



# Handling Missing Data in Within-Trial Cost-Effectiveness Analysis: A Review with Future Recommendations

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**Abstract** Cost-effectiveness analyses (CEAs) alongside randomised controlled trials (RCTs) are increasingly designed to collect resource use and preference-based health status data for the purpose of healthcare technology assessment. However, because of the way these measures are collected, they are prone to missing data, which can ultimately affect the decision of whether an intervention is good value for money. We examine how missing cost and effect outcome data are handled in RCT-based CEAs, complementing a previous review (covering 2003–2009, 88 articles) with a new systematic review (2009–2015, 81 articles) focussing on two different perspectives. First, we provide guidelines on how the information about missingness and related methods should be presented to improve the reporting and handling of missing data. We propose to address this issue by means of a quality evaluation scheme, providing a structured approach that can be used to guide the collection of information, elicitation of the assumptions, choice of methods and considerations of possible limitations of the given missingness problem. Second, we review the description of the missing data, the statistical methods used to deal with them and the quality of the judgement underpinning the choice of these methods. Our review shows that missing data in within-RCT CEAs are still often inadequately handled and the overall

level of information provided to support the chosen methods is rarely satisfactory.

## Key Points for Decision Makers

This is the first systematic review proposing a quality assessment of CEA studies based on how missingness in costs and effects is handled and reported (quality evaluation scheme, QES).

The recommendations, used in building the QES, guide the choice of the missing data method based on the description of the data and assumed missing data mechanism; this in turn should be informed by the available evidence and assessed using sensitivity analysis.

The review shows a currently inadequate handling of missingness for both outcomes in the literature.

This may in turn lead to bias or overconfidence in CEA results that decision makers should take into account in their evaluation of the quality of a study.

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## 1 Introduction

A well-known issue in cost-effectiveness analysis (CEA), especially within a randomised controlled trial (RCT) setting, is the presence of large proportions of missing data in either or both outcome variables, i.e. the cost and the clinical effectiveness or utility measures. Removing the unobserved cases (a method usually referred to as “complete case analysis”, CCA) generally leads to a loss in

efficiency and possible serious biases in the parameter estimates [1–4]. Consequently, the final conclusions of the study may be strongly influenced by the way in which missingness is handled, thus possibly reversing the decision about the cost-effectiveness of a new treatment compared with the standard option [5, 6].

While the problem of missing data is widely discussed in the general statistical literature, it has been less extensively addressed in the health economics one. Notable exceptions include Graves et al. [7], Briggs et al. [8], Oostenbrink et al. [9], Oostenbrink et al. [10], Burton et al. [11] and Lambert et al. [12], mainly focussing on the cost measures; Richardson and Manca [13], Wood et al. [14], Groenwold et al. [15], Powney et al. [16], Simons et al. [17] and Rombach et al. [18], with reference to health outcome measures; and Manca and Palmer [5], Harkanen et al. [19], Diaz-Ordaz et al. [20] and Faria et al. [21], who consider both outcomes.

Interestingly, recent reviews on the methods applied in within-trial CEAs [22–24] have concluded that CCA has historically represented the standard approach in health economics. As a result, we should be naturally sceptical about the conclusions achieved by CEAs performed in a context where missingness is not addressed in a “principled” way. We make reference to the concept of a principled approach to handle missingness in Sect. 2. Within this framework, subsequent inferences are valid under the stated assumptions, which in turn can be varied to test their impact on the decision-making.

The objective of this article is twofold: first, we collect guidelines from the literature about the way in which missingness should be analysed and reported in within-trial CEAs and embed them within a structured scheme. Second, we review the methods used to handle missingness in the studies between 2003–2015 by updating and extending the work of Noble et al. [22]. This is done with a view to assessing whether the methods have evolved over time and whether the quality level of missing data analyses is adequate. The paper is structured as follows: Sect. 2 illustrates Rubin’s classification of missing data mechanisms [1]. In Sect. 3, we provide a brief summary of the most popular missingness methods. In Sect. 4, we provide a structured approach, which we name quality evaluation scheme, which summarises the most important recommendations collected from literature about the way information and assumptions on missing data should be provided in CEA studies. Based on these guidelines, we also suggest a systematic approach for grading the studies given the overall level of information about missingness provided. Section 5 presents the methodology used to select the review’s articles and the main results derived from the different descriptive analyses performed. In Sect. 6, we apply the quality evaluation scheme to the reviewed articles in the

period 2009–2015 and show how they perform in terms of missing data handling. Finally, Sect. 7 summarises our findings and recommendations.

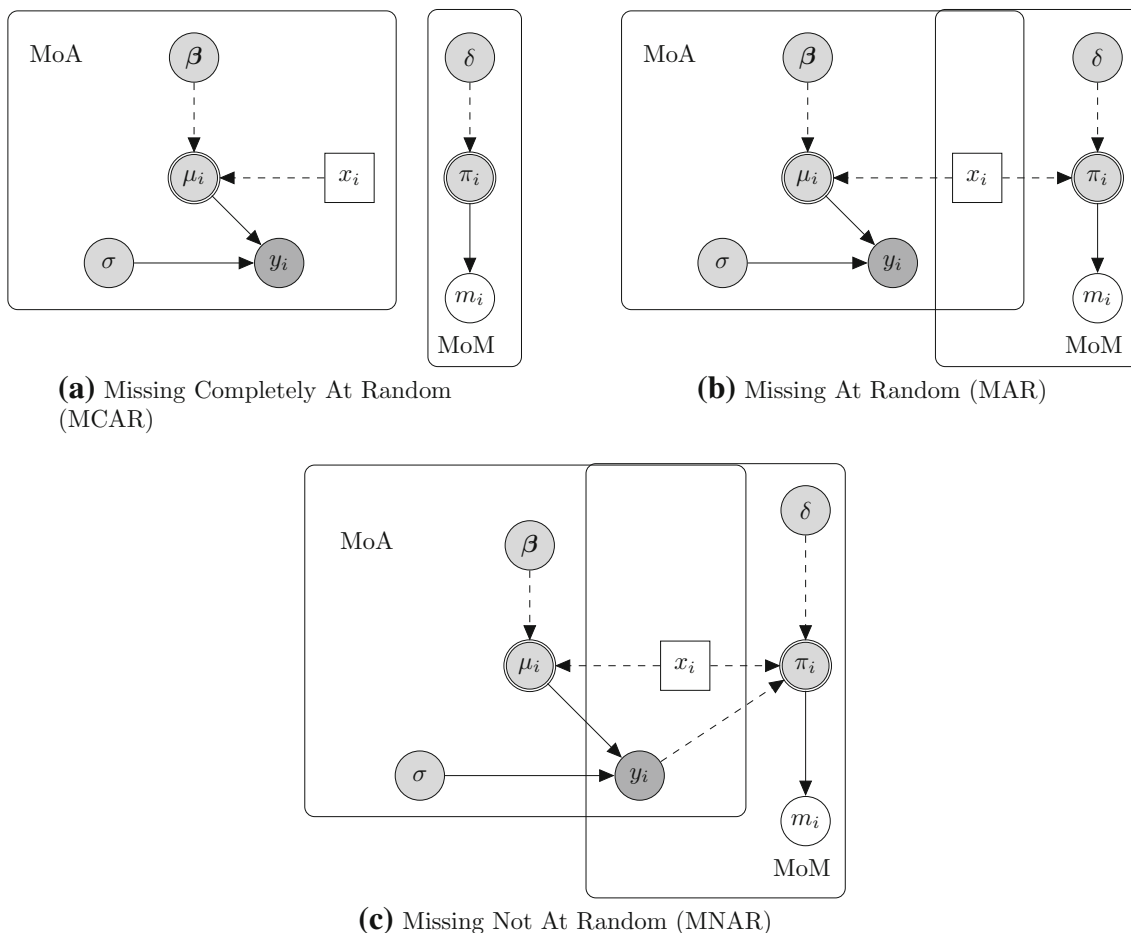
## 2 Missing Data Mechanisms

When analysing partially observed data, it is essential to investigate the possible reasons behind the missingness. This formally translates into an assumed missing data mechanism that is linked to the data generating process, as a key concept to address missingness in a “principled” way. We specifically refer to “principled” methods for missing data as those based on a well-defined statistical model for the complete data, and explicit assumptions about the missing value mechanism.

We consider a sample of  $i = 1, \dots, n$  individuals; for each, the relevant outcome is indicated as  $y_i$ , which is unobserved for some individuals. Typically, trial data also include a set of  $J$  covariates  $\mathbf{x}_i = (x_{1i}, \dots, x_{Ji})$ , e.g. sex, age or co-morbidities. While in general these may be partially or fully observed, in this section we consider only the latter case. In addition, we define a missingness indicator  $m_i$  taking value 1 if the  $i$ th subject is associated with missing outcome and 0 otherwise.

This setting can be modelled using two sub-models, or “modules”. The first module is the missing data mechanism, denoted as model of missingness (MoM). It describes a probability distribution for  $m_i$ , as a function of some unobserved parameters  $\pi_i$  and  $\delta$ , defining the probability of missingness in the outcome variable  $y_i$ . The second module is the data generating process of the outcome variable, denoted as model of analysis (MoA). This contains the main parameters of interest (e.g. the population average costs and benefits) and describes a probability model for the outcome  $y_i$ . As a general example, we can think of a simple regression model where  $y_i \sim N(\mu_i, \sigma)$ , and  $\mu_i = \beta_0 + \beta_1 x_i$ . In this case, the parameters of the MoA are the regression coefficients  $\boldsymbol{\beta} = (\beta_0, \beta_1)$  representing respectively the intercept and the slope, and the individual standard deviation  $\sigma$ .

The most accepted classification of missingness mechanisms is given by Rubin [1] and is based on three classes, according to how the missingness probability in the MoM is modelled. A simple graphical representation of the three classes is provided in Fig. 1. Variables and parameters are denoted by nodes of different shapes and colours according to their nature. Parameters  $(\beta_0, \beta_1, \sigma, \delta)$  are represented through grey circles. “Logical” quantities such as  $\mu_i$  and  $\pi_i$ , which are defined as a function of other parameters, are denoted by a double circle notation. Fully observed variables ( $m_i$ ) are represented with a white circle, while partially observed variables ( $y_i$ ) are denoted by a darker grey



**Fig. 1** Graphical representation of Rubin’s missing data mechanism classes, namely MCAR (a), MAR (b) and MNAR (c). Variables and parameters are represented through nodes of different shapes and colours. Parameters are indicated by *grey circles* with logical parameters defined by *double circles*, while predictor variables are

assumed fixed and drawn as *white squares*. Fully observed variables are denoted by *white circles*, partially observed variables by *darker grey circles*. Nodes are related to each other through *dashed* and *solid arrows* which respectively represent logical functions and stochastic dependence. *MoA* model of analysis, *MoM* model of missingness

circle. Finally, we show covariates ( $x_i$ ) as white squares to indicate that they are fully observed and not modelled. Rounded rectangles are used to show the extent of the two modules in terms of variables/parameters included. Arrows show the relationships between the nodes, with dashed and solid lines indicating logical functions and stochastic dependence, respectively.

Figure 1a illustrates the class of “missing completely at random” (MCAR), in which the probability of missingness is fully independent of any other partially or fully observed variable. Consequently, in Fig. 1a, MoA and MoM are not connected and  $\pi_i$  does not depend on any quantity in the MoA. This amounts to assuming that there is no systematic difference between partially and fully observed individuals in terms of the outcome  $y_i$ . In other words, in this case, we would be assuming that observed cases are a representative sample of the full sample.

Figure 1b shows a case of “missing at random” (MAR), in which the missingness probability may depend on a fully

observed variable. As a result, MoA and MoM are connected by means of the predictor variable affecting both the mechanisms generating  $y_i$  and  $m_i$ . Because of this relationship, the partially observed cases are systematically different from the fully observed cases; crucially, however, the difference is fully captured by  $x_i$ .

Figure 1c provides an example of “missing not at random” (MNAR). This is characterised by dependence of the probability of missingness on both the partially and fully observed variables. Thus, in Fig. 1c,  $\pi_i$  depends on both the fully observed predictor  $x_i$  and the partially observed outcome  $y_i$ . This means that the difference between fully and partially observed cases still depends on the missing values, even after taking  $x_i$  into account. Therefore, it is necessary to make more structured assumptions about this relationship that go beyond the information contained in the data.

While intuitively helpful, this framework may be too simplistic in some cases. Since the scope of this section is to provide a broad overview for Rubin’s classification, we

assumed the simplest case where missingness is present in a single response variable only, which may not hold in real applications. This is particularly likely in the context of CEA, in which we are concerned with a multivariate outcome, made of suitable measures of clinical benefits and costs, i.e.  $y_i = (e_i, c_i)$ . Missingness can occur for either or both the relevant outcomes, and this can lead to as many missingness mechanisms as the number of partially observed quantities (covariate missingness must also be considered). Additional complexity is given by whether data are obtained in a cross-sectional or longitudinal setting, static or time-varying covariates and more importantly the possible correlation between variables and missingness mechanisms and between the mechanisms themselves.

### 3 Approaches to Handle Missing Data

There are many different statistical approaches to deal with missingness, each relying on different assumptions. It is important to carefully select the approach in line with the setting-specific assumptions we assume to hold. For the sake of simplicity here we only broadly categorise these techniques. More in-depth and complete presentation and analysis can be found for example in Molenberghs et al. [4] and Schafer and Graham [25].

#### 3.1 Complete Case Analysis

This is a popular method in within-trial CEA studies, despite its limitations due to the strong assumption that only the fully observed cases are needed in order to correctly make inference. The critical disadvantage is that missing cases are simply discarded, thus reducing efficiency and possibly biasing the parameter estimates.

#### 3.2 Single Imputation

Single imputation (SI) methods replace the missing data with a single predicted value, such as the unconditional or conditional mean or the last value observed for a given case. This category includes last value carried forward [26], linear extrapolation [27], mean and conditional imputation [28]. Although sometimes valid, these methods are never recommended, as they typically require stronger assumptions than MCAR and always fail to take account of the uncertainty underlying the imputation process; i.e. they do not recognise that the imputed values are estimated rather than known.

#### 3.3 Multiple Imputation

A more sophisticated method is multiple imputation [MI, 1]. The underlying idea is to fill in the missing data with

plausible simulated values, drawn from the conditional predictive distribution of the missing given the observed values. Thus, the set of imputations can properly represent the information about the missing values that is contained in the observed data for the chosen model. This is repeated  $K$  times, leading to  $K$  imputed datasets that can be analysed via complete-data methods. The individual estimates are then combined into a single quantity, e.g. using Rubin's rules [1]; this captures the variability within and between imputations. However, the critical aspect is that valid inferences depend on the correct specification of the imputation model in terms of variable selection, distributions and correlations.

#### 3.4 Sensitivity Analysis

Sensitivity analysis (SA) is a technique used to determine how different input values in a model will impact the output, under a given set of assumptions. Missing data will invariably increase the underlying uncertainty, because they induce a lower level of information in the data. SA represents an extremely valuable tool to deal with the uncertainty induced by missingness. Indeed, when applied specifically to missing data, SA corresponds to exploring as many plausible missing data assumptions as possible and then assessing how consistent results are across the different scenarios. In particular, it is generally recommended to set MAR as the reference assumption and then explore different MNAR departures from MAR, to assess the robustness of the results to different plausible alternative missingness mechanisms. The purpose of such analysis is to account more fully for the uncertainty about the missingness. Usually SA is implemented through more advanced methods that are able to explicitly model a MNAR mechanism such as selection or pattern mixture models [4, 30].

#### 3.5 Others

Examples of other less commonly adopted methods that we found in the reviewed articles were: random draw, linear mixed-effects model [31], expectation-maximisation algorithm [32], input-case analysis, assumed zeros and two-part regression.

#### 3.6 Alternatives

There is a long list of possible alternatives that could be explored. Among the most important we refer to inverse probability weighting [33], data augmentation [34], likelihood-based methods [35] and doubly robust [36] and full Bayesian methods [30, 37].

## 4 Recommendations for Missing Data Analyses

The main contribution of this paper to the literature for missing data analysis recommendations is provided by the quality evaluation scheme, as a structured reporting and analysis system which aims to embed all the most important guidelines for authors in terms of missing data handling in CEA. These are listed in Table 1 and summarise the guidelines provided by previous review articles [14, 21–23]. The contribution of the scheme consists in providing a unique, general and structured framework that authors can use to more easily check that all the relevant information about missing data is used to inform the assumptions relating to the missing data in their analysis.

### 4.1 Quality Evaluation Scheme

In order to judge whether missing data in CEAs have been adequately handled, a full description of the missingness problem, details of the methods used to address it and a discussion on the uncertainty in the conclusions resulting from the missingness are required. With this in mind, we have assembled guidelines on how information relating to the missing data should be reported (Table 1). We define three broad categories (description, method, limitations). For each, information that we consider vital for

transparency is listed under “key considerations”, while other details that could usefully be provided as supplementary material are suggested under “optimal considerations”.

Using the list of key considerations in Table 1, one first determines whether no (all key considerations absent), partial (one or more key considerations absent) or full (all key considerations present) information has been provided for each component. From this, one computes a numerical score to summarise the overall information provided on missingness, weighting the components in a ratio of 3:2:1. This weighting scheme has been chosen based on some reasonable assumptions in terms of how the different analysis components could impact the results in terms of missing data handling. Specifically, we think the “limitations” component should not be weighted as much as the other two because of its limited impact on the conclusions. In the same way, we suggest that the “description” should be weighted more than the “method” component, as it generally drives the choice for the initial assumptions about the missingness. We are aware that other weighting schemes could be chosen, but in light of the given considerations, we think the proposed weights are a reasonable choice that we recommend. In addition, the robustness of the scheme to a different weight choice, where each component has exactly the same weight, has been tested to assess the sensitivity of the score assignment. While the

**Table 1** List of information content for each of the three components that one would like to observe in the studies to achieve full analysis reporting of missing data. The contents are divided into two subgroups: key and optimal considerations. The former are the statements to be considered as mandatory for transparency when conducting an economic evaluation in the presence of missing data.

The latter are additional considerations that further extend the analysis reporting of the missing data through supplementary materials. The lack of even one single key consideration is considered to indicate partial analysis reporting, while null analysis reporting is related to the absence of all key considerations

Description	Method	Limitations
<p><b>Key considerations</b></p> <ol style="list-style-type: none"> <li>1. Report the number of individuals with missing data for each variable in the reported analysis by treatment group</li> <li>2. Describe the missing data patterns for all variables included in the economic analysis (is missingness on one variable associated with missingness on another variable? Is there a longitudinal aspect to the data?)</li> <li>3. Discuss plausible reasons why values are missing (e.g. death)</li> </ol>	<p><b>Key considerations</b></p> <ol style="list-style-type: none"> <li>1. Identify a plausible missingness assumption for the specific patterns and setting analysed</li> <li>2. State the method and software used in the base-case analysis</li> <li>3. For more general methods, provide details about their implementation<sup>a</sup></li> <li>4. Perform a plausible robustness analysis; provide and discuss the results</li> </ol>	<p><b>Key considerations</b></p> <ol style="list-style-type: none"> <li>1. Acknowledge and quantify the impact of the missing data on the results</li> <li>2. State possible weaknesses and issues with respect to the method and assumptions</li> </ol>
<p><b>Optimal considerations</b></p> <ol style="list-style-type: none"> <li>1. Provide supplementary material about the preliminary analysis on missingness (e.g. descriptive plots and tables)</li> </ol>	<p><b>Optimal considerations</b></p> <ol style="list-style-type: none"> <li>1. Provide supplementary material about the method implementation in the base-case and robustness analysis (e.g. software implementation code)</li> </ol>	

<sup>a</sup> For example, in multiple imputation, state the imputation model specification and variables included, the number of imputations, post imputation checks

results do not show any significant changes in the classification of the articles, when using the alternative scheme, it is more difficult to discriminate across the articles due to a more limited score range.

Finally, one converts the scores into grades A–E. The relevance of the scores, and of the derived grades, in terms of decision analysis is mainly associated with a qualitative assessment of the articles. Studies that are graded in the top categories should be associated with a higher degree of confidence in their results, whereas more caution should be taken in the consideration of results coming from studies that are graded in the bottom categories. When qualitatively assessing the articles, the different grading assigned to each of them could be an indication of a lack in the robustness of the conclusions provided due to missingness uncertainty.

Figure 2 shows the process and weights used. Although the importance between the different components is subjective, we believe that the chosen structure represents a reasonable and relatively straightforward assessment scheme.

The resulting scores can be interpreted as follows:

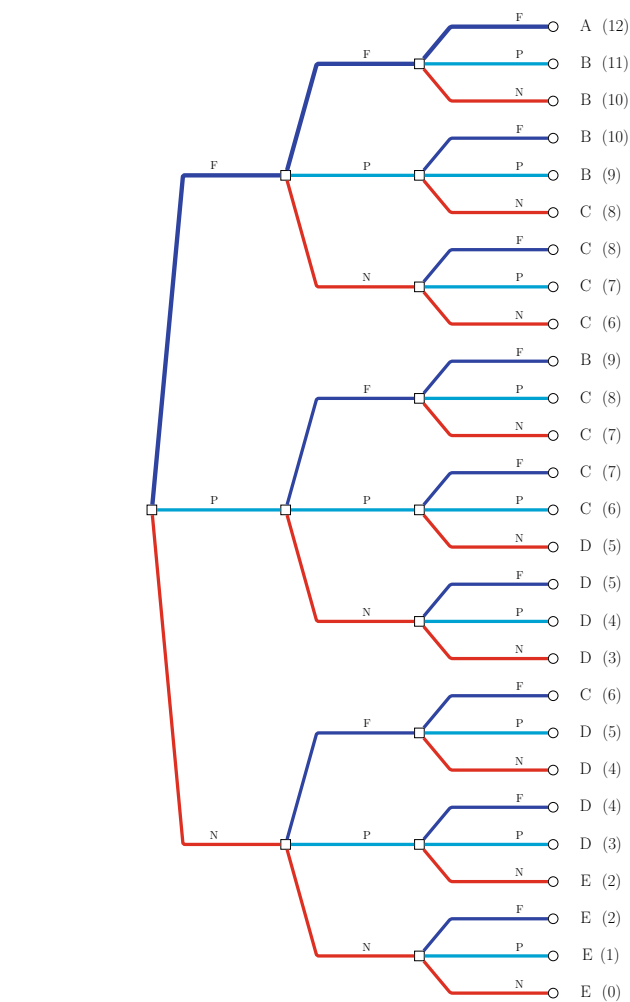
**A (12)** The highest quality judgement, identified by the upper thicker blue path in Fig. 2, including only those studies that simultaneously provide all the key considerations for all the components. It is the benchmark for a comprehensive explanation and justification of the adopted missing data method.

**B (9–11)** Includes studies providing full details for either the description or the method and at least partial information for the other components. Studies with no information about the limitations are only included in this category if full detail is provided for both the other components.

**C (6–8)** Studies for which information about missingness is not well spread across the components. All key considerations are provided either for the description or the method, but with only partial or no content in the other components. Alternatively, we can have partial content for description and method, and partial or full content for limitations.

**D (3–5)** Indicates a greater lack of relevant information about missingness. Despite possibly including key considerations on any of the components, the information provided will at most be partial for the description, in which case it will be combined with a total lack of content on either the method or the limitations.

**E (0–2)** The worst scenario, where the overall information about the missing data is considered to be totally unsatisfactory. No description is given, and we can observe at most only some of the key considerations for the method.



CONTENT \ SCORE	Description	Method	Limitations
Full (F)	6	4	2
Partial (P)	3	2	1
Null (N)	0	0	0

**Fig. 2** Diagram representation for the quality score categories. The table at the bottom shows how scores have been weighted according to the information provided on each component. In accordance with the table, different branches of the diagram correspond to different components. From left to right, the initial branches are related to the description, branches in the middle to the method, and final branches to the limitations. The branches' colour represents the different way the information provided in each analysis component is evaluated: red no information (N), light blue partial information (P), blue full information (F). Final scores (0–12) with associated ordered categories (E–A) show the overall level of information provided for each combination of component and content evaluation

## 5 Literature Review

### 5.1 Methods

Noble et al. [22] (henceforth NHT) reviewed the methods used to handle missing cost measures in 88 articles published during the period 2003–2009. We extend their

review, to include missing effects. Further, we use NHT's strategy to identify papers in the subsequent period, 1 April 2009 to 31 December 2015. Articles were considered eligible for the review only if they were cost-effectiveness analyses within RCTs, used individual patient-level data and mentioned missing data in the text. We relied on the search engines of three online full-text journal repositories: (1) Science-Direct.com, (2) bmj.com, and (3) The Database of Abstracts of Reviews of Effects (DARE) and NHS Economic Evaluation Database (NHS EED). The key words used in the search strategy were (cost effectiveness OR economic evaluation) AND missing data AND trial AND (randomised OR randomized). The on-line databases identified 1129 articles, most of which were duplicates. After abstract review, 128 articles were considered, of which 81 fulfilled the eligibility criteria.

We present and compare the articles reviewed for the two periods by type of analysis performed. First, we look at the base-case methods implemented, i.e. those used in the main analysis embedding the assumptions about missing data. Second, we consider any alternative methods discussed; when present, these assess the robustness of the results obtained in the main analysis against departures from the initial assumptions on missingness.

## 5.2 Base-Case Analysis

As shown in Fig. 3a, NHT found that CCA was the most popular base-case method, used in 31% of the papers; 23% were unclear about the technique adopted. Single imputation methods were well represented, with mean imputation and conditional imputation used in 10 and 9% of the articles, respectively. MI was found in 9% of the articles. Our analysis of the methods for missing effectiveness measures shows a similar pattern in Fig. 3c. CCA was used in 27% of the cases and with a sizeable proportion of papers unclear about the technique adopted (24%). Single imputation methods are here dominated by last value carried forward (LVCF) (10%), while a slightly higher proportion uses MI (15%).

In 2009–2015, MI replaces CCA as the most frequently used base-case method in both costs and effects, at 33 and 34%, respectively (Fig. 2b, d). However, CCA is still the method of choice in many papers (15% for costs and 21% for effects). The proportion of papers that are unclear about the chosen method is similar over the two time periods for costs, but halves in the later period for effects. This is plausible since clinical effectiveness measures and the estimate of treatment effect have been the main focus of the analyses, whereas costs are less frequently included as a primary outcome in the study research questions. This will translate into a more careful and reasoned examination of

the missingness problem in the effect compared with the cost analysis.

## 5.3 Robustness Analysis

With the term “robustness analysis” we refer to a different concept with respect to the one introduced in Sect. 3.4. In particular, we make this distinction so we can specifically refer to robustness analysis as any alternative analysis, compared with the base-case analysis, based on different missing data methods. By contrast, when applied to missing data, SA can be thought of as structurally varying the assumptions about the missingness model, whose plausibility can be assessed in light of known information.

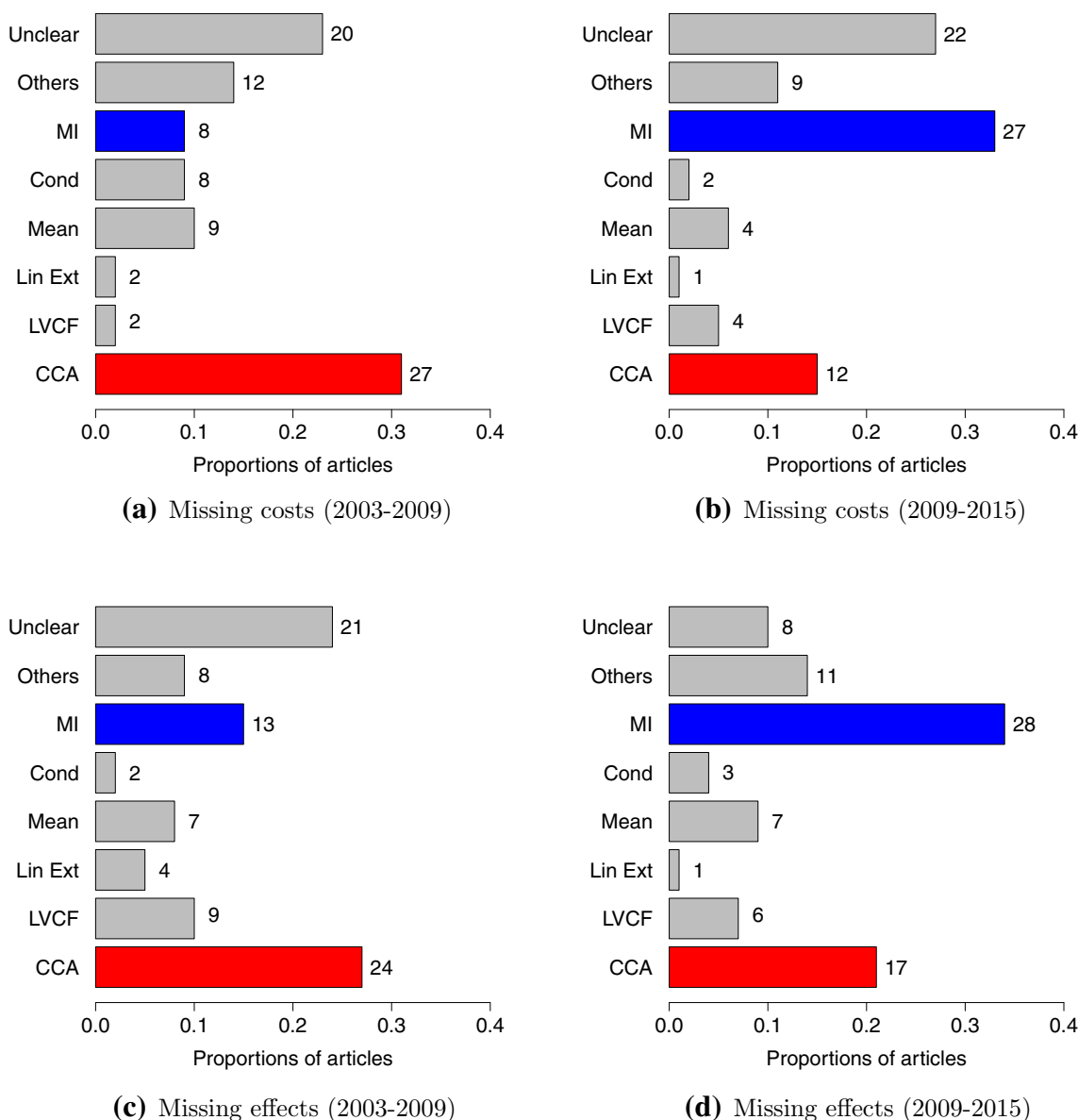
However, in practice, even robustness analyses are rarely performed in CEAs. This poses an important question related to the reliability of the findings, as they may be affected by the specific assumptions about the missing data. From both review periods it seems that a robustness analysis is infrequently used and typically involves only one alternative scenario. This is not likely to be an optimal choice as the main objective of this analysis is to explore as many plausible alternative missing data assumptions as possible.

NHT found that 75% (66/88) of the articles did not include any robustness analysis, with the remaining papers typically performing an analysis by comparing CCA and MI (based on missing costs only). Similar findings apply to missing effects, with about 76% (67/88) of the studies lacking any alternative missing data method. Similarly, in the 2009–2015 review, we observe no robustness analysis in the majority of the articles for both costs (75% or 61/81) and effects (70%, 51/81).

Figure 4 provides a pictorial overview of the alternative methods used for cost and effect data. For costs, most articles describe no alternative analysis. In the earlier period, the choice of alternative missingness methods seems well spread across CCA, MI and the use of more than one method, with a slightly more frequent adoption of MI. By contrast, in the later period, more cases use CCA as a robustness method in combination with MI as the base-case method.

Figure 4c, d describes the effects, with most of the articles not reporting any robustness analysis and with a significant decrease in MI analyses used for robustness, opposed to an increase in CCA, between the two periods. There is a similar pattern to the cost graphs towards CCA used as a robustness method in combination with MI as the base-case method.

One of the possible reasons that lead authors to use CCA as a robustness method is its simplicity of implementation. Although in many cases its underlying assumptions may not be credible, authors may use it to make comparisons



**Fig. 3** Review of base-case methods used to handle missing cost and effect data between 2003–2009 and 2009–2015. Legend: complete case analysis (CCA), last value carried forward (LVCF), linear extrapolation (Lin Ext), mean imputation (Mean), conditional imputation (Cond), multiple imputation (MI), any other method present in fewer than four articles (Others), unspecified method (Unclear). The category “Unclear” includes those articles for which it was not

with the base-case method as it is a quick and easy-to-perform alternative option.

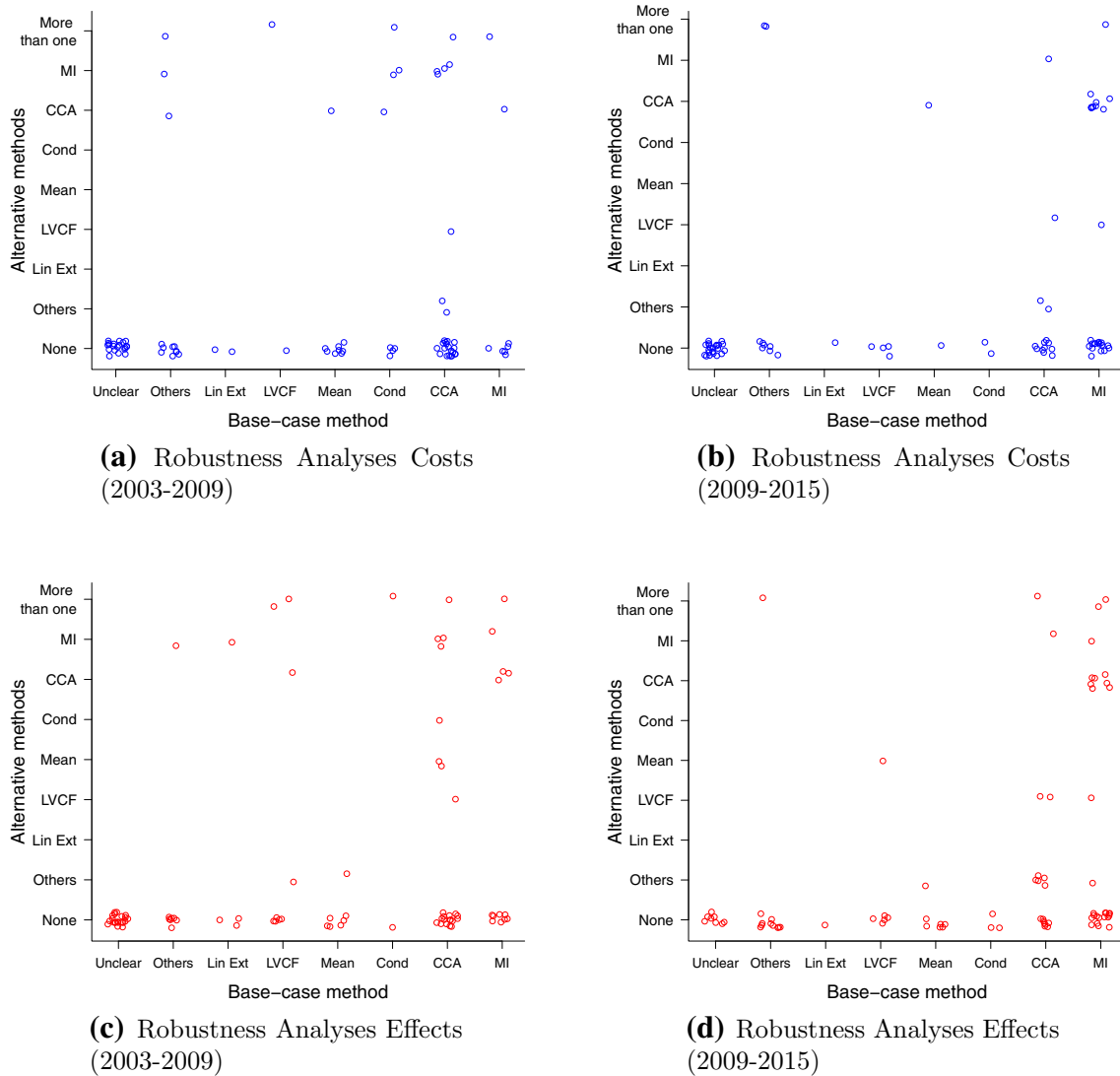
## 6 Grading the Articles

Comparing the information provided in the articles in our review against the list given in Sect. 4.1 allows us to qualitatively assess the quality of the reporting of how missingness has been handled in the reviewed CEA studies.

possible, based on the text, to understand the methodology used to deal with the missingness, while the category “Others” consists of the following methods: random draw, linear mixed-effects model, expectation-maximisation algorithm, input-case analysis, assumed zeros, two-part regression. The numbers to the right of the bars in the graphs are the number of papers including the corresponding method in the base-case analysis

To gain a fuller understanding of the current state of play, we also classify the articles from the perspective of the strength of the assumptions about the missingness mechanism. This is related to the choice of method, since each is underpinned by some specific missing data assumption. We can view the quality judgement and strength of assumptions as two dimensions providing a general mapping of how the missingness problem is handled. This applies to both the level of knowledge about the implications of a given missingness assumption on the





**Fig. 4** Comparison of methods used in the base-case analysis (x axis) and those used as alternatives in a robustness analysis (y axis) for the articles between 2003–2009 and 2009–2015 for missing costs and effects. Legend: unspecified methods (Unclear), other methods (Others), linear extrapolation (Lin Ext), last value carried forward (LVCF), mean imputation (Mean), conditional imputation (Cond), complete case analysis (CCA), multiple imputation (MI). The

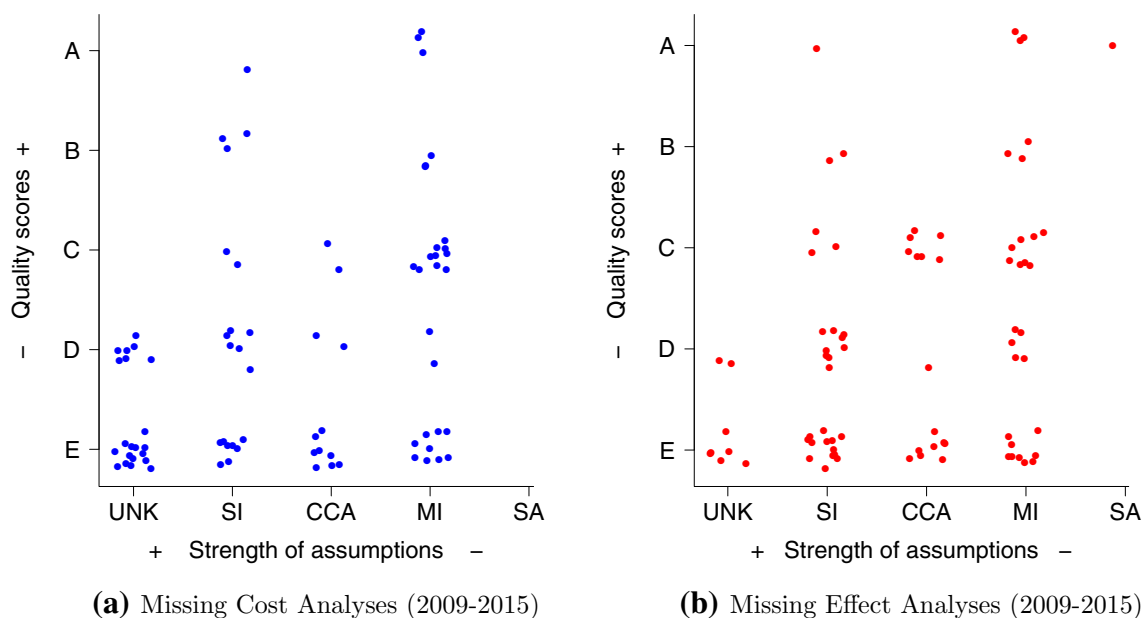
category “Unclear” includes those articles for which it was not possible, based on the text, to understand the methodology used to deal with the missingness, while the category “Others” consists of the following methods: random draw, linear mixed-effects model, expectation-maximisation algorithm, input-case analysis, assumed zeros, two-part regression

results and how these are translated into the chosen method. Details of our evaluation of both aspects are provided next, starting with the strength of assumptions.

We group the methods into five categories, broadly ordered according to the strength of the associated missingness assumptions. These are: single imputation (SI); complete case analysis; multiple imputation; and unknown (UNK), a residual group in which we classify studies that do not explicitly mention the method used. We associate this class with the strongest level of assumptions, since the lack of any method description may implicitly suggest (over-)confidence in a small effect of missingness on the results. By

contrast, we define sensitivity analysis (SA) as the least restrictive approach, which can assess the robustness of the results to different alternative missing data assumptions.

Figure 5 gives a graphical representation of both aspects for the articles reviewed between 2009–2015 in terms of the assumptions and justifications (quality scores) on missingness. In both graphs, more studies lie in the lower than in the upper part, indicating that fewer studies can be classified as high quality in terms of the considerations about missingness. This is highlighted by a greater concentration of points at the bottom of the figures (grade E). As we move along the vertical axis, this tends to reduce up



**Fig. 5** Joint assessment, in the reviewed articles between 2009–2015, for missing costs and effects, of two components. The *x*-axis is the missingness method assumptions: unknown (UNK), single imputation (SI), complete case analysis (CCA), multiple imputation (MI) and

sensitivity analysis (SA). The *y*-axis is the ordered classification for the quality judgement (scores) to support these assumptions: *E, D, C, B, A*

to the top level (grade A), where only very few cases are shown. Of particular interest is the (almost) total absence of articles that performed a sensitivity analysis (SA), clearly indicating very slow uptake of this technique.

A shift along the vertical axis in the graphs indicates an increase in the level of understanding about the implications for the results of different choices of the missing data assumptions. Therefore, we can argue that an upward movement in the plot will always improve the justification of a specific assumption. However, to be able to follow this path, we may have to rely on more sophisticated methods that can match the given missingness assumption; e.g. if we think our data are MNAR, then CCA assumptions are less likely to hold. The aim of an optimal analysis should be to select a method that can be fully justified by matching the description of the missing data problem to the assumptions underpinning the chosen method, i.e. map onto the upper section of the graphs.

As a concrete example about the importance of exploring different missingness assumptions in terms of the impact they may have on the CEA, we consider one of the reviewed studies that has been graded as “A” by our scheme [187]. The authors provide an assessment of the probability of accepting a given treatment against a comparator (CEAC) for different willingness to pay thresholds and missingness methods. For all the thresholds considered, substantial uncertainty is reflected by significant variations in the CEAC values according to the different missing data methods used. Specifically, the incorporation of external information leads

to missingness assumptions that significantly affect the uncertainty in the results, producing a decrease in the value of the CEAC, at the target willingness to pay threshold, from 71% in the base-case (CCA) to 53% in one alternative scenario (MI). This example should encourage authors to recognise the importance that a comprehensive examination of missingness via SA may have on the uncertainty around CEA conclusions.

## 7 Discussion

The objective of this paper is to critically appraise the issue of missing data analysis in within-trial CEAs. In addition, we aim at providing a set of recommendations to guide future studies towards a more principled handling and reporting of missingness. It is important that assumptions about missing data are clearly stated and justified. Sensitivity analysis is also important, in order to explore the impact of plausible alternative missing data assumptions on the results of the CEA. Often, a variety of techniques and analyses are used but not reported because of space limits; on-line appendices and supplementary material could be used to report these alternatives.

### 7.1 Descriptive Review

Figure 3 highlights a shift in the most popular base-case missingness method from CCA to MI, between the two

periods of the review. The reasons behind this change may be related to some drawbacks of CCA and the relatively recent wide development of software to perform MI.

First, even under a strong missing data assumption such as MCAR, CCA remains inefficient because it ignores the predictive information contained in the partially observed cases. Non-negligible rates of missingness on a few variables of interest may cause large portions of the sample to be discarded. Second, CCA may cause serious biases in the parameter estimates. Indeed, the condition for validity of CCA does not fit neatly into Rubin's classes [38] in the important cases when: missing data affect the covariates; or the partially observed outcome has a longitudinal nature.

Arguably, a very important factor in the increasing popularity of MI is the recent availability of specific computer routines or packages (e.g. STATA or R; see [2]). This probably led to some abuse of the method as noted by Molenberghs et al. [4]. On the one hand, MI generally allows the inclusion of a larger number of variables/predictors in the imputation model than used in the analysis model, which potentially makes the assumption of MAR more plausible and thus the overall analysis less likely to be biased. On the other, the performance of MI depends on the correct specification of the imputation model (i.e. complexity in the analysis model is reflected in the imputation model) and care is required in its construction. Although essential, these details can be overlooked and are not often included in the reporting of the analysis, undermining its reliability.

From the comparison of the base-case methods used for the costs and effects between 2009 and 2015 (Fig. 3), we observe a marked reduction in the number of methods not clearly described for the effects, compared with those for the costs. A possible reason for this is that, while clinical effectiveness measures are often collected through self-reported questionnaires, which are naturally prone to missingness, cost measures rely more on clinical patient files, which may ensure a higher completeness rate. It was not possible to confirm this interpretation in the reviewed studies due to the high proportions of articles not clearly reporting the missing rates in both 2003–2009 and 2009–2015 periods, for effect ( $\approx 45$  and  $\approx 38\%$ ) and cost data ( $\approx 50$  and  $\approx 62\%$ ). In addition, clinical outcomes are almost invariably the main objective of RCTs, and as such they are usually subject to more advanced and standardised analyses. Arguably, costs are often considered as an add-on to the standard trial: for instance, sample size calculations are almost always performed with the effectiveness measure as the only outcome of interest. Consequently, missing data methods are less frequently well thought through for the analysis of the costs. However, this situation is likely to change as cost data from different perspectives (e.g.

caregivers, patients, society, etc.) are being increasingly used in trials, leading to the more frequent adoption of self-report cost data, which may start to exhibit similar missingness characteristics to effect data.

Our review identified only a few articles using more than one alternative method (Fig. 4). This situation indicates a gap in the literature associated with an under-implementation of sensitivity analyses, which may significantly affect the whole decision-making process outcome, under the perspective of a body who is responsible for providing recommendations about the implementation of alternative interventions for health care matters.

Limiting the assessment of missingness assumptions to a single case is unlikely to provide a reliable picture of the underlying mechanism. This, in turn, may have a significant impact on the CEA and mislead its conclusions, suggesting the implementation of non-cost-effective treatments, whose definition will depend on the assumption the modeller thinks is more likely to hold in the given setting. Sensitivity analysis represents an important tool to properly account for more structured uncertainty related to the missing data, and its implementation may provide a more realistic picture of the impact that the assumptions have on the final conclusions.

## 7.2 Quality Assessment

Despite the fact that our quality evaluation scheme has not been tested/validated by independent assessors, we believe Sect. 4.1 provides some reasonable justification for its application to the reviewed articles. Generally speaking, most papers in our review achieved an unsatisfactory quality score under our classification (Fig. 5). Indeed, our benchmark area on the top-right corner of the graphs is barely reached by less than 7% of the articles, for both cost and effect data. The opportunity of reaching such a target might be precluded by the choice of the method adopted, which may not be able to support less restrictive assumptions about missingness, even when this would be desirable. As a result, when simple methods cannot be fully justified, it is necessary to replace them with more flexible ones that can relax assumptions and incorporate more alternatives. In settings such as those involving MNAR, sensitivity analysis might represent the only possible approach to account for the uncertainty due to the missingness in a principled way. However, due to the lack of studies either performing a SA or providing high quality scores on the assumptions, we argue that missingness is not adequately addressed in most studies. This could have the serious consequence of imposing too restrictive assumptions about missingness and affect the outcome of the decision-making process.

We suggest that authors may use Table 1 as a convenient tool to check that all relevant information on missing data is taken into account in determining the assumptions in the analysis. All the key considerations should be fully satisfied, if possible. These criteria summarise previously published missing data recommendations from various settings, drawing them together within a general, simple and easy-to-read checklist table.

The classification of the studies into ordered categories (Fig. 2) according to the information provided on missing data (Table 1) is potentially a valuable tool for meta-analysis. The proposed quality evaluation scheme could be used by analysts to assign scores and grade individual studies based on their overall quality level in terms of missingness handling. These grades could then be taken into account in assigning different weights to the individual studies within the meta-analysis framework, in order to reflect a different degree of confidence in their results.

### 7.3 Conclusions

Given the common problem of missing effect and cost data in within-trial CEAs, many study conclusions could be based on imprecise economic evidence. This is a potentially serious issue for bodies such as the National Institute for Health and Care Excellence (NICE) who use these evaluations in their decision making, thus possibly leading to incorrect policy decisions about the cost-effectiveness of new treatment options.

Our review shows, over time, a significant change from more to less restrictive methods in terms of the assumptions on the missingness mechanism. This is an encouraging movement towards a more suitable and careful missing data analysis. Nevertheless, improvements are still needed, as only a small number of articles provide transparent information or perform a sensitivity analysis.

Our guidelines could represent a valuable tool to improve missing data handling. By carefully thinking about each component in the analysis, we are forced to explicitly consider all the assumptions we make about missingness and assess the impact of their variation on final conclusions. The main advantage is a more comparable formalisation of the uncertainty as well as a better indication of possible issues in assessing the cost-effectiveness of new treatments.

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preparation and contributed to the construction of the recommendations and preparation of the review. All authors contributed to and approved the final version of the manuscript.

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