



Universiteit
Leiden
The Netherlands

Ordinal outcome analysis improves the detection of between-hospital differences in outcome

Ceyisakar, I.E.; Leeuwen, N. van; Dippel, D.W.J.; Steyerberg, E.W.; Lingsma, H.F.

Citation

Ceyisakar, I. E., Leeuwen, N. van, Dippel, D. W. J., Steyerberg, E. W., & Lingsma, H. F. (2021). Ordinal outcome analysis improves the detection of between-hospital differences in outcome. *Bmc Medical Research Methodology*, 21(1). doi:10.1186/s12874-020-01185-7

Version: Publisher's Version

License: [Creative Commons CC BY 4.0 license](https://creativecommons.org/licenses/by/4.0/)

Downloaded from: <https://hdl.handle.net/1887/3247847>

Note: To cite this publication please use the final published version (if applicable).

RESEARCH ARTICLE

Open Access



Ordinal outcome analysis improves the detection of between-hospital differences in outcome

I. E. Ceyisakar^{1*} , N. van Leeuwen¹, Diederik W. J. Dippel², Ewout W. Steyerberg^{1,3} and H. F. Lingsma¹

Abstract

Background: There is a growing interest in assessment of the quality of hospital care, based on outcome measures. Many quality of care comparisons rely on binary outcomes, for example mortality rates. Due to low numbers, the observed differences in outcome are partly subject to chance. We aimed to quantify the gain in efficiency by ordinal instead of binary outcome analyses for hospital comparisons. We analyzed patients with traumatic brain injury (TBI) and stroke as examples.

Methods: We sampled patients from two trials. We simulated ordinal and dichotomous outcomes based on the modified Rankin Scale (stroke) and Glasgow Outcome Scale (TBI) in scenarios with and without true differences between hospitals in outcome. The potential efficiency gain of ordinal outcomes, analyzed with ordinal logistic regression, compared to dichotomous outcomes, analyzed with binary logistic regression was expressed as the possible reduction in sample size while keeping the same statistical power to detect outliers.

Results: In the IMPACT study (9578 patients in 265 hospitals, mean number of patients per hospital = 36), the analysis of the ordinal scale rather than the dichotomized scale ('unfavorable outcome'), allowed for up to 32% less patients in the analysis without a loss of power. In the PRACTISE trial (1657 patients in 12 hospitals, mean number of patients per hospital = 138), ordinal analysis allowed for 13% less patients. Compared to mortality, ordinal outcome analyses allowed for up to 37 to 63% less patients.

Conclusions: Ordinal analyses provide the statistical power of substantially larger studies which have been analyzed with dichotomization of endpoints. We advise to exploit ordinal outcome measures for hospital comparisons, in order to increase efficiency in quality of care measurements.

Trial registration: We do not report the results of a health care intervention.

Keywords: Between-hospital variation, Observational data, Comparative effectiveness research, Statistical power, Ordinal outcome analysis, Proportional odds analysis, Benchmarking

* Correspondence: iris.kohen@gmail.com

¹Centre for Medical Decision Making, Department of Public Health, Erasmus MC - University Medical Center, PO Box 2040, 3000, CA, Rotterdam, The Netherlands

Full list of author information is available at the end of the article



© The Author(s). 2020 **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

Background

There is an ever-growing demand for information on performance of hospitals to improve quality of care [1]. Clinical outcomes are commonly used to determine which hospitals are allegedly performing better or worse, and which are to be labelled as potential outliers [2, 3]. However, comparing outcomes between hospitals has its limitations. The observed differences in outcome between hospitals are often partly due to chance [4] and are only partly explained by actual differences in the quality of care [5]. Lack of power to detect differences between hospitals is a common problem for several clinically relevant outcome indicators. For example, complication rates are generally low and the small number of events leads to underpowered statistical analyses [6, 7]. Furthermore one of the most commonly used clinical measures is the (standardized) mortality ratio (SMR) [8, 9], which has a variety of disadvantages and methodological issues when used as a quality of care measure [10–12]. The main issue being that mortality is an especially rare outcome in many patient groups, leading to low power when trying to detect hospitals with aberrant outcomes [13].

Many clinical continuous or ordinal outcome scales do exist and are recorded, but these are often dichotomized (favorable and unfavorable) in quality of care comparisons, for reasons of simplicity. Examples of ordinal outcome measures are the modified Rankin Scale (for stroke), the Glasgow Outcome Scale (for Traumatic Brain Injury (TBI)), the Guillain Barré syndrome disability score, the NYHA Functional Classification (for heart failure) and the Rutherford Classification (for peripheral artery disease). Dichotomization has been shown to lead to a loss of clinically and statistically relevant information in several studies [14–17] while analysis on the full ordinal scale with proportional odds analysis, prevents this loss of information [18, 19]. Simulation studies and empirical validation studies in clinical trials have demonstrated that ordinal analysis increases statistical power compared to binary outcome analysis [18–21]. For clinical trials it has already been advised not to dichotomize ordinal outcome scale but to exploit the full ordinal nature of the scale, to allow for detection of smaller treatment effects [15, 19]. However, this potential gain in efficiency has not been assessed for hospital comparisons.

Our aim, therefore, is to quantify the gain in power, or reduction in sample size, that can be achieved by using ordinal compared to dichotomous outcomes as a measure of quality of care for hospital comparisons.

Methods

Simulation studies were performed with patients sampled from two databases. The databases consisted

of hospital data of patients with either TBI in the International Mission on Prognosis And Clinical Trial Design in Traumatic Brain Injury (IMPACT) study [22], and stroke patients in the PRomoting ACute Thrombolysis in Ischemic Stroke (PRACTISE) trial [23].

The IMPACT study was a project was organized as a collaborative venture between the Erasmus University in Rotterdam, The Netherlands, the University of Edinburgh, Scotland, and the Virginia Commonwealth University Medical College in Richmond, Virginia in order to collect data from available randomized controlled trials (RCTs) and observational studies in TBI conducted between 1984 and 2007. Although inclusion criteria differed for the different RCTs data extraction was guided by a data dictionary to standardize the format of variables entered into data set, to guarantee the quality of the data.

The PRACTISE study is a national cluster-randomised-controlled trial. All patients > 18 years with acute stroke who were admitted to the hospital within 24 h from onset of symptoms were included in the trial. Patients admitted within 4 h were assessed in detail and were followed up to 3 months after onset by telephone. Twelve hospitals participating hospitals were assigned to the regular or high-intensity intervention.

We sampled patients from the original data sets and the patients were appointed to one of the 250 fictitious hospitals. The simulations included two scenarios, one in which the hospital influenced the outcome of the patient (A) and one in which outcome of the patient was completely independent of the hospital (B). In the first scenario (A) hospitals were given a “center effect”; a coefficient for the effect of hospital on outcome drawn from a normal distribution with $m = 0$ and $SD = 0.35$. The true outcomes of the hospitals all differed from 0, as can be seen in Fig. 1a. This meant that patients from one hospital had a higher chance of a good outcome than those of another [20], i.e. that ‘true’ hospital differences in outcome existed. Analysis of scenario A was done to determine the sensitivity (type II error) which could be achieved using either ordinal outcomes or dichotomized outcomes. Since all hospitals were assigned a center effect, the analysis which found the most hospitals with performances deviating from the mean had the best sensitivity for an effect.

In scenario B specificity was tested (Fig. 1b) by checking if the analyses did not find more than 5% of differently performing hospitals when there was no true difference in hospital performance.

To simulate outcomes, a multinomial generalized logit regression model was fitted to predict the probability for

Illustration of the data generation process of hospital effects

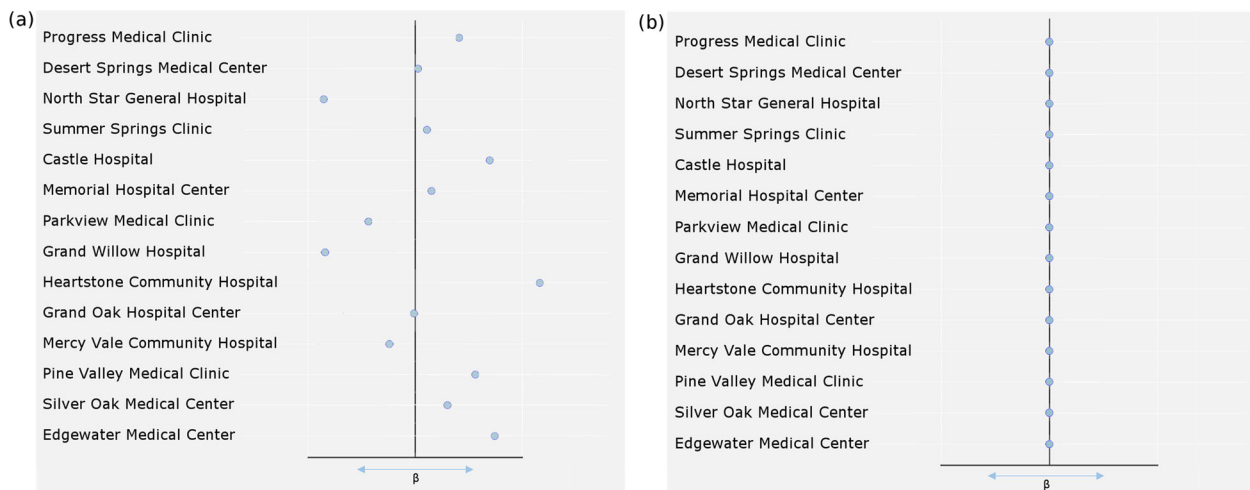


Fig. 1 Illustration of the data generation process for testing specificity and sensitivity: (a) when a center effect is added (β), resulting in every hospital performing to different degrees, better or worse than the mean (b) without a hospital effect added ($\beta = 0$) all hospitals perform the same

outcomes for each patient based on the given baseline covariates. Furthermore, in scenario A the probability for outcome was either increased or decreased depending on the hospital the patient was in.

For the baseline covariates of the TBI patients well known prognostic baseline characteristics were used: Glasgow Coma Scale (GCS) motor score, age and pupillary reactivity (both pupils reactive, one pupil reactive, no pupil reactivity) [22]. In the stroke data the following covariates were used: baseline National Institute of Health Stroke Scale (NIHSS) score, age, history of ischemic stroke, atrial fibrillation, an diabetes mellitus [23].

In TBI, we used the 5-point ordinal Glasgow Outcome Scale (GOS) at 6-months as an outcome measure (Fig. 2a). For stroke, we used the modified Rankin Scale (mRS) at 3 months, a 7-point ordinal scale (Fig. 2b). These are the most commonly used outcome measures for these conditions. In both scales, the worst disability state and death were combined for ethical reasons, resulting in a 4-point outcome scale for TBI, and a 6-point outcome scale for stroke [19, 23, 24]. Both ordinal outcome measures were thereafter dichotomized, into favorable (good recovery or moderate disability) and unfavorable outcome (severe disability, vegetative state and death) as well as dichotomized for mortality (including severe disability). Dichotomization for mortality was done to illustrate the case in which only mortality rates are measured.

To demonstrate the differences in sensitivity to detect hospital outliers the simulation was repeated with different number of patients per hospital, ranging from 25 to

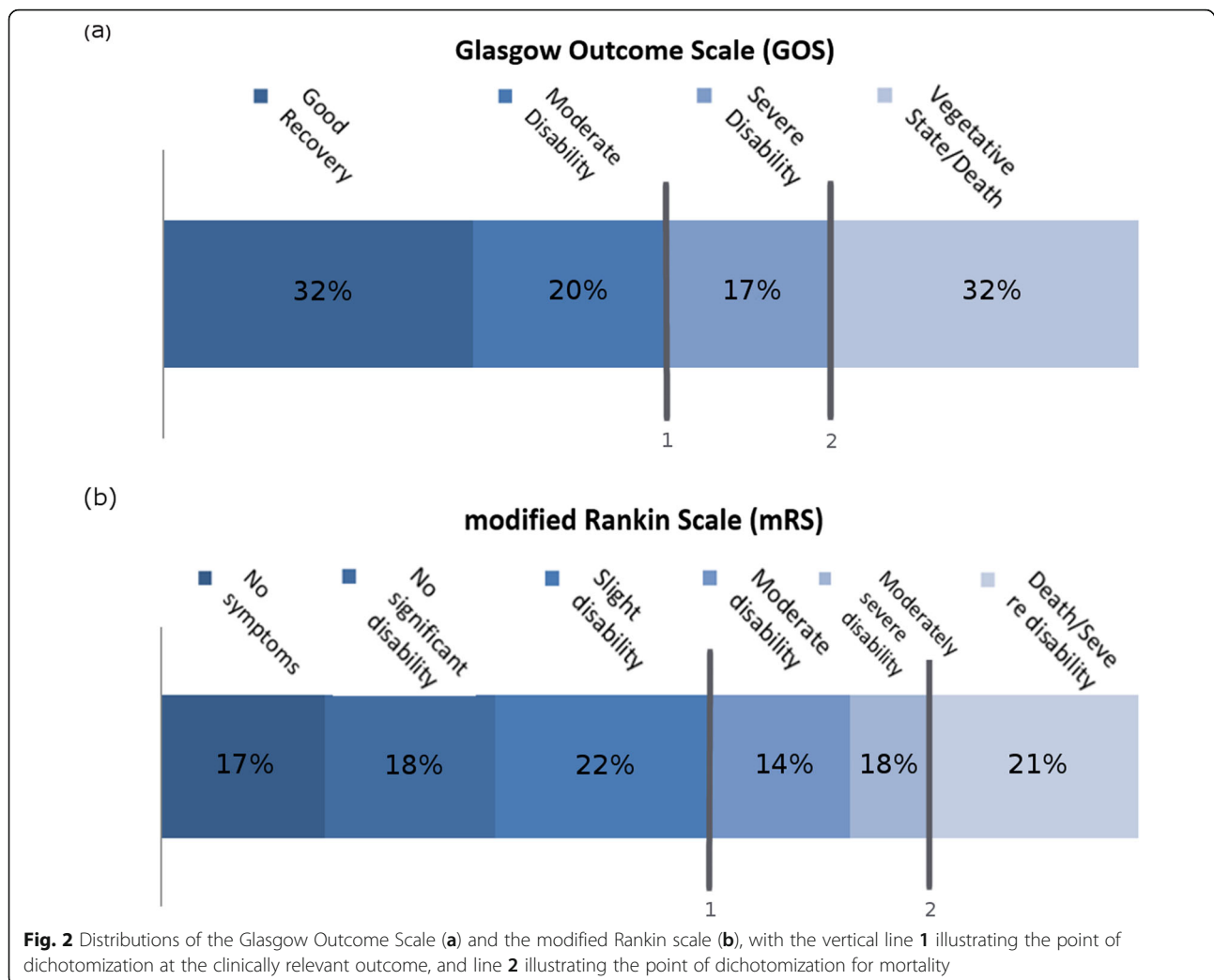
200, which were distributed over 250 hospitals. Simulations were run 500 times.

Analysis

Outcomes were analyzed on (1) an ordinal scale, (2) dichotomized as favorable vs. unfavorable outcomes, and (3) dichotomization for death vs. alive. The binary outcomes were analyzed with standard fixed effect logistic regression models, the ordinal outcomes were analyzed with proportional odds fixed effect logistic regression models [25, 26]. All models were adjusted for previously mentioned baseline covariates based on which the outcomes had been predicted, and included hospital as a categorical variable. This yielded an estimated center effect per hospital compared to mean center effects. Hospitals with predicted center effect values outside the 95% confidence intervals (CIs) of the overall mean were scored as outliers.

The ability of the model to determine which hospitals were outliers was measured by counting how many outliers the analysis would find in different scenarios. This means that in scenario A, the analysis which found the most outliers was determined as the most sensitive, and in scenario B the analyses were meant to have less than 5% outliers.

Higher power in the analyses results in higher rate of correctly identified outliers. Therefore, we could translate the ability to find outliers to the possibility of sample size reduction. The ability of regression models to determine which hospitals had aberrant outcomes, given dichotomized and ordinal outcomes



was expressed in potential efficiency gains. The difference between ordinal and dichotomized outcomes was expressed as potential efficiency gain: the possible reduction in sample size while keeping the same statistical power to detect outliers. All analyses were done using R Statistical Software 3.3.0. The script can be found in [Appendix \[27–33\]](#).

Results

The IMPACT study included data from eight randomized controlled trials and three observational studies [22]. Data from 9578 patients was used, which came from 265 different centers, which admitted between 1 and 453 patients, which were mostly (78%) male, and had a median age of 30 (interquartile range (IQR): 21–45) (Table 1).

The PRACTISE trial was a cluster randomized trial of studying the implementation of IV thrombolytic

treatment in the Netherlands. It included observational data of 1657 patients in 12 centers [23]. Hospitals had a minimum of 28 and maximum of 310 patients, who had a median age of 73 (IQR: 62–80) (Table 2).

In the IMPACT study 4949 (52%) of the patients had a favorable outcome and 4629 (48%) had an unfavorable outcome. Of these, 3031 (32%) were in vegetative state or died (Fig. 2). In the PRACTISE trial 933 (56%) of the patients had a favorable outcome and 724 (44%) had an unfavorable outcome. Of these, 351 (21%) were in severely disabled state or died.

Sensitivity

More patients per hospital increased the percentage of hospitals which are correctly found to be deviant from the mean (Fig. 3). Further, use of ordinal outcomes instead of dichotomized for favorable versus unfavorable outcome allowed for less patients in the

Table 1 Baseline characteristics of patients enrolled in the IMPACT study

	n = 9578
Age (median, IQR)	30 (21–45)
Sex	
Male (N, %)	7446 (78%)
Pupillary reactivity	
Reactive to light (N, %)	7664 (80%)
Not reactive to light (N, %)	1914 (20%)
Motor score	
Makes no movements (N, %)	1490 (16%)
Extension to painful stimuli (N, %)	1166 (12%)
Abnormal flexion to painful stimuli (N, %)	1244 (13%)
Flexion / Withdrawal to painful stimuli (N, %)	2208 (23%)
Localizes to painful stimuli (N, %)	2593 (27%)
Obeys commands (N, %)	291 (3%)

analysis without loss of power; the use of ordinal outcomes compared to dichotomized outcomes allowed for up to 13% less patients in the analysis without a loss of power in the IMPACT study (Fig. 3a) and for up to 32% less patients in the PRACTISE trial (Fig. 3b). For example, a mean of 73 patients per hospital was needed to detect the same percentage deviant hospitals when ordinal outcomes were used compared to on average 134 patients per hospital when the dichotomization favorable versus unfavorable was used in the PRACTISE trial. Moreover, dichotomization for mortality required even more patients in the analysis

compared to dichotomization for favorable versus unfavorable outcome, in this example 200 patients per hospital. This meant that the required number of patients could be reduced by 63% for the PRACTISE trial and up to 37% for the IMPACT study. The variation across simulations was relatively small (Appendix Figure 4).

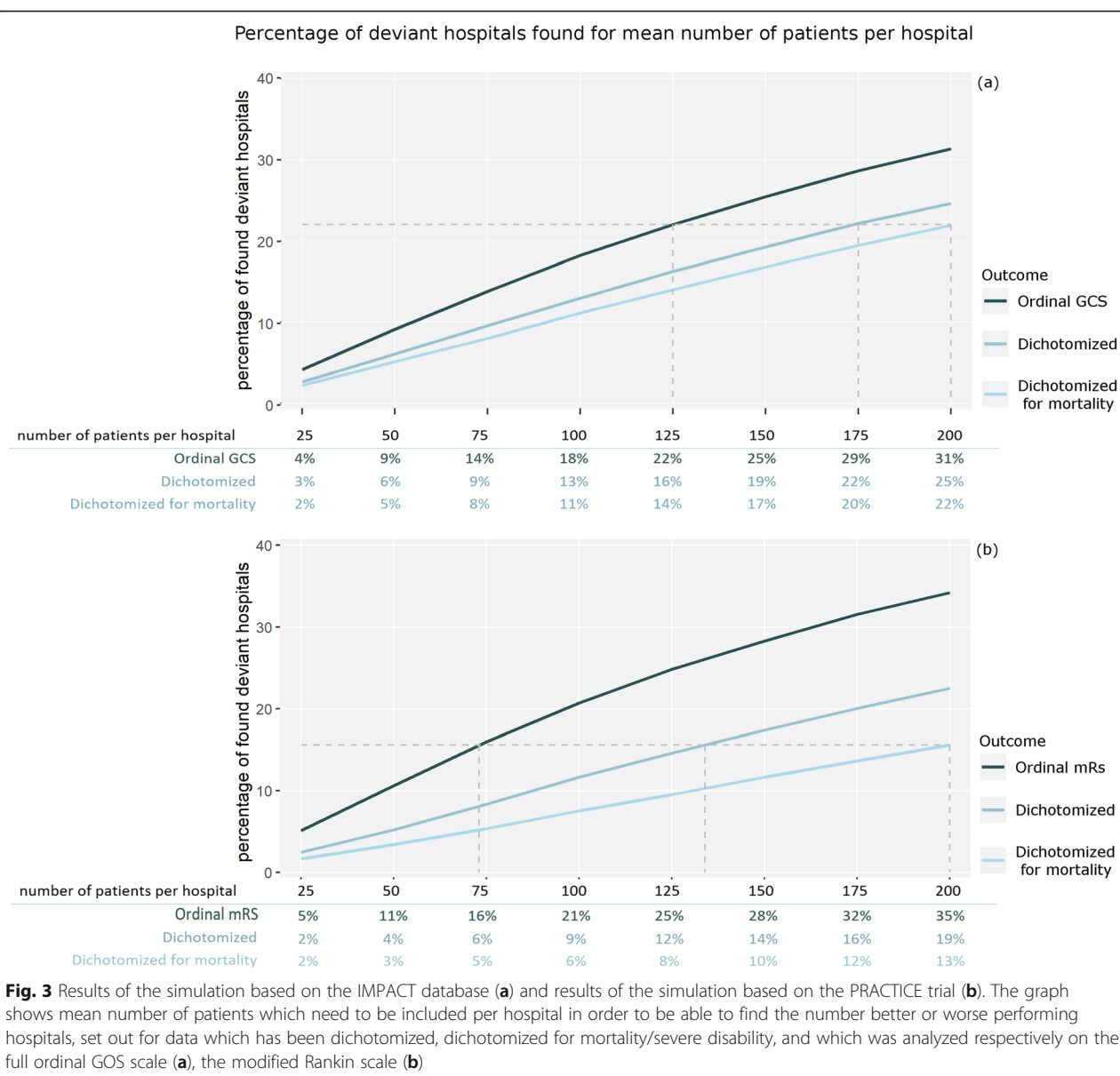
Specificity

To determine specificity, the simulations were performed without simulating true center effects. For all analyses an increase in sensitivity was not associated

Table 2 Baseline characteristics of patients enrolled in the PRACTICE trial

	n = 1657
Age (median, IQR)	73 (62–80)
Sex	
Male (N, %)	902 (54%)
Atrial fibrillation	
Present (N, %)	296 (18%)
Not present (N, %)	1361 (82%)
Diabetes mellitus	
Present (N, %)	274 (17%)
Not present (N, %)	1383 (84%)
History of ischemic stroke	
Present (N, %)	331 (20%)
Not present (N, %)	1326 (80%)
NIHSS ^a (mean)	8

^aNIHSS indicates National Institutes of Health Stroke Scale; indicator of Stroke severity



with a decrease in specificity: the type I error did not differ between analytical approaches and was in all cases below 1%.

Discussion

This study aimed to assess how much power could be gained by using ordinal analysis instead of dichotomous analysis to detect between center differences in outcome. Use of ordinal outcomes in both stroke and TBI hospital comparisons, increased statistical efficiency of the estimation of differences between centers. The increase in statistical power resulted in a substantial reduction in required sample size when using ordinal instead of dichotomous outcomes. This sensitivity increase came without loss of specificity.

Our results are in line with previous studies on estimating treatment effects in RCTs [34–36]. Previous studies on ordinal outcome analysis in trials, showed an increase in power, and higher potential of detecting treatment effects [15, 19, 20, 37], with sample size reductions up to 40%. The current study shows the use of ordinal data is not only of added value in RCTs that assess treatment effects, but also in observational data to assess differences between centers in outcome. It illustrates to what extent sample size can be reduced without loss of power compared to the use of a dichotomous outcome. In the example databases on stroke and TBI, a reduction in sample size of 37 and 63% was achieved. The difference in power gain between the two examples could be partly

explained by the fact that the mRS is used as a 6-point ordinal scale (originally 7) while the GOS is used as a 4-point ordinal scale (originally 5). An ordinal scale with a higher number of levels may contain more information, and may provide more discriminability. In addition, the efficiency gain of an ordinal outcome is optimal if the proportional odds assumption perfectly holds [38, 39].

In our analysis we used odds based on the true data from the IMPACT study and PRACTICE trial, in which the proportional odds assumption is not perfectly met. It has however been shown that even if proportional odds assumptions are violated, analysis of the ordinal scale is still beneficial over dichotomization and results are robust regardless of the violation [20, 40, 41]. In the past the importance of assumption of proportionality might have been stressed too much. More important than the proportional odds assumption is the ordering of the adjacent outcomes. If there is agreement among stakeholders that each score on a certain scale is more favorable than a one point lower score, testing for proportional odds assumptions can be considered redundant [41]. If not, a potential solution is to combine adjacent categories of the scale that are not perceived ordinal, e.g. dead and vegetative state.

This study illustrates how much information is lost, not only by discarding the ordinal outcomes but when dichotomization leads to low event rates. This is the case when only mortality ratios are considered, and especially when mortality at a fixed time point is used. Compared to ordinal outcomes mortality as outcome requires much larger sample sizes, in order to find potential differences in quality of care.

Using ordinal outcomes, when available, instead of dichotomous outcomes to compare hospitals is therefore strongly recommended. For stroke and TBI this is easily done, as most centers will be familiar with the use of these scales in research projects and clinical practice. We do however recognize that several medical conditions or fields do not have a relevant ordinal outcome scales. Ideally relevant ordinal scales for important conditions should be developed or refurbished and implemented.

The benefits of the use of ordinal scales have also been shown to have their limits. The chance of misclassification, even by extensively trained medical staff, is higher with the use of ordinal scales. This phenomenon is represented as the inter-rater reliability [42]. Misclassification has been included in the simulation, if misclassification is however larger than expected it can possibly lead to an underestimation of the error rates and an overestimation of the statistical power of the ordinal analyses [42–46]. Furthermore, in our analysis we

collapsed vegetative state and mortality for the GOS, and similarly we collapsed mRS 5 (severe disability) with mRS 6 (death) into one state. For the GOS it is more of a common practice since it is questionable whether vegetative state is a better outcome than mortality. This has also been done for mRS, although patients in mRS 5 are awake and aware, and on average this is clearly a preferred health status over death. Clinically this might be a debatable choice, it is however done on occasion and in our analysis it makes comparison to the GOS easier and yields a more conservative estimate of the gain in power [23, 24].

Dichotomization was done on the collapsed scale which adds possible misclassification to the dichotomized outcome scale, while true mortality ratios would not have any misclassification. At the same time including vegetative state and severe disability cases increases incidence rates and therefore the power of the analysis.

In this paper we repeatedly refer to reduction in sample size using ordinal instead of dichotomous outcomes. However, since statistical power is a major challenge in hospital comparisons, we would like to stress that by this we point out efficiency gain by using ordinal outcome analysis. Most (studies on) hospital comparisons are underpowered, and thus we do not advise aiming for smaller sample sizes when using ordinal outcomes. In this paper only one aspect in performing hospital comparisons is addressed. In general, to be able to perform valid and efficient hospital comparisons one should focus on 1) using larger sample sizes [47], 2) use ordinal outcome analyses and 3) sufficient case-mix adjustment.

Strengths and limitations

The advantage of performing simulations on quality of care data is that we have a priori knowledge of which hospitals deviate from the mean. A limitation of basing the simulation on real datasets is that it limits the variety of situations which are simulated. Furthermore, the number of patients per hospital was constant in our study, instead of a mix of smaller and larger hospitals as one would see in reality.

Conclusion

Use of the ordinal outcomes instead of the binary outcomes for hospital comparisons, results in considerable efficiency gains. In quality of care research, where lack of power is a substantial problem, using ordinal clinical outcomes could be a way to increase possibilities to find outliers when comparing hospitals. In cases where an ordinal scale is available we strongly advise to exploit the ordinal scale and to not dichotomize in any way.

Appendix

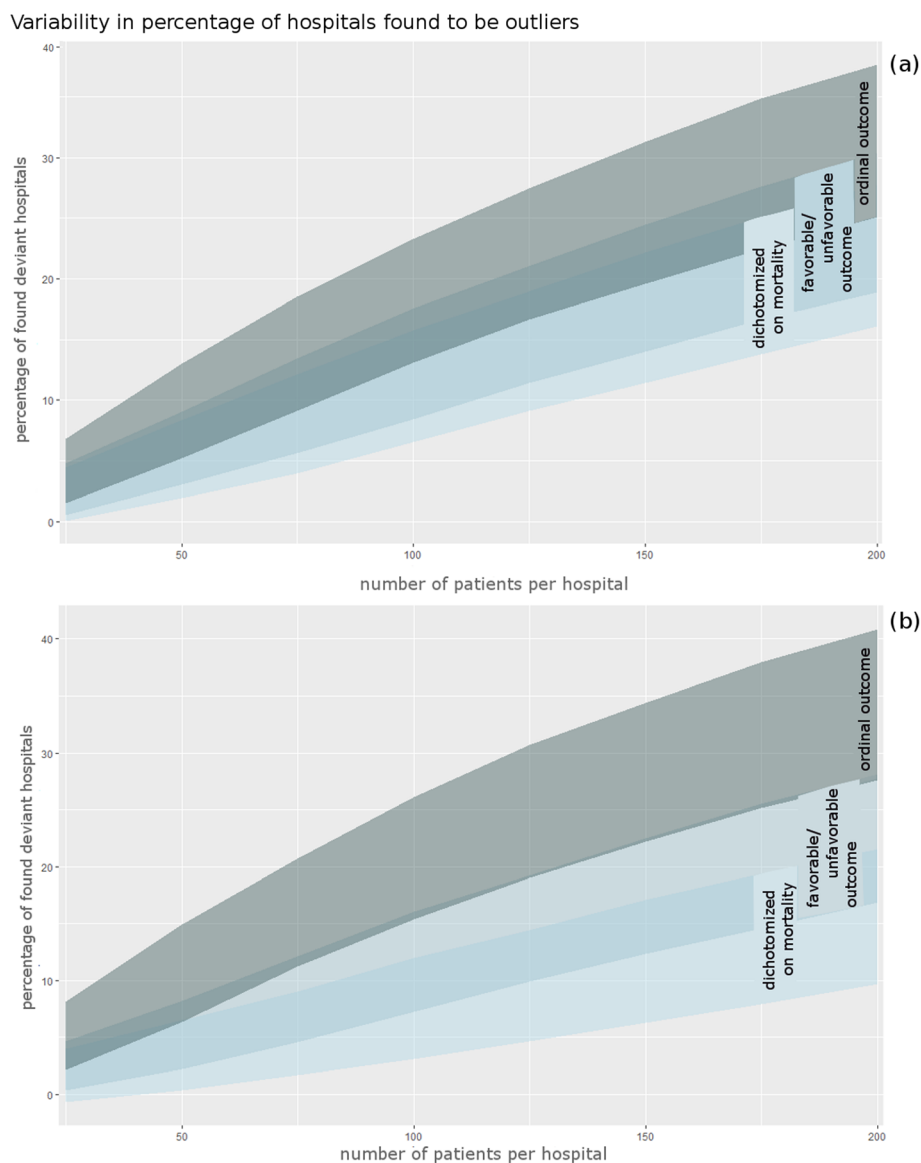
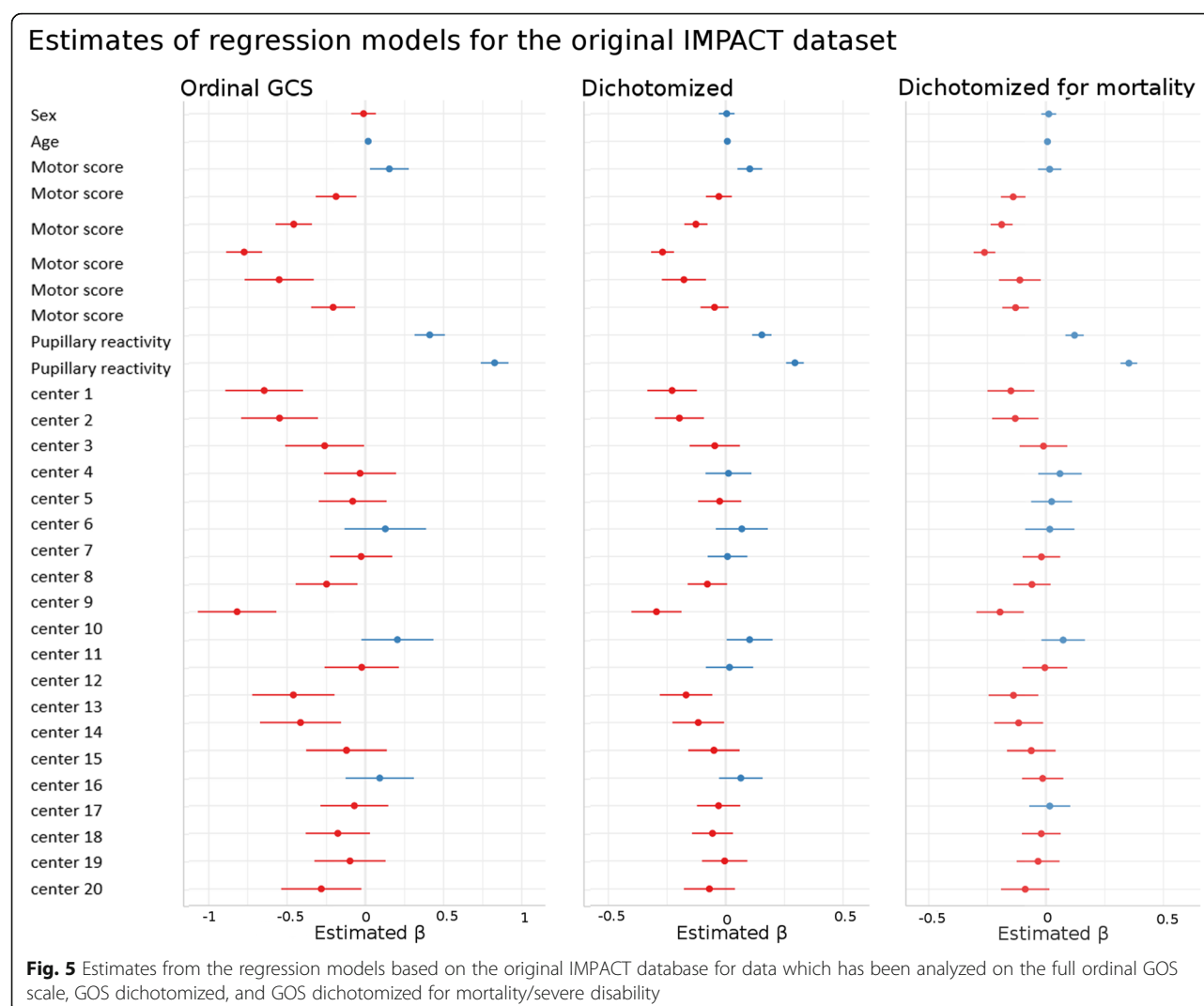


Fig. 4 Results of the simulation based on the IMPACT database (a) and results of the simulation based on the PRACTICE trial (b). The graph shows the variability in number of patients which need to be included per hospital in order to be able to find the number better or worse performing hospitals, set out for data which has been dichotomized, dichotomized for mortality/severe disability, and which was analyzed respectively on the full ordinal GOS scale (a), the modified Rankin scale(b)



Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12874-020-01185-7>.

Additional file 1.

Abbreviations

TBI: Traumatic brain injury; SMR: Standardized mortality ratio; IMPACT: International Mission on Prognosis And Clinical Trial Design in Traumatic Brain Injury; PRACTISE: PRomoting ACute Thrombolysis in Ischemic Stroke; GCS: Glasgow Coma Scale; mRS: Modified Rankin Scale; NIHSS: National Institute of Health Stroke Scale; CIs: Confidence intervals; IQR: Interquartile range

Acknowledgements

We'd like to thank all contributors to the *International Mission on Prognosis And Clinical Trial Design in Traumatic Brain Injury* study and the *PRomoting ACute Thrombolysis in Ischemic Stroke* trial. Foremost: Andrew I.R. Maas, Anthony Marmarou, Gordon D. Murray, Sir Graham M. Teasdale and Maaike Dirks, Louis W. Niessen, Jeroen D.H. van Wijngaarden, Peter J. Koudstaal, Cees L. Franke, Robert J. van Oostenbrugge, Robbert Huijsman, Mirella M.N. Minkman.

Authors' contributions

HFL and IEC planned the study, developed the model and IEC and NvL wrote the paper, IEC built the final version of the model and analysed the data. DWJD provided data and insight into clinic processes. DWJD, HFL and EWS provided valuable input in the writing process and expert knowledge. EWS and HFL statistical and analytical, DWJD from a medical point of view. All authors revised and approved the final version of the manuscript.

Funding

This study was performed without funding.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available because participants gave no consent for data sharing.

Ethics approval and consent to participate

PRomoting ACute Thrombolysis in Ischemic Stroke (PRACTISE): The medical ethics committees in each participating center assessed the study protocol. The protocol has been set up according to the revised Consolidated Standards of Reporting Trials (CONSORT) statement for cluster-randomized trials and has been published earlier. International Mission on Prognosis And Clinical Trial Design in Traumatic Brain Injury study: The study has been approved by the Ethical Committees of all participating centres and have been performed in accordance with the

ethical standards laid down in the Declaration of Helsinki and its later amendments.
Centre for Medical Decision Making, Department of Public Health, Erasmus MC cooperated in the development and realization of these two studies (PRACTISE and IMPACT) and therefore participating researchers had access to the data.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

¹Centre for Medical Decision Making, Department of Public Health, Erasmus MC - University Medical Center, PO Box 2040, 3000, CA, Rotterdam, The Netherlands. ²Department of Neurology, Stroke Center, Erasmus MC - University Medical Center, Rotterdam, The Netherlands. ³Department of Medical Statistics and Bioinformatics, Leiden University Medical Center, Leiden, The Netherlands.

Received: 7 July 2020 Accepted: 2 December 2020

Published online: 06 January 2021

References

- Hibbard JH. What can we say about the impact of public reporting? Inconsistent execution yields variable results. *Ann Intern Med*. 2008;148:160–1.
- Bilimoria KY, Cohen ME, Merkow RP, Wang X, Bentrem DJ, Ingraham AM, et al. Comparison of outlier identification methods in hospital surgical quality improvement programs. *J Gastrointest Surg*. 2010;14:1600–7.
- Krumholz HM, Lin Z, Normand S-LT. Measuring hospital clinical outcomes; 2013.
- Lingsma HF, Steyerberg EW, Eijkemans MJC, Dippel DWJ, Scholte Op Reimer WJM, van Houwelingen HC. Comparing and ranking hospitals based on outcome: Results from The Netherlands Stroke Survey. *QJM*. 2009;103:99–108.
- Lingsma HF, Roozenbeek B, Li B, Lu J, Weir J, Butcher I, et al. Large between-center differences in outcome after moderate and severe traumatic brain injury in the international mission on prognosis and clinical trial design in traumatic brain injury (IMPACT) study. *Neurosurgery*. 2011;68:601–7.
- Van Dishoeck AM, Koek MBG, Steyerberg EW, Van Benthem BHB, Vos MC, Lingsma HF. Use of surgical-site infection rates to rank hospital performance across several types of surgery. *Br J Surg*. 2013;100:628–37.
- Seaton SE, Barker L, Lingsma HF, Steyerberg EW, Manktelow BN. What is the probability of detecting poorly performing hospitals using funnel plots? *BMJ Qual Saf*. 2013;22:870–6.
- Jarman B, Pieter D, Van Der Veen AA, Kool RB, Aylin P, Bottle A, et al. The hospital standardised mortality ratio: a powerful tool for Dutch hospitals to assess their quality of care? *Qual Saf Heal Care*. 2010;19:9–13.
- Jarman B, Gault S, Alves B, Hider A, Dolan S, Cook A, et al. Explaining differences in English hospital death rates using routinely collected data. *BMJ*. 1999;318:1515–20.
- Tu YK, Gilthorpe MS. Revisiting the relation between change and initial value: a review and evaluation. *Stat Med*. 2007;26:443–57.
- Van Den Bosch WF, Kelder JC, Wagner C. Predicting hospital mortality among frequently readmitted patients: HSMR biased by readmission. *BMC Health Serv Res*. 2011;11:57.
- van Gestel YRBM, Rutten HJT, de Hingh IHJT, van den Broek EVD, Nieuwenhuijzen GAP, Coebergh JWW, et al. The standardised mortality ratio is unreliable for assessing quality of care in rectal cancer. *Neth J Med*. 2013;71:209–14.
- Van Gestel YRBM, Lemmens VEPP, Lingsma HF, De Hingh IHJT, Rutten HJT, Coebergh JWW. The hospital standardized mortality ratio fallacy: a narrative review. *Med Care*. 2012;50:662–7.
- MacCallum RC, Zhang S, Preacher KJ, Rucker DD. On the practice of dichotomization of quantitative variables. *Psychol Methods*. 2002;7:19–40.
- Altman DG, Royston P. The cost of dichotomising continuous variables. *BMJ*. 2006;332:1080.
- Royston P, Altman DG, Sauerbrei W. Dichotomizing continuous predictors in multiple regression: a bad idea. *Stat Med*. 2006;25:127–41.
- Maas AI, Murray G, Henney H, Kassem N, Legrand V, Mangelus M, et al. Efficacy and safety of dexamethasone in severe traumatic brain injury: results of a phase III randomised, placebo-controlled, clinical trial. *Lancet Neurol*. 2006;5:38–45.
- Valenta Z, Pitha J, Poledne R. Proportional odds logistic regression - effective means of dealing with limited uncertainty in dichotomizing clinical outcomes. *Stat Med*. 2006;25:4227–34.
- Roozenbeek B, Lingsma HF, Perel P, Edwards P, Roberts I, Murray GD, et al. The added value of ordinal analysis in clinical trials: an example in traumatic brain injury. *Crit Care*. 2011;15:R127.
- McHugh GS, Butcher I, Steyerberg EW, Marmarou A, Lu J, Lingsma HF, et al. A simulation study evaluating approaches to the analysis of ordinal outcome data in randomized controlled trials in traumatic brain injury: results from the IMPACT project. *Clin Trials*. 2010;7:44–57.
- Saver JL. Novel end point analytic techniques and interpreting shifts across the entire range of outcome scales in acute stroke trials. *Stroke*. 2007;38:3055–62.
- Marmarou A, Lu J, Butcher I, McHugh GS, Mushkudiani NA, Murray GD, et al. IMPACT database of traumatic brain injury: design and description. *J Neurotrauma*. 2007;24:239–50.
- Dirks M, Niessen LW, Van Wijngaarden JDH, Koudstaal PJ, Franke CL, Van Oostenbrugge RJ, et al. Promoting thrombolysis in acute ischemic stroke. *Stroke*. 2011;42:1325–30.
- Goyal M, Menon BK, Van Zwam WH, Dippel DWJ, Mitchell PJ, Demchuk AM, et al. Endovascular thrombectomy after large-vessel ischaemic stroke: a meta-analysis of individual patient data from five randomised trials. *Lancet*. 2016;387:1723–31.
- Li B, Lingsma HF, Steyerberg EW, Lesaffre E. Logistic random effects regression models: a comparison of statistical packages for binary and ordinal outcomes. *BMC Med Res Methodol*. 2011;11:77.
- Brant R. Assessing proportionality in the proportional odds model for ordinal logistic regression. *Biometrics*. 1990;46:1171.
- RStudio Team. RStudio: integrated development environment for R. 2015.
- R Core Team. R: A Language and Environment for Statistical Computing. 2016.
- Feng D. miscF: Miscellaneous Functions; 2016.
- Yee TW. VGAM: vector generalized linear and additive models; 2016.
- Elff M. memisc: Tools for Management of Survey Data and the Presentation of Analysis Results; 2016.
- Harrell FE Jr. Hmisc: Harrell Miscellaneous; 2016.
- Harrell FE Jr. rms: Regression Modeling Strategies; 2016.
- Savitz SI, Benatar M, Saver JL, Fisher M. Outcome analysis in clinical trial design for acute stroke: physicians' attitudes and choices. *Cerebrovasc Dis*. 2008;26:156–62.
- Saver JL, Gornbein J. Treatment effects for which shift or binary analyses are advantageous in acute stroke trials. *Neurology*. 2009;72:1310–5.
- Bath PMW, Lees KR, Schellinger PD, Altman H, Bland M, Hogg C, et al. Statistical analysis of the primary outcome in acute stroke trials. *Stroke*. 2012;43:1171–8.
- Machado SG, Murray GD, Teasdale GM. Evaluation of designs for clinical trials of neuroprotective agents in head injury. *J Neurotrauma*. 1999;16:1131–8.
- Bolland K, Sooriyachchi MR, Whitehead J. Sample size review in a head injury trial with ordered categorical responses. In: *Statistics in Medicine*; 1998. p. 2835–47.
- Bath PMW, Gray LJ, Collier T, Pocock S, Carpenter J. Can we improve the statistical analysis of stroke trials? Statistical reanalysis of functional outcomes in stroke trials. *Stroke*. 2007;38:1911–5.
- Maas AR, Steyerberg E, Marmarou A, McHugh G, Lingsma H, Butcher I, et al. IMPACT recommendations for improving the design and analysis of clinical trials in moderate to severe traumatic brain injury. *Neurotherapeutics*. 2010;7:127–34.
- Senn S, Julious S. Measurement in clinical trials: A neglected issue for statisticians?. *Statist Med*. 2009;28:3189–209.
- Van Swieten JC, Koudstaal PJ, Visser MC, Schouten H, Van Gijn J. Interobserver agreement for the assessment of handicap in stroke patients. *Stroke*. 1988;19:604–7.
- Wilson JTL, Hareendran A, Grant M, Baird T, Schulz UGR, Muir KW, et al. Improving the assessment of outcomes in stroke: use of a structured

interview to assign grades on the modified Rankin scale. *Stroke*. 2002;33:2243–6.

44. Quinn TJ, Dawson J, Walters MR, Lees KR. Reliability of the modified Rankin scale: a systematic review. *Stroke*. 2009;40:3393–5.
45. Lu J, Murray GD, Steyerberg EW, Butcher I, Mchugh GS, Lingsma H, et al. Effects of Glasgow outcome scale misclassification on traumatic brain injury clinical trials. *J Neurotrauma*. 2008;25:641–51.
46. Choi SC, Clifton GL, Marmarou A, Miller ER. Misclassification and treatment effect on primary outcome measures in clinical trials of severe neurotrauma. *J Neurotrauma*. 2002;19:17–22.
47. Van Dishoeck AM, Lingsma HF, Mackenbach JP, Steyerberg EW. Random variation and rankability of hospitals using outcome indicators. *BMJ Qual Saf*. 2011;20:869–74.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Ready to submit your research? Choose BMC and benefit from:

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

At BMC, research is always in progress.

Learn more biomedcentral.com/submissions

