

Cost-effectiveness of craniotomy versus decompressive craniectomy, for UK patients with traumatic acute subdural hematoma

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ABSTRACT

Objective: To estimate the cost-effectiveness of craniotomy, compared with decompressive craniectomy (DC) in UK patients undergoing evacuation of acute subdural haematoma (ASDH).

Design: Economic evaluation undertaken using health resource use and outcome data from the 12-month multi-centre, pragmatic, parallel-group, randomised, RESCUE-ASDH trial.

Setting: UK secondary care.

Participants: 248 UK patients undergoing surgery for traumatic ASDH randomised to craniotomy (N=126) or DC (N=122).

Interventions: Surgical evacuation via craniotomy (bone flap replaced) or decompressive craniectomy (bone flap left out with a view to replace later cranioplasty surgery).

Main outcome measures: In the base-case analysis costs were estimated from an NHS and personal social services perspective. Outcomes were assessed via the Quality-Adjusted Life Years (QALY) derived from the EQ-5D-5L questionnaire (cost-utility analysis) and the Extended Glasgow Outcome Scale (GOSE) (cost-effectiveness analysis). Multiple imputation and regression analyses were conducted to estimate the mean incremental cost and effect of craniotomy compared to DC. The most cost-effective option was selected, irrespective of the level of statistical significance as is argued by economists.

Results: In the cost-utility analysis the mean incremental cost of craniotomy compared to DC was estimated to be -£5,520 (95% confidence interval (CI) -£18,060 to £7,020) with a mean QALY gain of 0.093 (95% CI 0.029 to 0.156). In the cost-effectiveness analysis, the mean incremental cost was estimated to be -£4,536 (95% CI -£17,374 to £8,301) with an odds ratio of 1.682 (95% CI 0.995 to 2.842) for a favourable outcome on the GOSE.

Conclusions: In a UK population with traumatic ASDH craniotomy was estimated to be cost-effective compared to decompressive craniectomy: craniotomy was estimated to have a lower mean cost, higher mean QALY gain and higher probability of a more favourable outcome on the GOSE (though not all estimated differences between the two approaches were statistically significant).

Trial registration and ethics: Ethical approval for the trial was obtained from the North West – Haydock Research Ethics Committee in the United Kingdom on 17th July 2014 (14/NW/1076). The trial was registered prospectively: ISRCTN87370545.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- This study is based on individual patient-level data from a large, pragmatic, multi-centre randomised trial.
- It is both the first randomised trial and the first economic evaluation to compare craniotomy to decompressive craniectomy.
- Multiple imputation was undertaken to account for missing data.
- For ethical reasons, baseline EQ-5D-5L scores were taken at discharge from neurosurgical unit (NSU), rather than at randomisation.
- A number of sensitivity analyses were undertaken to assess the robustness of conclusions to different assumptions in relation to these and other aspects.

BACKGROUND

In the UK an estimated 1.3 million people live with a traumatic brain injury related disability and the annual societal cost has been estimated to be £15 billion (2015 cost levels).¹ Acute subdural hematoma (ASDH) is a common consequence² where craniotomy and decompressive craniectomy (DC) are the two mainstay treatments for surgical evacuation of the hematoma.³ Both involve the removal of a piece of skull (bone-flap) to evacuate the hematoma. With craniotomy the bone-flap is replaced, whereas with DC it is not. DC may help alleviate brain swelling and is undertaken with the view to a further operation being performed to rebuild the skull (cranioplasty). Craniotomy has the advantage that a patient will not need a later operation to rebuild the skull, but it may fail to control brain swelling in some patients. A systematic review found few studies comparing the two procedures, none of which were randomised, with contrasting evidence as to which was superior.³

Given this uncertainty as to whether craniotomy or DC is the more effective treatment for patients with ASDH, the choice of treatment is generally left to the discretion of the surgeon.³ However, guidance/recommendations for the provision of different treatment options are now often based on estimated levels of cost-effectiveness.⁴ Moreover, levels of cost-effectiveness may differ between these two surgical procedures as, for example, DC often requires cranial reconstruction by means of cranioplasty, which has additional costs and a

significant complication profile,⁵ but may better alleviate brain swelling, translating into quality-of-life benefits.⁵ Thus, here we report an economic evaluation⁶ that was conducted alongside the RESCUE-ASDH (Randomized Evaluation of Surgery with Craniectomy for Patients Undergoing Evacuation of Acute Subdural Hematoma) trial,⁵ to compare the cost-effectiveness of craniotomy versus DC for UK patients with traumatic ASDH.

METHODS

Participants

The RESCUE-ASDH trial⁵ is a multicentre, international, pragmatic, parallel-group, randomised trial that compared craniotomy with DC. Patients were eligible if they were ≥ 16 years, had an ASDH on CT scan, and the admitting surgeon felt that the hematoma needed evacuating either by craniotomy or DC. The economic evaluation was nested within the RESCUE-ASDH trial and based on UK participants only.

Treatment and randomisation

Enrolled patients had their ASDH evacuated in the operating room under general anaesthesia. The bone-flap was raised, the dura opened, and the hematoma evacuated, after which patients were randomly assigned to receive either craniotomy (bone-flap restored before skin closure) or DC (bone-flap removed prior to skin closure with a view to being restored later). Patients were only randomised if either treatment was feasible, those patients whose brain was too swollen to allow replacement of the bone flap were not randomised. These patients would have the bone flap left out and were not included in the ITT analysis presented within this paper. As a pragmatic study, management of patients pre-, intra-, and post-operatively was undertaken according to each centre's standard of care.

Blocked randomisation (block size 4) with 1:1 ratio was used, with allocation stratified by geographical region, age group, severity of injury and CT findings.⁵ Patients randomised to craniotomy could have a DC at a later stage if their condition deteriorated and at the discretion of the treating clinician. It was not possible to blind patients, relatives and treating clinicians but the primary outcome (see below) was adjudicated centrally by blinded investigators.

Measuring costs

Costs were estimated from a UK NHS and Personal Social Services (PSS) perspective.⁷ Resource use data was collected via two methods: hospital-recorded data and a patient self-report (12-month follow-up) questionnaire (PSRQ). Both methods of data collection were developed in consultation with hospital staff/patients and focussed on big cost drivers/resources that were expected to differ between arms.⁸ All resource use items that

were costed (see below) were estimated in £ Sterling for the 2018/19 financial year, resource use items undertaken for research purposes were not costed.

The hospital-recorded data included the following resource use items: details of the intervention (craniotomy or DC) including length of operation and graft details; time spent in the intensive care unit (ICU) and neurosurgical unit (NSU) during initial (index) admission; cranioplasties and shunt placements (these could be received as part of the index admission and/or after discharge from the NSU); any further neurosurgical procedures received during index admission.

The 12-month follow-up PSRQ could be completed by a relative/friend/carer if the participant was unable to complete it and referred only to the time since discharge from NSU.

Information requested included the following resource use items: overnight stays in a hospital or other healthcare facility (length of stay, ward type, any associated skull/brain operation); healthcare professional visits (professional seen, frequency and most common location); head/brain scans (MRI, CT or 'other'); time in a care home; help received from a family member/friend or carer.

After assigning unit costs to the resource use items (see Supplemental Table S1 for unit costs), the costs associated with both the hospital-recorded data and PSRQ resource use items, excluding wider societal costs (care home and help/carer costs), were summed to estimate the total NHS and PSS cost per participant. For each group the mean total costs were estimated over the 12-month follow-up period, along with the associated p-value for the mean cost difference between groups. An exception to the above was that, to avoid double-counting, patient self-reported post-discharge overnight stays with an associated skull/brain operation would not be costed if the total reported number was less than the total reported number of hospital-recorded post-discharge cranioplasty and shunt procedures (including revisions). In line with previous work,⁹ the higher of the two values was considered the most accurate. It should also be noted that patients who were known to have died post-discharge (mortality is collected as part of the primary outcome, see below) were not sent the PSRQ. As such, post-discharge costs for these participants would have been treated as missing and estimated via imputation (see below for details of the imputation methods, where time post-discharge was included in the MI model). In contrast, cost data for participants who died before discharge from their index admission would not have been considered missing as hospital-recorded data would still have been available for such participants (post-discharge costs were set as equal to zero for such participants).

Measuring outcomes

To estimate health-related quality-of-life, and conduct a cost-utility analysis,⁶ in line with UK NICE guidance,^{4,7} the five-dimension EuroQoL five-level questionnaire (EQ-5D-5L)¹⁰ was combined with mortality data to estimate quality-adjusted life-year (QALY)⁶ scores. Participants completed the EQ-5D-5L at discharge from NSU (assumed baseline score), 6- and 12-months follow-up (if discharged from NSU by these time points). As recommended at the time of analysis,¹¹ the crosswalk mapping function¹² was used to convert responses into utility scores (range: -0.594 (worse than death) to 1 (full health)). Participants who died were assigned a utility score of 0 on their date of death (death was collected as part of the hospital-recorded data as it was required for the primary outcome, see below). Utility values were used to estimate QALYs over 12 months, based on the total area under the curve method and linear interpolation.¹³

For ease of interpretation, as is convention,¹⁴ the trial primary outcome measure, the (ordinal) extended Glasgow Outcome Scale (GOSE),¹⁵⁻¹⁸ at 12 months, was converted into a binary scale using a fixed dichotomy analysis (i.e. favourable vs. unfavourable)⁵ to enable a cost-effectiveness analysis⁶ to be undertaken. Favourable outcomes were defined as upper severe disability or better; while unfavourable outcomes included death, vegetative state and lower severe disability. A sliding dichotomy analysis⁵ was also undertaken and is described in the Supplemental Material (Appendix 2).

Missing data

Missing data is common in randomised trials and can lead to bias and lack of precision.¹⁹ As recommended, patterns of missing data were examined to explore the mechanism of missingness.¹⁹ Accordingly, multiple imputation (MI) with chained equations (MICE) under MAR (missing at random) was used to impute missing costs and outcome data, by treatment group. The “mi impute chained” command (Stata 17.0 [StataCorp LP, College Station, TX]) was used to create 30 data sets (based on recommendations in relation to the level of missing data¹⁹) that were then pooled using Rubin’s rules.²⁰

Due to the way data was collected/different levels of missing data, missing data for costs was imputed for total index admission costs (hospital-recorded data collection), total cranioplasty and shunt costs (hospital-recorded data collection over 12-month trial period), and total post-discharge costs (patient self-report questionnaire data collection at 12 months). These three costs were then combined to estimate total NHS and PSS costs. For outcomes, missing data was imputed for utility scores (EQ-5D-5L) at baseline, 6 and 12 months, Glasgow Coma Scale (GCS) score^{21,22} at baseline and GOSE score at 12 months.

In addition to these costs and outcomes, the MI model also included age (years), sex and time post-discharge (the number of days from discharge to the 12-month point or death).

Incremental analyses

For both the cost-utility and cost-effectiveness analyses, a 12-month within-trial, intention-to-treat (ITT) approach was adopted. In this base-case analysis, patients were analysed according to the treatment to which they were randomised, regardless of treatment received. No discounting was undertaken.

For the cost-utility analysis, to estimate the mean incremental cost and incremental effect (QALY gain) associated with craniotomy compared with DC, seemingly unrelated regression (SUR) analysis was undertaken.²³ Regressions included those baseline variables expected to be predictive of total costs and outcomes: age (years), sex and baseline utility score. Assuming dominance,⁶ where an intervention was both more costly and less effective, did not occur the incremental cost-effectiveness ratio (ICER = mean incremental cost / mean incremental QALY),⁷ for craniotomy versus DC, would be estimated.⁶ In the UK, NICE refers to a cost-effectiveness threshold of £20,000 to £30,000 per QALY.⁷ As such, if craniotomy had an ICER below this level, this would suggest it is cost-effective, compared with DC. It should be noted that economists have argued that decisions about treatment adoption should be made based on mean estimates, irrespective of whether such differences are statistically significant.²⁴ Therefore, the treatment option which is estimated to be most cost-effective should be provided.²⁵ This approach is consistent with the objective of maximizing benefits from a given budget.

For the cost-effectiveness analysis, in terms of the incremental effect, the outcome (based on the GOSE) had a binary scale (favourable/unfavourable) and logistic regression²⁶ was undertaken to estimate the odds ratio (95% CI) of a favourable outcome for craniotomy compared with DC. Separately, the mean incremental cost associated with craniotomy compared with DC was estimated using linear regression. Both regressions included variables age (years) and sex, which were expected to be predictive of total costs and GOSE outcomes. Together, in the absence of dominance, the incremental cost and incremental effect would enable the ICER to be estimated in terms of the cost per percentage increase in the odds of a favourable outcome.

Decision uncertainty

To estimate the level of uncertainty associated with the decision,¹⁹ the probability of craniotomy being cost-effective, compared with DC, at a threshold of £20,000/QALY on the cost-effectiveness acceptability curve (CEAC)²⁵ was calculated. This was estimated by

combining the mean coefficients and covariance matrix from the SUR model, as described in Faria et al.¹⁹ The CEAC was only estimated in relation to the cost-utility analysis.

Sensitivity analyses

The above analysis constituted the base-case analysis⁶ and was carried out in accordance with a pre-specified health economic analysis plan (HEAP) (see: <https://www.rescueasdh.org/trial-documents>). To assess the robustness of conclusions, sensitivity analyses (SA) were undertaken.⁶ To analyse the data from a wider cost perspective the care home and carer costs (which were excluded from the base-case analysis) were added to the total NHS and PSS costs (SA wider cost perspective). A further sensitivity analysis (for the cost-utility analysis only) tested the use of the EQ-5D-5L score at discharge from NSU as the baseline for QALY calculations. As any benefits could already have been partially/wholly achieved by discharge, QALY scores were re-estimated with the assumption that, given the grave nature of the condition and following expert advice, participants had the lowest possible EQ-5D-5L score at baseline (date of index surgery): -0.594 (SA lowest EQ-5D-5L baseline score). Four further sensitivity analyses (including a per protocol analysis) were conducted and are presented in the Supplemental Material (Appendix 3). "SA wider cost perspective" deviated from the HEAP, for reasons explained in the Supplemental Material (Appendix 4)

Patient and public involvement

The aforementioned patient self-report questionnaire was developed in consultation with non-trial patients.

RESULTS

Participants

Between September 2014 and April 2019 248 UK patients were recruited, 126 in the craniotomy arm and 122 in the DC arm. Compared with the 450 patients recruited to the full (international) trial (the baseline characteristics of which are summarised in Table 1 of Hutchinson et al.⁵), these UK patients are slightly older (3.5 years on average) and more likely to be on antithrombotic medication (Table 1).

Levels of missing data were slightly lower in the craniotomy group compared with the DC group for cost variables and outcome variables (except at baseline) (Supplemental Table S2).

Costs

Levels of resource use by intervention arm are summarised in Table 2, under three main categories: (i) Hospital-recorded index-admission; (ii) Hospital-recorded cranioplasties and shunts; (iii) Patient-reported (PSRQ) post-discharge.

The hospital-recorded index-admission data shows that, length of stay in ICU and NSU was slightly lower in the craniotomy group compared with the DC group, but not significantly so. Only small numbers of other neurosurgical operations were reported. With regard to cranioplasties and shunts (index admission and post-discharge), as expected, more patients in the DC group had cranioplasties than in the craniotomy group (DC is pre-requisite to a cranioplasty). There were, however, patients who were randomised to craniotomy that went on to have a DC, 21 of which had a cranioplasty in the 12-month follow-up period. Most cranioplasties used a synthetic material. Shunts were uncommon and occurred at a similar frequency between the groups. In terms of the patient-reported (PSRQ) post-discharge resource use, there were no significant differences between the groups for any of the parameters measured.

Mean cost estimates are summarised in Table 3 and divided into the same three main categories. As expected, given the procedure complexity and recovery time, total NHS and PSS costs are high in both groups. High index admission costs particularly accounted for this, largely due to the high cost of ICU stays, along with post-discharge costs, largely due to the high cost of overnight stays on a rehabilitation unit. There were however few significant differences between groups, the only notable one being the cost of cranioplasty procedures which, for aforementioned reasons, was significantly higher in the DC group. As the number of post-discharge hospital-recorded cranioplasty/shunt procedures exceeded patient-reported over-night stays with an associated skull/brain operation (Table 2), the latter has not been costed.

Outcomes

Outcomes are summarised in Table 4. Follow-up mean EQ-5D-5L scores were higher in the craniotomy group compared with the DC group, significantly so at 12 months. Furthermore, the change (increase) in EQ-5D-5L score from baseline was significantly higher at both 6 and 12 months in the craniotomy group compared with the DC group. There was no significant difference between groups for the total QALY score, based on available data.

At 12 months the percentage of favourable GOSE scores was higher, but not significantly, in the craniotomy group compared with the DC group.

Analyses

Cost-utility analysis

For the base-case (based on ITT/MI), the mean difference in cost for the craniotomy group compared with the DC group was -£5,520 (95% CI -£18,060 to £7,020) with a mean QALY difference of 0.093 (95% CI 0.029 to 0.156) (Table 5). Craniotomy therefore dominated DC; it was estimated to be associated with both lower costs and more benefit.

Cost-effectiveness analysis

For the craniotomy group compared with the DC group, the mean difference in cost was -£4,536 (95% CI -£17,374 to £8,301) with an odds ratio of favourable outcome on the GOSE score of 1.682 (95% CI 0.995 to 2.842) (Table 5). Again, craniotomy therefore dominated DC.

Decision uncertainty

The base-case probability that craniotomy was cost-effective compared with DC, at a threshold of £20,000/QALY, was 87% (Table 5). This indicates a high degree of certainty associated with the cost-utility analysis decision that craniotomy compared with DC is cost-effective at that threshold.

Sensitivity analyses

In the sensitivity analyses, from a wider cost perspective and using the lowest EQ-5D-5L baseline score (for the cost-utility analysis only), craniotomy was again found to dominate DC (see Table 5). Results of further sensitivity analyses, all of which are consistent with the base-case results, are presented in Supplemental Table A1 (Supplemental Material, Appendix 3).

DISCUSSION

Main findings

In this UK population of patients with traumatic ASDH that warrants surgical evacuation, based on the results of the cost-utility and cost-effectiveness analyses, craniotomy dominated DC as it was estimated to have a lower mean cost, a higher mean QALY gain / higher probability of a more favourable outcome on the GOSE. Craniotomy was therefore estimated to be cost-effective, on the basis that the associated level of significance is considered to be irrelevant.^{24,25} In the cost-utility analysis (QALY outcome), there was only an estimated 13% probability (at a threshold of £20,000/QALY) of making the wrong decision by choosing craniotomy. The results of the sensitivity analyses are in keeping with this result.

Within this study it is important to highlight that costs were estimated from the viewpoint of the UK NHS and PSS and that associated resource use and outcome data was based only on participants from UK sites. As, for example, unit costs may differ outside the UK it is important to note that it is unclear whether these results are generalisable to sites outside the UK. Further associated research may therefore be warranted in relation to this and that $\geq 20\%$ of patients who were randomised to craniotomy went on to have a DC (as an ITT approach was adopted these patients were included in the craniotomy arm in the base-case analysis).

Strengths and limitations

Regarding health-related quality-of-life, QALY scores (EQ-5D-5L recorded at all time points) were available for 53% of participants only and the amount of missing data was greater at discharge than at 6 and 12 months (Supplemental Table S2). Some missing EQ-5D-5L baseline (NSU discharge) data may be due to participants being discharged at short notice or at the weekend when a research nurse was not available. As some patients had not yet been discharged from hospital by 6 months, this may explain the higher rates of missing data at this time point compared with 12 months. Post-discharge costs (based on patient self-report data) were also missing for 27.4% of patients at 12 months (Supplemental Table S2). Such missing data is a limitation, but we did impute missing data and take an ITT approach, which meant that all patients were still included in the analysis.

A further limitation is that, for ethical reasons, baseline EQ-5D-5L scores were taken at discharge from NSU, rather than at randomisation. Therefore, any benefits could be underestimated by assuming this score is the baseline score. To test the potential impact of this, a sensitivity analysis (SA lowest EQ-5D-5L baseline score) assumed the baseline EQ-5D-5L score to be that of worst possible health state (-0.594). The results differ little from the base-case (Table 5) with craniotomy still dominating DC. It should also be noted that, in the cost-effectiveness analysis, as the cost and outcome regressions are performed separately any correlation between the cost and outcome variables would not be accounted for. A final limitation is that the 12 month follow-up period may not be sufficient to capture all expected cranioplasties. For example, of those randomised to DC (122), only 62 had received a cranioplasty within the 12 month follow-up period. As such, further cranioplasties (aside from those who were randomised to but did not receive DC (8/122) and those who had died (31/122)) could take place beyond the 12 month period. Though this is a limitation, the inclusion of such costs would only be expected to increase the long term incremental cost of DC and therefore not change the conclusion that craniotomy dominated DC.

Comparisons with other studies

We are not aware of any previous economic evaluations that have specifically compared craniotomy with DC for patients with ASDH. Previous economic evaluations of DC have been undertaken,²⁷⁻³¹ but these have had different comparators, and used a variety of different populations/methods (most developed a decision analytical model to estimate costs and benefits,²⁹⁻³¹ and the two papers^{27,28} that used actual patient data were not based on randomised data and were of a smaller sample size than used here, with different cost perspectives and timeframes. Thus, it is difficult to make direct comparisons to our study, and the use of different methods may explain why there were differences in the results as to whether DC was estimated to be cost-effective or not.²⁷⁻³¹

Implications

In a UK population of patients with traumatic ASDH, craniotomy was estimated to have a lower mean cost, a higher mean QALY gain and a higher probability of a more favourable outcome on the GOSE, dominating DC. Based on the QALY, there was a high probability that craniotomy, compared with DC, was cost-effective (at a threshold of £20,000/QALY). When sensitivity analyses were conducted, the main conclusion (that craniotomy was therefore estimated to be cost-effective) remained unchanged. Consequently, the health economic analysis supports the recommendation, based on the primary outcome,⁵ that a craniotomy should be undertaken, rather than a DC, if it is operatively feasible to replace the bone-flap.

Contributors:

GRB, DAT, HM, BG, AGK, CT, HA, MM, CJM, AB, ATK, DKM and PJH contributed to the conception/design of the work. SCP, GRB, DAT, HM, BG, AGK, CT, HA, MM, CU, SH, MW, DB, AZ, CJM, MGS, YZA, ST, EV, AEH, IST, DKM, PJH contributed to the acquisition of data. SCP, GRB and DT conducted the analysis. All authors contributed to the interpretation of data/drafting of the paper (led by SCP and GRB) and approved the final manuscript.

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Study protocol is available at <https://fundingawards.nihr.ac.uk/award/12/35/57>

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Data availability statement: Reasonable requests to make relevant anonymised participant level data available will be considered by the trial team. The trial protocol¹⁴ and a pre-

specified health economic analysis plan (HEAP) (see: <https://www.rescueasdh.org/trial-documents>) are also available.

REFERENCES

1. Parsonage M. *Traumatic brain injury and offending. An economic analysis*. 2016.
2. Wilberger JE, Harris M, Diamond DL. Acute subdural hematoma: morbidity, mortality, and operative timing. *J Neurosurg* 1991; 74: 212–8.
3. Phan K, Moore JM, Griessenauer C, et al. Craniotomy versus decompressive craniectomy for acute subdural hematoma: systematic review and meta-analysis. *World Neurosurg* 2017; 101: 677-685.e2.
4. NICE. *NICE health technology evaluations: the manual (PMG 36)*. 2022.
5. Hutchinson PJ, Adams H, Mohan M, et al. Decompressive Craniectomy versus Craniotomy for Acute Subdural Hematoma. *NEJM* 2023; 388: 2219–2229.
6. Drummond M, Sculpher M, Claxton K, et al. *Methods for the economic evaluation of health care programmes*. 4th ed. Oxford, UK: Oxford University Press, 2015.
7. NICE. *Guide to the methods of technology appraisal 2013*, <https://www.nice.org.uk/process/pmg9> (2013, accessed 24 April 2024).
8. Ramsey SD, Willke RJ, Glick H, et al. Cost-effectiveness analysis alongside clinical trials II - An ISPOR good research practices task force report. *Value in Health* 2015; 18: 161–172.
9. Byford S, Leese M, Knapp M, et al. Comparison of alternative methods of collection of service use data for the economic evaluation health care interventions. *Health Econ* 2007; 16: 531–536.
10. Herdman M, Gudex C, Lloyd A, et al. Development and preliminary testing of the new five-level version of EQ-5D (EQ-5D-5L). *Qual Life Res* 2011; 20: 1727–36.
11. NICE. *Position statement on use of the EQ-5D-5L value set for England (updated October 2019)*. National Institute for Health and Care Excellence, 2019.

12. Van Hout B, Janssen MF, Feng YS, et al. Interim scoring for the EQ-5D-5L: Mapping the EQ-5D-5L to EQ-5D-3L value sets. *Value in Health* 2012; 15: 708–715.
13. Manca A, Hawkins N, Sculpher MJ. Estimating mean QALYs in trial-based cost-effectiveness analysis: The importance of controlling for baseline utility. *Health Econ* 2005; 14: 487–496.
14. Hutchinson P. *Randomised Evaluation of Surgery with Craniectomy for patients Undergoing Evacuation of Acute Subdural Haematoma (RESCUE-ASDH) trial protocol version: 3.0*, <https://www.fundingawards.nihr.ac.uk/award/12/35/57> (2018, accessed 12 April 2024).
15. Jennett B, Bond M. Assessment of outcome after severe brain damage. *The Lancet* 1975; 1: 480–484.
16. Teasdale GM, Pettigrew LEL, Wilson JTL, et al. Analyzing outcome of treatment of severe head injury: a review and update on advancing the use of the Glasgow Outcome Scale. *J Neurotrauma* 1998; 15: 587–597.
17. Wilson JTL, Slieker FJA, Legrand V, et al. Observer variation in the assessment of outcome in traumatic brain injury: experience from a multicenter, international randomized clinical trial. *Neurosurgery* 2007; 61: 123–128.
18. Wilson JTL, Pettigrew LEL, Teasdale GM. Structured interviews for the Glasgow Outcome Scale and the extended Glasgow Outcome Scale: guidelines for their use. *J Neurotrauma* 1998; 15: 573–580.
19. Faria R, Gomes M, Epstein D, et al. A Guide to Handling Missing Data in Cost-Effectiveness Analysis Conducted Within Randomised Controlled Trials. *Pharmacoeconomics* 2014; 32: 1157–1170.
20. Little R, Rubin D. *Statistical analysis with missing data*. 2nd ed. Hoboken, New Jersey: Wiley, 2002.
21. Teasdale G, Jennett B. Assessment of coma and impaired consciousness. A practical scale. *Lancet* 1974; 2: 81–4.
22. Teasdale G, Murray G, Parker L, et al. Adding up the Glasgow Coma Score. *Acta Neurochir Suppl (Wien)* 1979; 28: 13–6.

23. Willan AR, Briggs AH, Hoch JS. Regression methods for covariate adjustment and subgroup analysis for non-censored cost-effectiveness data. *Health Econ* 2004; 13: 461–475.
24. Claxton K. The irrelevance of inference: A decision-making approach to the stochastic evaluation of health care technologies. *J Health Econ* 1999; 18: 341–364.
25. Fenwick E, O'Brien BJ, Briggs AH. Cost-effectiveness acceptability curves—facts, fallacies and frequently asked questions. *Health Econ* 2004; 13: 405–415.
26. Hosmer Jr DW, Lemeshow S, Sturdivant RX. *Applied logistic regression*. John Wiley & Sons, 2013.
27. Malmivaara K, Kivisaari R, Hernesniemi J, et al. Cost-effectiveness of decompressive craniectomy in traumatic brain injuries. *Eur J Neurol* 2011; 18: 656–662.
28. Ho KM, Honeybul S, Lind CRP, et al. Cost-effectiveness of decompressive craniectomy as a lifesaving rescue procedure for patients with severe traumatic brain injury. *J Trauma* 2011; 71: 1637–1644.
29. Whitmore RG, Thawani JP, Grady MS, et al. Is aggressive treatment of traumatic brain injury cost-effective? *J Neurosurg* 2012; 116: 1106–1113.
30. Alali AS, Naimark DMJ, Wilson JR, et al. Economic evaluation of decompressive craniectomy versus barbiturate coma for refractory intracranial hypertension following traumatic brain injury. *Crit Care Med* 2014; 42: 2235–2243.
31. Behranwala R, Aojula N, Hagana A, et al. An economic evaluation for the use of decompressive craniectomy in the treatment of refractory traumatic intracranial hypertension. *Brain Inj* 2021; 35: 444–452.

Table 1. Baseline characteristics of UK patients

Characteristics	Craniotomy (N=126)	DC (N=122)
Age (mean±SD) – yr, n	52.3±16.4, 126	51.7±15.9, 122
Male sex – No. /total n (%)	96/126 (76.2)	101/122 (82.8)
Any antithrombotic medication — No. / n (%) ^a	21/115 (18.3)	22/110 (20.0)
Presence of major extracranial injury requiring admission — No. / n (%)	66/123 (53.7)	57/120 (47.5)
Glasgow Coma Scale (GCS) 3-8*	85/120 (70.8)	72/119 (60.5)
Initial CT brain findings		
Presence of midline shift > 5mm — No. / n (%)	106/124 (85.5)	105/121 (86.8)
Compression / absence of basal cisterns — No. / n (%)	101/124 (81.5)	102/121 (84.3)
Presence of parenchymal contusions <25cc — No. / n (%)	58/125 (46.4)	60/121 (49.6)

DC= decompressive craniectomy; N=number allocated to that trial arm; No.=number of associated patients; n=number of patients for whom data were available;*A GCS score of 3–8 is defined as ‘severe brain injury’.

Table 2. Levels of resource use according to intervention arm over 12-month treatment period for all UK patients (based on available data)

Resource use	Craniotomy (N=126)	DC (N=122)	P-value‡
Hospital-recorded, index admission			
Primary intervention received, not as randomised, No.	13 (n = 126)	8 (n = 122)	-
Duration of index surgery (hours), mean ± SD (No. / n)	2.57 ± 0.89 (122/122)	2.50 ± 0.93 (110/110)	0.603
ICU length of stay (index admission) (days), mean ± SD (No. / n)	11.85 ± 8.61 (123/126)	13.52 ± 11.28 (121/122)	0.189
NSU length of stay (index admission) (days), mean ± SD (No. / n)	16.75 ± 24.92 (93/122)	21.30 ± 31.10 (99/120)	0.210
Further DCs (index admission), No.	15 (n=116)	4 (n = 116)	-
Further haematoma evacuations (index admission), No.	9 (n = 116)	2 (n = 116)	-
Further wound revisions (index admission), No.	1 (n = 116)	6 (n = 116)	-
Further other cranial operations (index admission)*, No.	3 (n = 116)	2 (n = 2)	-
Hospital-recorded (cranioplasties and shunts (index admission and post-discharge))			
Primary cranioplasties, No.	21 (n = 124)	62 (n = 121)	-
Cranioplasties requiring synthetic plate, No. (%)	17 (81.0%) (n = 21)	46 (74.2%) (n = 62)	-
Cranioplasty revisions, No.	5 (n = 124)	7 (n = 121)	-
Cranioplasties (primary/revisions) requiring re-admission, No.	17 (n = 124)	58 (n = 121)	-
Primary shunts, No.	5 (n = 126)	4 (n = 118)	-
Shunt revisions, No.	5 (n = 126)	2 (n = 118)	-
Shunts (primary/revisions) requiring re-admission, No.	4 (n = 126)	4 (n = 118)	-
Post-discharge cranioplasty/shunt related procedures (combined), No.	21 (n = 124)	61 (n = 118)	-
Patient-reported, post-discharge			
Overnight stay with associated skull/brain operation, No.	13 (n = 111)	32 (n = 95)	-
Any overnight stay excluding skull/brain operation, No. reporting ≥1 stay	61 (n = 111)	54 (n = 95)	-
Overnight stay on rehabilitation unit, [†] (days), mean ± SD (No. / n)	32.51 ± 63.09 (45/111)	35.10 ± 68.80 (36/90)	0.782

Overnight stay on NSU, [†] (days), mean ± SD (No. / n)	0.49 ± 2.00 (8/111)	1.14 ± 5.57 (5/95)	0.252
Overnight stay on ICU, [†] (days), mean ± SD (No. / n)	0.13 ± 1.33 (1/111)	0.07 ± 0.72 (1/95)	0.731
Overnight stay on other ward, [†] (days), mean ± SD (No. / n)	4.94 ± 18.08 (20/109)	3.04 ± 17.00 (10/93)	0.447
Healthcare professional contact, N reporting ≥1 visit	64 (n = 109)	47 (n = 94)	-
Hospital doctor (visits), mean ± SD (No. / n)	0.60 ± 1.33 (28/106)	0.61 ± 1.46 (24/92)	0.980
Nurse (visits), mean ± SD (No. / n)	2.20 ± 16.53 (8/107)	0.76 ± 5.28 (7/92)	0.426
General Practitioner (visits), mean ± SD (No. / n)	1.23 ± 2.44 (36/106)	1.09 ± 1.93 (30/93)	0.656
Physiotherapist (visits), mean ± SD (No. / n)	2.38 ± 7.11 (29/105)	4.03 ± 11.19 (19/91)	0.213
Occupational therapist (visits), mean ± SD (No. / n)	1.56 ± 3.41 (32/105)	2.22 ± 7.22 (19/92)	0.407
Speech therapist (visits), mean ± SD (No. / n)	0.55 ± 2.29 (10/107)	0.31 ± 1.40 (9/90)	0.386
Social worker (visits), mean ± SD (No. / n)	0.16 ± 0.77 (6/107)	0.12 ± 0.44 (7/92)	0.665
Community care assistant (visits), mean ± SD (No. / n)	2.68 ± 21.44 (3/106)	2.84 ± 20.45 (3/92)	0.958
Emergency department (visits), mean ± SD (No. / n)	0.10 ± 0.53 (5/107)	0.18 ± 0.61 (10/93)	0.321
Psychologist/neuropsychologist (visits), mean ± SD (No. / n)	0.27 ± 1.24 (7/107)	0.46 ± 2.72 (7/93)	0.514
Other health care professional (visits), mean ± SD (No. / n)	0.03 ± 0.22 (2/107)	0.04 ± 0.33 (2/93)	0.699
Head/brain scan, No. reporting ≥1 scan	47 (n = 111)	44 (n = 93)	-
MRI scans, mean ± SD (No. / n)	0.31 ± 0.62 (27/111)	0.33 ± 0.56 (28/93)	0.745
CT scans, mean ± SD (No. / n)	0.33 ± 0.67 (27/111)	0.45 ± 0.73 (33/93)	0.228
Other scans, mean ± SD (No. / n)	0.04 ± 0.19 (4/111)	0.02 ± 0.15 (2/93)	0.543
Patient-reported, post-discharge (wider resource use)			
Time in a care home (weeks), mean ± SD (No. / n)	1.79 ± 7.14 (10/109)	3.53 ± 10.40 (12/91)	0.164
Help from carer (hours), mean ± SD (No. / n)	971 ± 2,017 (46/99)	1,000 ± 2,225 (36/86)	0.925

DC= decompressive craniectomy; N=number allocated to that trial arm; No.=number of patients in receipt of the resource item in question i.e. excluding zero values; n=number of patients for whom data were available; SD=standard deviation; ‡ for the mean cost difference between groups; *Excluding cranioplasties and shunts; †Excluding those reported (by the patient) to be associated with a skull/brain operation (estimates were instead based on hospital-recorded data, see Table S1).

Table 3. Estimates of mean cost (UK £ sterling, 2018/19) by treatment group over 12-month treatment period for all patients (based on available data)

Cost component	Craniotomy (N=126)	DC(N=122)	P-value‡
Hospital-recorded, index admission			
Index neurosurgical procedure, mean cost ± SD	3,648 ± 1,264 (n=122)	3,560 ± 1,315 (n = 110)	0.603
Length of stay in NSU (index admission), mean cost ± SD	6,109 ± 9,085 (n = 122)	7,766 ± 11,339 (n = 120)	0.210
Length of stay in ICU (index admission), mean cost ± SD	20,039 ± 14,566 (n = 126)	22,873 ± 19,077 (n = 122)	0.189
Further DCs (index admission), mean cost ± SD*	307 ± 859 (n = 116)	82 ± 536 (n = 116)	0.017
Further haematoma evacuations (index admission), mean cost ± SD	165 ± 638 (n = 116)	37 ± 279 (n = 116)	0.048
Further wound revision (index admission), mean cost ± SD	18 ± 198 (n = 116)	110 ± 551 (n = 116)	0.092
Further other cranial operations (index admission),† mean cost ± SD	55 ± 340 (n = 116)	37 ± 279 (n = 116)	0.653
Total cost per patient (index admission), mean cost ± SD	30,790 ± 19,710 (n = 109)	34,759 ± 24,481 (n = 102)	0.195
Hospital-recorded cranioplasties and shunts (index admission and post-discharge)			
Cranioplasty procedures, mean cost ± SD	1,059 ± 2,485 (n = 124)	3,055 ± 3,352 (n = 122)	<0.0001
Shunt procedures, mean cost ± SD	212 ± 1,121 (n = 126)	150 ± 834 (n = 118)	0.626
Cranioplasty/shunt same day discount, mean cost ± SD §	-17 ± 132 (n = 124)	0 ± 0 (n = 118)	0.167
Total cost per patient (cranioplasties and shunts), mean cost ± SD	1,258 ± 2,983 (n = 124)	3,228 ± 3,677 (n = 118)	<0.0001
Patient-reported, post-discharge			
Overnight stays on rehabilitation unit, mean cost ± SD**	16,375 ± 31,784 (n = 111)	17,677 ± 34,660 (n = 90)	0.782
Overnight stays on NSU, mean cost ± SD**	177 ± 729 (n = 111)	415 ± 2,029 (n = 95)	0.252
Overnight stays on ICU/HDU, mean cost ± SD**	213 ± 2,247 (n = 111)	125 ± 1,215 (n = 95)	0.731
Overnight stays on 'other' ward, mean cost ± SD**	1,746 ± 6,396 (n = 109)	1,076 ± 6,015 (n = 93)	0.447
All healthcare professional visits, mean cost ± SD	682 ± 1,108 (n = 103)	782 ± 1,578 (n = 88)	0.612
All head/brain scans, mean cost ± SD	66 ± 105 (n = 111)	93 ± 101 (n = 93)	0.436
Total cost per patient (post-discharge PSRQ), mean cost ± SD	19,699 ± 34,193 (n = 99)	17,948 ± 32,183 (n = 81)	0.726

Time in a care home (wider perspective only), mean cost ± SD	3,321 ± 13,230 (n = 109)	6,550 ± 19,272 (n = 91)	0.164
Carer time (wider perspective only), mean cost ± SD	16,762 ± 34,828 (n = 99)	17,271 ± 38,419 (n = 86)	0.925
Overall NHS and PSS cost per patient, mean cost ± SD	48,509 ± 46,934 (n = 86)	53,573 ± 47,092 (n = 67)	0.510

DC= decompressive craniectomy; N=number allocated to that trial arm; n=number of patients for whom data were available; SD=standard deviation; PSS=Personal Social Services; ‡ for the mean cost difference between groups; *Based on mean duration of DC (from all index procedures) of 2.50 (n=110) hours for all randomized patients; †Excluding cranioplasties and shunts; §A discount was applied to account for those shunt and cranioplasty procedures that occurred on the same day and were therefore assumed to be associated with a slightly shorter operation duration and NSU stay; **Overnight stays excluding those associated with a skull/brain operation.

Table 4. Estimates of mean outcomes by treatment group over 12-month treatment period for all patients (based on available data)

Item	Craniotomy (N=126)	DC (N=122)	P-value‡
Baseline EQ-5D-5L score, mean ± SD	0.260 ± 0.353 (n = 87)	0.302 ± 0.366 (n = 91)	0.441
6-month EQ5D-5L score, mean ± SD	0.427 ± 0.392 (n = 102)	0.370 ± 0.393 (n = 94)	0.311
6-month change in EQ5D-5L score, mean ± SD	0.184 ± 0.345 (n = 74)	0.073 ± 0.319 (n = 71)	0.046
12-month EQ5D-5L score, mean ± SD	0.471 ± 0.402 (n = 111)	0.336 ± 0.414 (n = 103)	0.016
12-month change in EQ5D-5L score, mean ± SD	0.218 ± 0.367 (n = 79)	0.073 ± 0.361 (n = 78)	0.013
Total QALY score, mean ± SD	0.351 ± 0.335 (n = 68)	0.338 ± 0.366 (n = 64)	0.830
12-month GOSE score, % favourable**	47.9 (n = 121)	37.4 (n = 115)	0.102

N=number allocated to that trial arm; n=number for whom data were available; DC= decompressive craniectomy; SD=standard deviation; QALY=Quality Adjusted Life Years. GOSE= Extended Glasgow Outcome Scale; GCS= Glasgow Coma Score; ‡ for the mean difference between groups; *Favourable for the GCS score was defined as 9–15 points (moderate to minor brain injury) while unfavourable was defined as 3–8 points (severe brain injury); **Favourable for the GOSE score was defined as upper severe disability or better; †If GCS at baseline is between 3 and 8, a favourable outcome will be defined as upper severe disability or better on 12-month GOSE. If GCS at baseline is between 9 and 15, a favourable outcome will be defined as lower moderate disability or better on 12-month GOSE.

Table 5. Estimates of the mean incremental cost, incremental effect (QALY gain or odds ratio), and cost effectiveness of craniotomy compared with DC in the base-case and two sensitivity analyses (based on imputed data)

Cost utility analysis	Incremental cost (95% CI) (N=126)	QALY gain (95% CI) (N=122)	ICER	CEAC*
Base-case: imputed	-£5,520 (-£18,060 to £7,020)	0.093 (0.029 to 0.156)	Dominant	87%
SA wider cost perspective	-£17,793 (-34,658 to -928)	0.094 (0.030 to 0.159)	Dominant	99%
SA lowest EQ-5D-5L baseline score	-£5,445 (-£17,547 to £6,658)	0.089 (0.025 to 0.152)	Dominant	87%
Cost effectiveness analysis	Incremental cost (95% CI)	Odds ratio (95% CI)‡	ICER	
Base-case	-£4,536 (-£17,374 to £8,301)	1.682 (0.995 to 2.842)	Dominant	-
SA wider cost perspective	-£16,900 (-£33,807 to £7)	1.693 (0.998 to 2.871)	Dominant	-

DC= decompressive craniectomy; N=number allocated to that trial arm and included in the analysis – imputation was undertaken as part of all presented analyses; 95% CI=95% confidence interval; ICER =incremental cost-effectiveness ratio, described in the Methods; Dominant = lower mean costs and higher mean effect; SA:sensitivity analysis, described in the Methods; QALY=Quality Adjusted Life Years; ‡ for a favourable outcome for craniotomy compared with DC, based on the GOSE (Extended Glasgow Outcome Scale), as described in the Methods; *Probability of being cost-effective on the cost-effectiveness acceptability curve (CEAC) at a threshold of £20,000 per QALY.