD, McClanahan SF, Beck JD. A comparison of increment and incidence density analyses in evaluating the anticaries effects of two dentifrices. Caries Res 1999;33:16–22.

15. Slade GD, Caplan DJ. Methodological issues in longitudinal epidemiologic studies of dental caries. Community Dent Oral Epidemiol 1999;27:236–48.
16. Slade GD, Caplan DJ. Impact of analytic conventions on outcome measures in two longitudinal studies of dental caries. Community Dent Oral Epidemiol 2000;28:202–10.
17. Kallestal C, Stenlund H. Different analytical approaches in an experimental cohort study on preventive measures for caries in adolescents. A comparison between incidence density and increment analysis. Caries Res 2003;37:44–50.
18. Elley WB, Irving JC. The Elley-Irving socio-economic index 1981 census revision. N Z J Educ Stud 1985; 20:115–28.
19. Irving JC, Elley WB. A Socio-Economic Index for the Female Labour Force in New Zealand. N Z J Educ Stud 1977;12:154–63.