



Adverse reaction to metal debris due to fretting corrosion between the acetabular components of modular dual-mobility constructs in total hip replacement: a systematic review and meta-analysis

Jonathan M. R. French¹
Paul Bramley²
Sean Scattergood¹
Nemandra A. Sandiford³

- Modular dual-mobility (MDM) constructs can be used to reduce dislocation rates after total hip replacement (THR). However, there are concerns about adverse reaction to metal debris (ARMD) as a result of fretting corrosion between the metal liner and shell. This systematic review reports outcomes following THR using MDM components. It was registered with PROSPERO and conducted in line with Cochrane and PRISMA recommendations.
- Sixteen articles were included overall, with meta-analysis performed on relevant subsets using a random intercept logistic regression model. Estimated median incidence of ARMD requiring revision surgery within study follow-up period was 0.3% (95% CI 0.1 – 1.8%, from 11 cohort studies containing 1312 cases).
- Serum metal ion levels were mildly raised in 7.9% of cases, and significantly raised in 1.8%, but there was no correlation with worse clinical hip function scores within studies. Dislocation rate was 0.8%. Revision rate was 3.3%.
- There are mixed reports of wear on the backside of the metal liner from the acetabular shell and screw heads. Both implant design and component malseating are implicated, but currently it is unclear to what extent each factor is responsible.
- Studies were poor quality with high risk of confounding, especially from trunnion corrosion. We have made recommendations for further work. In the meantime, surgeons should be aware of the potential risk of ARMD when considering using an MDM prosthesis, and, if selecting one, must ensure proper seating of the liner and screws intra-operatively.

Keywords: ALTR; ARMD; arthroplasty; hip replacement; metal; modular dual-mobility

Introduction

Dislocation remains a major challenge following total hip replacement (THR), occurring after 0.5% to 5% of primary and 5% to 30% of revision procedures.^{1–4} Dual-mobility (DM) constructs are one option for patients deemed at high risk. The concept, pioneered by Bousquet and Rambert in the 1970s, uses two articulating surfaces to combine the stability of a large femoral head with Sir John Charnley’s low-friction arthroplasty principle.^{5,6} DM constructs comprise a small femoral head articulating within a mobile polyethylene liner, that itself articulates within a fixed acetabular shell. These components improve stability by increasing the head–neck ratio, range of motion, and jump distance.⁷ Several studies have reported lower dislocation rates with DM implants, most marked in revision arthroplasty.^{4,8,9}

Modular dual-mobility

The original, ‘anatomical’ dual-mobility (ADM) constructs use a monoblock acetabular shell, lacking a central cup or screw holes, and therefore limiting use for complex revision surgery. More recently, modular dual-mobility (MDM) constructs have been developed (for example MDM by Stryker Ltd, Berkshire, UK, and the Delta TT system by Lima Orthopaedics UK Ltd, Herts, UK), where a modular cobalt–chromium (CoCr) liner sits within the traditional titanium acetabular shell. This adds the advantages of the traditional porous metal shell, with its options for supplementary acetabular screw fixation, use of metal augments, and ability to visualize complete seating of the cup through the screw holes. However, the combination of the CoCr liner and titanium shell creates a new interface for potential fretting corrosion and subsequent adverse reaction to metal debris (ARMD).

Adverse reaction to metal debris

ARMD is an umbrella term used to describe joint failures associated with pain, a large sterile effusion of the hip and/or macroscopic necrosis/‘metallosis’.¹⁰ Diagnosis is based on clinical suspicion, raised serum metal ion levels, magnetic resonance imaging (MRI), and ultimately intra-operative and histological findings. ARMD was first noted in metal-on-metal (MoM) THR, occurring between bearing surfaces and also as a result of fretting corrosion at the modular neck–head junction. For the purposes of this review, ARMD encompasses other terms found in the literature such as ‘metallosis’, pseudotumour, adverse local tissue reaction (ALTR), and aseptic lymphocyte-dominated vasculitis-associated lesion (ALVAL).

Aim

The aim of this systematic review was to find and review all relevant studies to establish outcomes following THR with an MDM construct, with a particular focus on ARMD.

Methods*Study criteria*

Inclusion criteria were all clinical studies of adult patients receiving an MDM hip replacement as either a primary or revision procedure. Exclusion criteria were studies which were not specifically on MDM constructs or which grouped MDM with other hip replacements in analysis, case reports, review articles, expert opinion pieces, bio-mechanical studies, animal studies, in vitro studies, book chapters, conference abstracts, and non-English-language articles. In cases of multiple articles reporting on the same patient cohort, the latest article was included and the others excluded.

Outcome measures

The primary outcome measure was the rate of ARMD requiring revision surgery, as defined by primary studies. Secondary outcome measures were mean postoperative cobalt (Co) and chromium (Cr) levels, proportion of patients with raised metal ion levels, evidence of corrosion on implant analysis, clinical hip scores, dislocation rate, and revision rate.

Literature search

A systematic search of the literature was undertaken on 7 June 2020. The full search strategy is available in Appendix 1. Search terms included variations on hip or acetabular replacement in combination with modular dual mobility, with no date restriction. The search was performed in Medline, EMBASE, CINAHL, Cochrane Library, and Prospero. Reference lists of selected studies

were also manually searched. A proposal for the systematic review was submitted to PROSPERO in May 2020 (CRD42020177033).

Data extraction and risk of bias assessment

Two reviewers (JF and SS) independently screened titles and abstracts to identify potentially useful articles. Disputes were settled by a third reviewer (NS). Data extracted included study design, type of arthroplasty (primary/revision), indication for arthroplasty, mean follow-up, implant manufacturer, femoral head material, use of supplementary acetabular screws, dislocation rate, revision rate, ARMD rate, mean serum metal ion values, and proportion of patients with raised serum metal ion measurements (Co or Cr ≥ 1 $\mu\text{g/L}$, and Co or Cr ≥ 7 $\mu\text{g/L}$).

A ‘normal’ cut-off value of Co or Cr ≥ 1 $\mu\text{g/L}$ was chosen due to it being the most common amongst included studies. If the incidence of cases above this value was not expressed, the most conservative estimate was taken from the range. For example, if results were expressed as ‘mean Co 0.85 range 0.5–2.3 $\mu\text{g/L}$, Cr 0.61 range 0.5–1.3 $\mu\text{g/L}$ ’, the study would be counted as having one case of Co or Cr levels ≥ 1 $\mu\text{g/L}$, as potentially one case could have been responsible for both upper limit values. If studies included more than one postoperative serum metal ion measurement (e.g. at 1 and 2 years postoperatively), the latest value was used.

Risk of bias of included studies was assessed using the Methodological Index for Non-Randomised Studies (MINORS) scoring system;¹¹ a validated tool for assessing study quality which gives a score out of 16 for non-comparative, and 24 for comparative studies. Again, two reviewers independently scored each article (JF and SS) with a third to settle disputes (NS).

Statistical analysis

Meta-analysis was undertaken to synthesise values for (a) the incidence of ARMD requiring revision surgery (b) incidence of dislocation (c) incidence of revision (d) incidence of a serum cobalt or chromium level ≥ 1 $\mu\text{g/L}$ (e) incidence of a serum cobalt or chromium level ≥ 7 $\mu\text{g/L}$ (f) mean serum values of cobalt (g) mean serum values of chromium. Given that the data are observational, and that there were substantial differences in population, type of implant, femoral head material, length of follow-up, primary or revision procedure, and indication for surgery, a random-effects approach was undertaken for all analyses. For analyses (a) to (e) the data are proportions of patients who have a relatively rare outcome and values of zero are common. For these reasons a random intercept logistic regression model was used, with confidence intervals derived using the t distribution.¹² For analysis (a), only cohort studies with detailed clinical follow-up were

included in order to give an accurate estimate of incidence. Convergence was achieved for all models. For analyses (f) and (g) a random-effects meta-analysis was performed using the restricted maximum likelihood estimator for heterogeneity, and the Knapp-Hartung method was used for confidence intervals. However not all studies reported all values necessary for these analyses. When either the mean serum values or standard deviation were unavailable they were estimated from the available values.¹³ Funnel plots were inspected for evidence of bias. All analysis was performed in R,¹⁴ using the metafor package.¹⁵

Results

The initial search yielded 99 articles. After screening for duplicate publications, 46 were excluded, leaving 53. Screening by title and abstract excluded a further 21, leaving 32 articles which underwent full-text review. Out of these, 16 were identified for overall inclusion¹⁶⁻³¹ (Fig. 1³²), with meta-analysis performed on specific subsets as described below.

The 16 included studies were grouped into four types: seven cohort studies of MDM hip replacements looking specifically for ARMD with serum metal ion measurements, five cohort studies of general outcomes following MDM hip replacements, three implant retrieval retrospective case series, and one retrospective radiological study. Average follow-up ranged from 1.1 to 5.1 years. Table 1 summarizes key study characteristics.

The incidence rate of ARMD requiring revision surgery following MDM THR was estimated to be 0.3% from meta-analysis (95% CI 0.1 – 1.8%, 6 from 1312 cases). This calculation was based on data from 11 cohort studies, and excluded implant retrieval case series (see Table 1 and Fig. 2). Fig. 2 is a forest plot for ARMD incidence from the included studies. Forest and funnel plots for all other analyses can be found in Appendix 2. There did not appear to be a correlation between follow-up length and incidence of ARMD.

Data on dislocation were only reported in six studies, with 14 reported in 1109 cases. The estimated median incidence of dislocation was 0.8% (95% CI 0.1 – 4.3%).

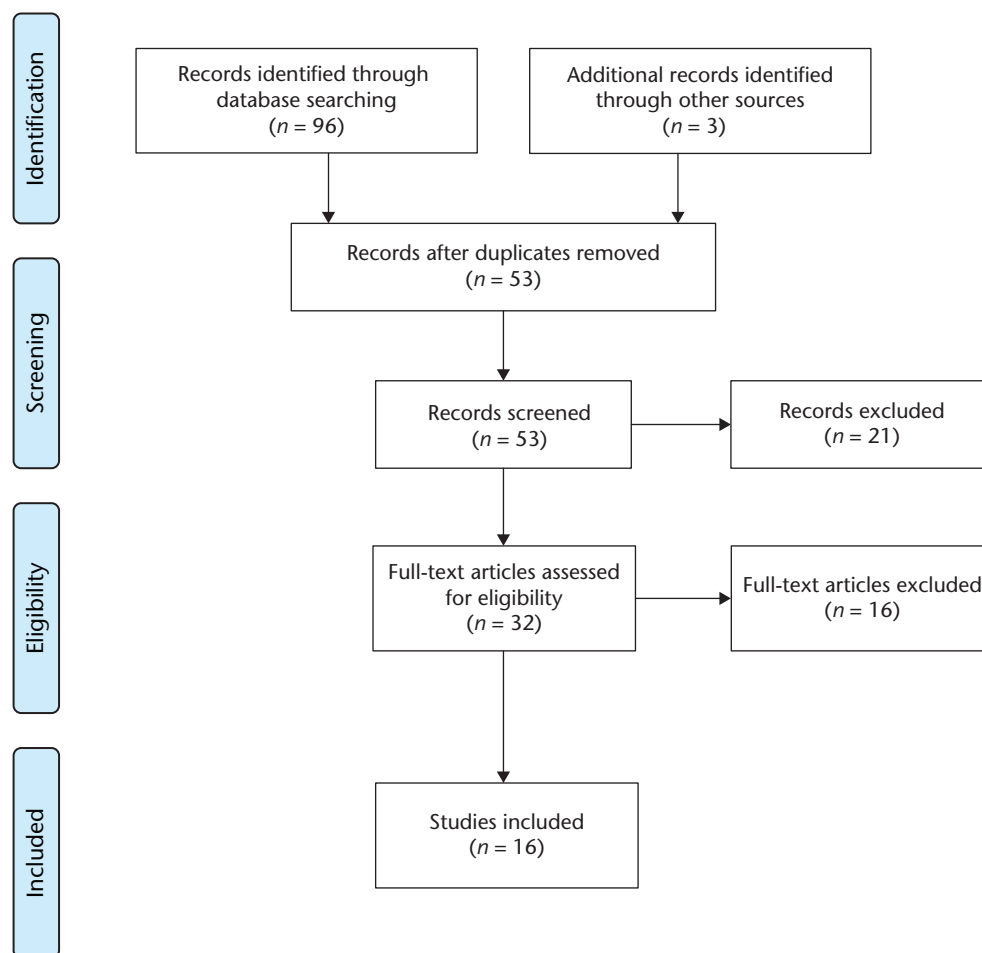


Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram outlining the systematic review process.³²

Table 1. Summary of all study characteristics, grouped by study type. A dash (–) denotes data that were unreported. An asterisk (*) denotes data excluded from meta-analysis, e.g. case series are unable to contribute data on incidence

	Study	Study design (single centre unless specified)	Primary or revision THR	Number of cases	Average follow-up (years)	Implant (company)	Mean age (years)	Mean BMI (kg/m ²)	Dislocations, n (%)	Revisions, n (%)	ARMD, n (%)
With serum metal ion measurements	Civinini et al, 2020 ¹⁶	Cross-sectional study	Revision	37	5.1	Delta TT System (Lima)	63.7	26.5	–	–	0
	Markel et al, 2019 ¹⁹	Prospective cohort, non-comparative	Primary	39	2	MDM (Stryker)	61.7	28.4	–	–	0
	Chalmers et al, 2019 ²⁰	Prospective cohort, non-comparative	Both	24	4	MDM (Stryker)	63.0	31.0	–	Excluded	0
	Nam et al, 2019 ²²	Prospective cohort, non-comparative	Primary	43	2	MDM (Stryker)	52.6	27.9	–	0	0
	Diamond et al, 2018 ²³	Retrospective cohort, non-comparative	Revision	60	3.21	MDM (Stryker)	65.5	30.9	–	6 (10%)	2 (3.3%)
	Barlow et al, 2017 ²⁴	Prospective case-series of various well functioning primary THRs	Primary	20	1.3	MDM (Stryker)	66.8	–	Excluded	Excluded	Excluded
	Matsen Ko et al, 2016 ²⁷	Retrospective cohort, non-comparative	Primary	100	2.3	MDM (Stryker)	–	–	1	0	2
Without serum metal ion measurements	Dubin et al, 2019 ¹⁷	Retrospective cohort: MDM vs. ADM	Primary	287	2.86	MDM (Stryker)	67.9	29.3	0	5 (1.7%)	0
	Li et al, 2019 ¹⁸	Retrospective cohort: MDM vs. conventional	Revision	94	3.15	MDM (Stryker)	63.6	29.6	2 (2.13%)	9 (9.57%)	1 (1%)
	Huang et al, 2019 ²¹	Retrospective cohort, multi-centre, non-comparative	Revision	315	3.3	MDM (Stryker)	65.8	31.4	9 (3.8%)	30 (9.5%)	0
	Sutter et al, 2017 ²⁵	Retrospective cohort, non-comparative	Revision	64	3.17	MDM (Stryker)	59.0	29.4	2 (3.1%)	18.80%	1 (1.6%)
	Harwin et al, 2017 ²⁶	Retrospective cohort, multi-centre, non-comparative	Primary	249	3.3	MDM (Stryker)	66.0	34.0	0	2 (0.8%)	0
Implant retrieval analyses	Kolz et al, 2020 ³⁰	Implant retrieval case series: MDM	Both	12	2.16	MDM (Stryker)	–	26.0	N/A	N/A	*
	Lombardo et al, 2019 ²⁹	Implant retrieval analysis: ADM vs. MDM	–	18	1.12	MDM (Stryker)	70.5	30.0	N/A	N/A	*
	Tarity et al, 2017 ²⁸	Implant retrieval analysis: MDM vs. MoM	Both	18	1.25	MDM (Stryker)	64.0	27.0	N/A	N/A	*
Radiological	Romero et al, 2020 ³¹	Retrospective cohort: MDM	Primary	551	–	MDM (Stryker)	67.9	28.3	–	–	–

Notes. THR, total hip replacement; BMI, body mass index; ARMD, adverse reaction to metal debris; MDM, modular dual-mobility; ADM, ‘anatomical’ dual-mobility; MoM, metal-on-metal.

Revision rates were reported in eight studies, with 70 revisions out of 1212, giving an estimated median incidence of 3.3% (95% CI 0.9 – 11.7%).

The mean postoperative serum cobalt level across all studies was calculated to be 0.81 µg/L (95% CI 0.11 – 1.51 µg/L), and chromium was 0.77 µg/L (95% 0.2 – 1.34 µg/L), both from 279 cases in seven studies. Estimated median incidence of a serum cobalt or chromium ion

measurement ≥1 µg/L was 7.9% (95% CI 3.5 – 16.8%) and ≥7 µg/L was 1.8% (95% CI 0.7 – 4.2%). Table 2 summarizes study metal ion levels with relevant study characteristics.

No studies reported a statistically significant correlation between raised serum metal ions and lower clinical hip function scores, which were universally good across all 12 cohort studies.

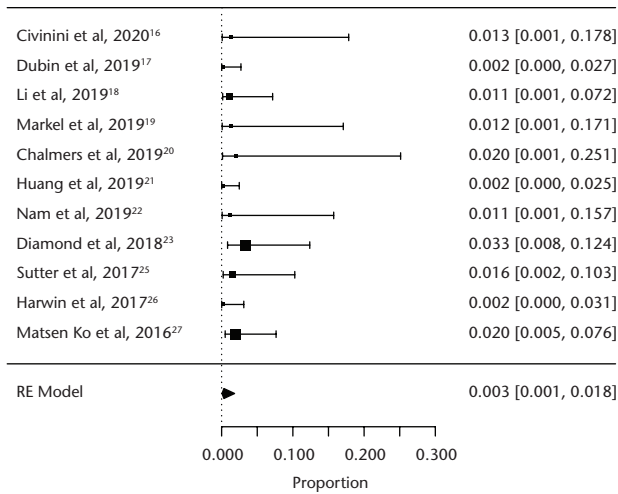


Fig. 2 Forest plot showing adverse reaction to metal debris (ARMD) incidence.

Of the implant retrieval studies, two did not show any significant overall increase in fretting corrosion in MDM compared to both ADM and MoM prostheses.^{28,29} The third, most recent, implant retrieval study reported clinically significant material loss in all implants of varying severity.³⁰

Mean MINORS scores were 7.8 (/16) for non-comparative and 14.4 (/24) for comparative studies, showing that the quality of studies was generally low, with a high risk of bias (Appendix 3).

Discussion

The estimated incidence of ARMD following MDM hip replacement is 0.3% (95% CI 0.1 – 1.8%). This is higher than the 0.032% reported in all non-MoM primary hip

replacements on retrospective review of the National Joint Registry for England, Wales, Northern Ireland and the Isle of Man.³³ Additionally, included studies had relatively short mean follow-up periods, ranging from 1.1 to 5.1 years; whereas revisions for ARMD in MoM hips are performed on average 5.6 years after index surgery. The incidence is therefore a concern and requires further study. Surgeons should be aware of the potentially increased rate of ARMD as an additional risk when considering use of these constructs during preoperative planning. More reassuringly, the rate of ARMD is substantially lower than the 3.7% estimated in MoM hip replacements.³³

The proportion of patients who had a Co or Cr measurement of $\geq 1 \mu\text{g/L}$ postoperatively was 7.9% (95% CI 3.5 – 16.8%). The clinical significance of these values is unclear as there was no correlation clinically within studies, and additionally there are no established ‘normal’ metal ion levels following THR.²⁴ Here, the cut-off value of $\geq 1 \mu\text{g/L}$ was selected as it was the most commonly used. For MoM hip replacements the MHRA (Medicines & Healthcare Products Regulatory Agency, UK regulatory body) advise a cut-off value of $\geq 7 \mu\text{g/L}$ for either cobalt or chromium.³⁴ This threshold has a high specificity (89%) but low sensitivity (52%) for ARMD.³⁵ From our meta-analysis, 1.8% (95% CI 0.7 – 4.2%) of patients had Co or Cr levels above this threshold. More recently, implant-specific cut-offs for MoM hip replacements have been suggested, for example a cobalt level of $\geq 2.15 \mu\text{g/L}$ for a unilateral Birmingham MoM THR,³⁶ suggesting that it may not be appropriate to use one blanket threshold for all designs. Two recent studies specifically on standard metal-on-polyethylene (MoP) constructs reported > 90% sensitivity and specificity using a threshold cut-off of cobalt $\geq 1.0 \mu\text{g/L}$ for diagnosing ARMD, likely as a result of trunnion corrosion.^{37,38} On the

Table 2. Serum metal ion levels by study, with relevant characteristics such as femoral head material and use of acetabular screws. An asterisk (*) is used to indicate where individual data were not specified, necessitating a conservative estimate (see Methods)

Study	Primary or revision THR	Number	Implant	Femoral head material	Acetabular screw fixation	ARMD, n (%)	Average serum metal ion levels ($\mu\text{g/L}$), mean unless specified	Number of cases with Co or Cr $\geq 1 \mu\text{g/L}$	Number of cases with Co or Cr $\geq 7 \mu\text{g/L}$
Civinini et al, 2020 ¹⁶	Revision	37	Delta TT System (Lima)	CoCr	All pts (mean 4.2 screws, range 2–7)	0	Co 1.99 (95% CI 0.81–3.17, range 0.07–16.05), Cr 2.08 (95% CI 0.9–3.2, range 0.02–11.8)	11 (29.7%)	2*
Markel et al, 2019 ¹⁹	Primary	39	MDM (Stryker)	Ceramic	–	0	Co 0.63 (SD 0.36), Cr 0.63 (SD 0.38)	4 (10.3%)	0
Chalmers et al, 2019 ²⁰	Both	24	MDM (Stryker)	Ceramic	All patients	0	Co 0.3 (range 0.2–0.6), Cr 0.76 (0.1–12.0)	1 (4.2%)	1 (4.2%)
Nam et al, 2019 ²²	Primary	43	MDM (Stryker)	14 CoCr, 29 ceramic	–	0	Co 0.16 (SD 0.23; range 0.04–0.94), Cr 0.14 (SD 0.053; range 0.07–0.26)	0	0
Diamond et al, 2018 ²³	Revision	60	MDM (Stryker)	59 CoCr, 1 ceramic	‘Most commonly, 2 or 3’	2 (3.3%), both recurrent	Median Co 0.42 (range 0.21–9.42), Cr 0.4 (range 0.1–6.1)	2* (3.3%)	1 (1.7%)
Barlow et al, 2017 ²⁴	Primary	20	MDM (Stryker)	10 CoCr, 10 ceramic	–	0	Co 0.85 (SD 0.54, range 0.5–2.3), Cr 0.61 (SD 0.26, range 0.5–1.3)	1* (5%)	0
Matsen Ko et al, 2016 ²⁷	Primary	100	MDM (Stryker)	99 CoCr, 1 ceramic	–	2	‘Average’ Co 0.7 (range 0.0–7.0), Cr 0.6 (range 0.1–2.7)	9 (9%)	1 (1.0%)

Notes. THR, total hip replacement; ARMD, adverse reaction to metal debris; Co, cobalt; Cr, chromium; MDM, modular dual-mobility.

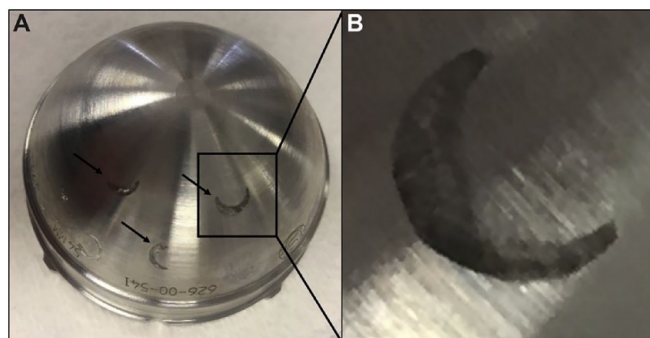


Fig. 3 Photograph showing fretting on the backside of the modular metal liner from acetabular screw heads.

Source: Reproduced with the authors' permission, courtesy of Lombardo et al.²⁹

other hand there are studies that report no correlation between preoperative serum metal ion levels and intra-operative scoring for severity of ARMD.³⁹ Considering this conflicting evidence, currently metal ion levels should be regarded as an unproven surrogate marker for ARMD, and therefore no strong conclusions can be drawn from the mean postoperative Co value of 0.81 $\mu\text{g/L}$ (95% CI 0.11 – 1.51 $\mu\text{g/L}$). The figure might be useful as a reference value against which further work can be compared.

Regarding the source of metal-based debris, results of implant retrieval studies were also varied. Kolz et al found significant material loss on the metal liner in all 12 of their cases, but those revised for ARMD ($n = 3$) did not show significantly higher fretting corrosion scores.³⁰ The two other studies found no significant increase in fretting corrosion of MDM compared to MoM or ADM constructs ($n = 36$),^{28,29} with no cases revised due to ARMD. Whilst this is somewhat reassuring, there was one reported case of macroscopic damage on the backside of the inner metal liner seemingly from acetabular screw heads (Fig. 3). This occurrence was also reported in the included cohort study by Sutter et al,²⁵ where, during the revision procedure for pain and raised serum chromium ions (7.3 $\mu\text{g/L}$), metal staining of soft tissues and mild scuffing from loose screw heads on the backside of the metal liner was noted, without visible wear of the femoral component. Unfortunately, the usage of acetabular screws is sparsely reported in the literature (Table 2), limiting further conclusions. Another theory is provided by the radiographic study of 551 cases, finding that 5.8% of MDM liners were malseated on retrospective evaluation.³¹ Subsequent in vitro modelling in the same study suggested that liner malseating can lead to lower fretting onset loads. Taken together, these results corroborate findings by Kolz et al³⁰ describing three different patterns of wear, and suggest that debris generation in MDM constructs is likely a combination of intrinsic (component design) and extrinsic (surgical) factors. Surgeons, if choosing to use an MDM

construct, should therefore take extra care to ensure that screw heads are completely recessed within the holes of the acetabular shell, and the metal liner is properly seated. We recommend a low threshold for postoperative imaging and serum metal ion testing.

The estimated median incidence of dislocation was 0.8% (95% CI 0.2 – 2.9). Both primary and revision procedures were grouped together in this analysis due to low number of cases. The results broadly align with the 0.46–3% quoted in meta-analyses of all DM constructs specifically examining dislocation rate,^{4,8} and is in accordance with findings that DM constructs can be used to minimize risk of dislocation following THR.

Limitations

The main limitation of this review is that the primary evidence is of low quality with high risk of bias, mostly comprising small, clinically heterogeneous, retrospective cohort studies. The main methodological weakness of studies was a lack of control against confounding from fretting corrosion at the head–neck taper junction; the majority (12 of 16) of the studies either used CoCr femoral heads, made no distinction between cases using CoCr or ceramic heads in analysis, or did not report femoral head material.^{16–18,21–23,25–30}

The use of ARMD requiring revision surgery as the primary outcome measure is also a limitation as it does not take into account non-operatively managed cases. This is especially relevant considering the relatively short follow-up period and possibility of publication bias; the incidence of 0.3% is therefore likely an under-estimate.

For metal ion levels, source data were not obtained from individual studies. Two of seven studies did not express incidence of cases with either Co or Cr measurements ≥ 1 $\mu\text{g/L}$ ^{23,24}, and conservative estimates had to be taken from the range, also likely resulting in an under-estimate.

More broadly, meta-analysis of observational data should not be considered as accurate as meta-analysis of trial data. The nature of cohort and cross-sectional studies means that results are vulnerable to confounding, as mentioned above, that cannot be adjusted for in this analysis. Results should therefore be considered to be the best available estimates, but still potentially confounded. Additionally, the choice to use a random-effects model is appropriate given the heterogeneous data, but this can increase vulnerability to publication bias.

Recommendations for further work and conclusion

There is a need for a large comparative study of patients with MDM versus ADM hip replacements using ceramic femoral heads. If a cohort with entirely ceramic heads

is not possible, differing femoral head materials should be grouped separately in analysis. A suitable alternative design would be MDM with a CoCr femoral head versus conventional MoP hip replacements. Supplementary screw use with the MDM acetabular component should be reported. Outcome measures should include clinical hip function scores, pre and postoperative serial serum metal ion measurements, with MRI where possible. Optimum average follow-up would be five years or longer. Full summary statistics should be reported to prevent future meta-analyses having to estimate values from the range.

ARMD is a rare but significant complication following total hip replacement using an MDM construct. Its incidence appears higher than that reported in non-MoM hip replacements, but lower than that of MoM hip replacements. MDM hip replacements are associated with raised serum metal ion levels postoperatively. There is no evidence thus far that these elevations are associated with increased risk of ARMD or correlate with worse clinical hip function scores. There are mixed reports of fretting corrosion on the backside of the modular liner from the acetabular shell and/or screws. Malseating of components is a likely contributing factor. However, study quality is low and results are open to confounding, particularly from trunnion corrosion. Pending further work, if using MDM constructs, surgeons should carefully weigh the possibility of increased risk of ARMD against its benefits as part of the normal preoperative planning decision making process. If MDM components are used, great care should be taken to correctly seat acetabular screws and the liner within the acetabular shell.

AUTHOR INFORMATION

¹Bristol Royal Infirmary, University Hospitals Bristol NHS Trust, Bristol, UK.

²Sheffield Teaching Hospitals NHS Foundation Trust, Sheffield, UK.

³Southland Teaching Hospital, Invercargill, New Zealand.

Correspondence should be sent to: Jonathan French, Bristol Royal Infirmary, Upper Maudlin Street, Bristol, BS2 8HW, UK.
Email: jmrfr@hotmail.co.uk

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SUPPLEMENTAL MATERIAL

Supplemental material is available for this paper at <https://online.boneandjoint.org.uk/doi/suppl/10.1302/2058-5241.6.200146>

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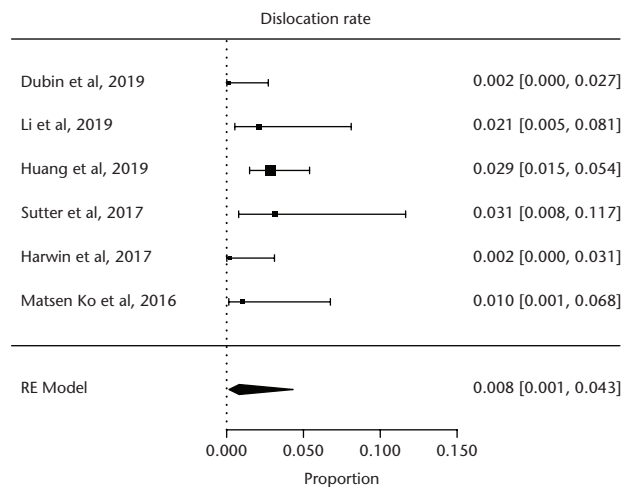
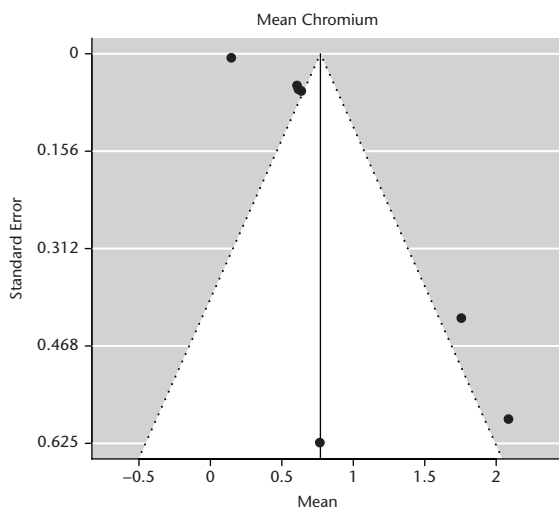
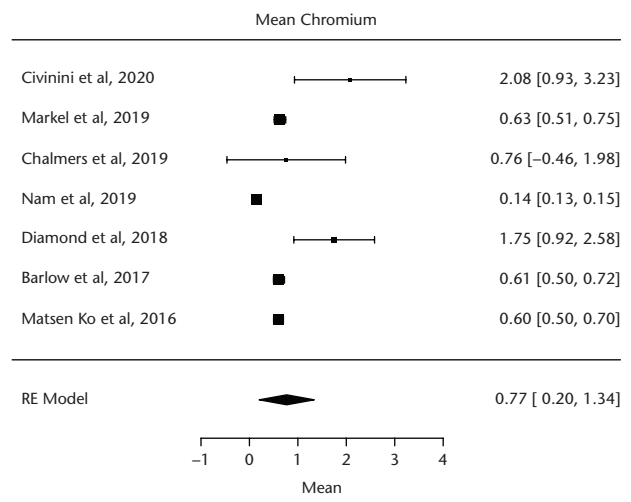
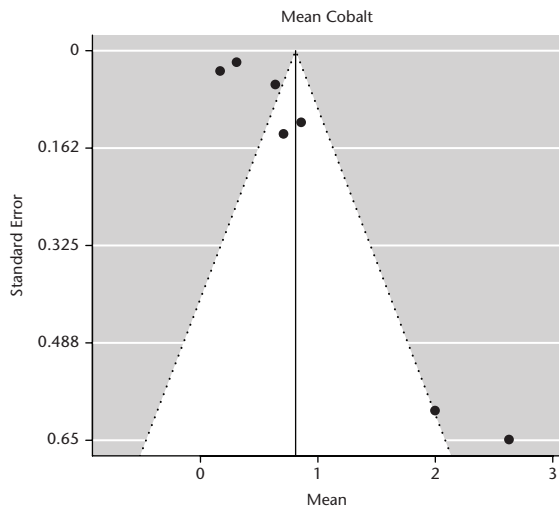
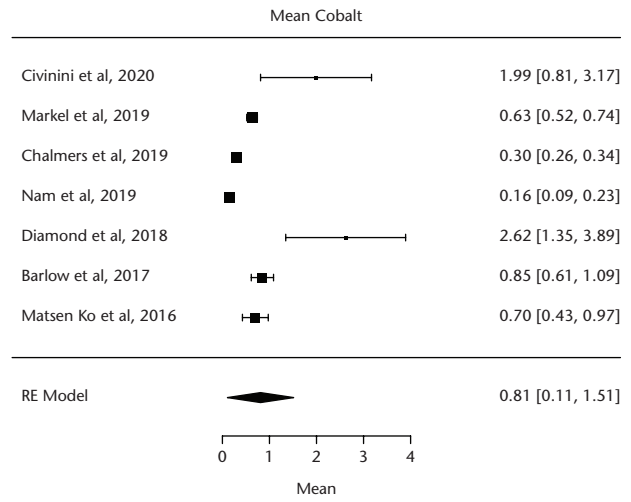
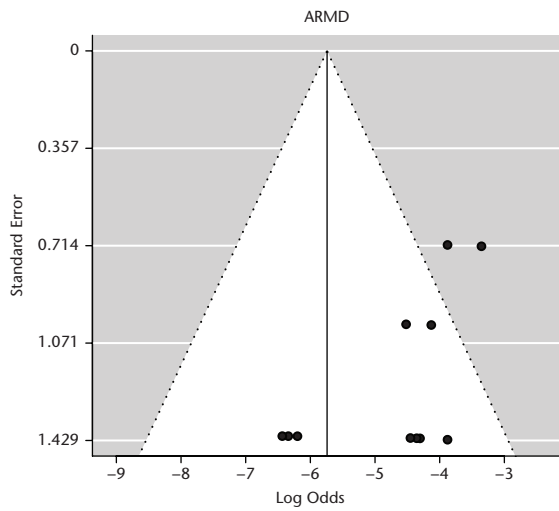
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Appendix 1. Healthcare Databases Advanced Search (HDAS) strategy

Search terms used in HDAS:

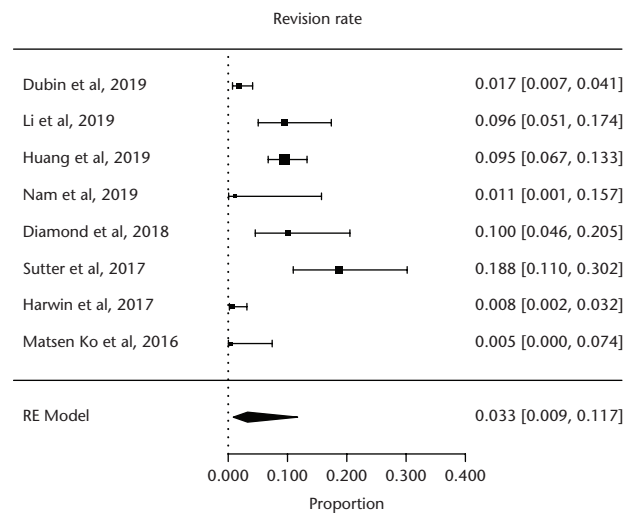
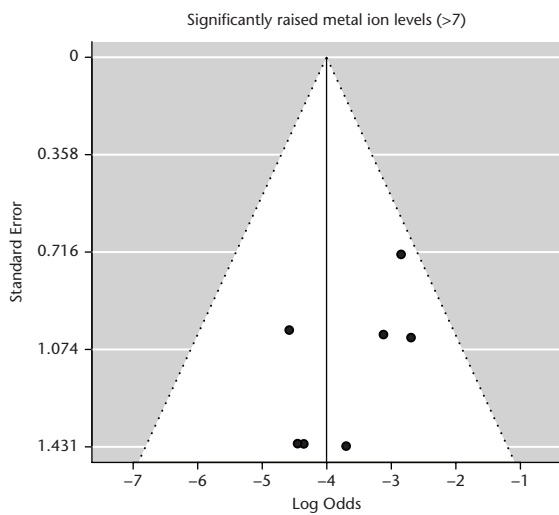
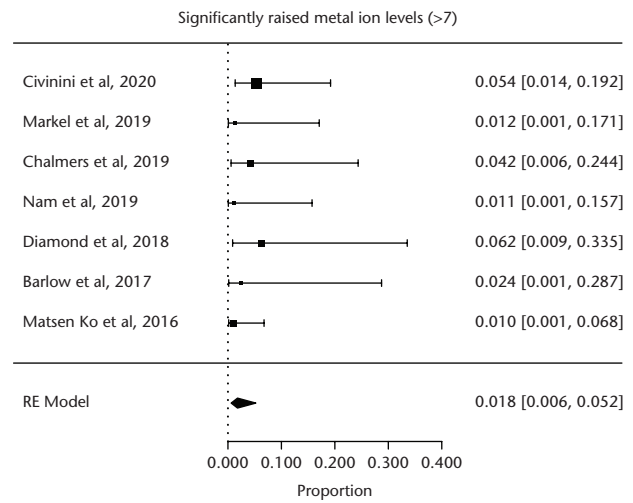
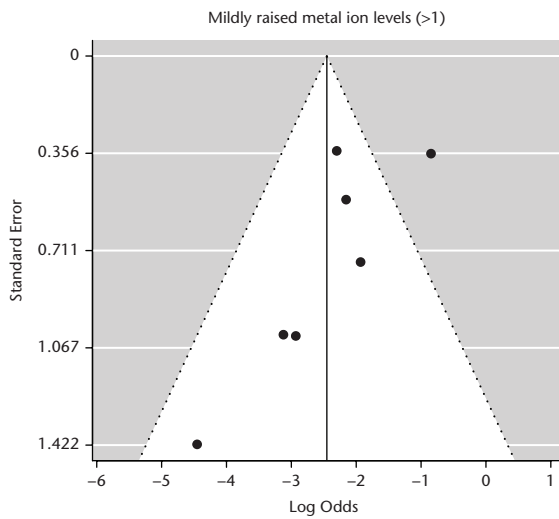
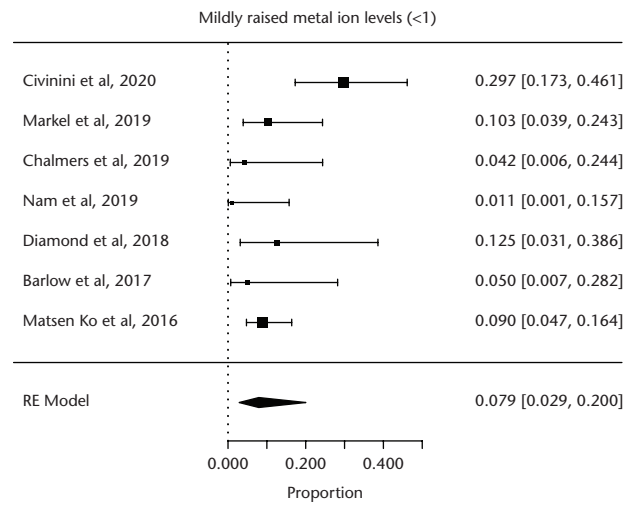
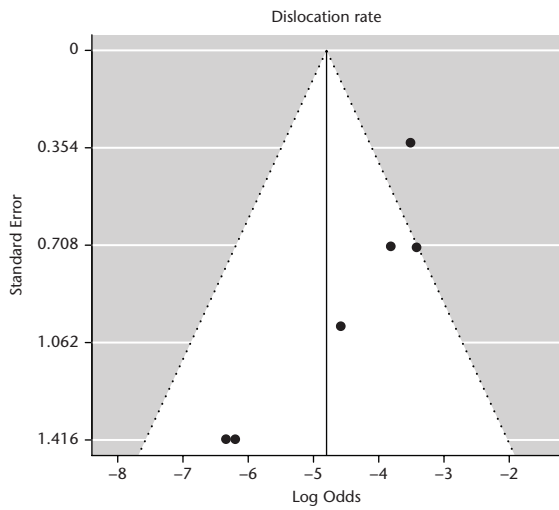
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2. ((hip OR acetabul*) ADJ4 arthroplast*).ti,ab
3. ((hip OR acetabul*) ADJ4 implant*).ti,ab
4. ((hip OR acetabul*) ADJ4 prosthesis).ti,ab
5. exp "ARTHROPLASTY, REPLACEMENT"/
6. (1 OR 2 OR 3 OR 4 OR 5)
7. (modular dual mobility).ti,ab
8. (modular dual-mobility).ti,ab
9. (7 OR 8)
10. (6 AND 9)

Appendix 2. All other forest and funnel plots from meta-analysis



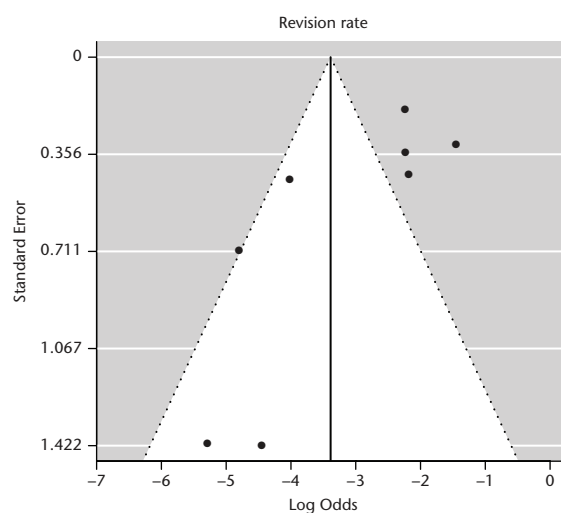
(continued)

Appendix 2 (continued)



(continued)

Appendix 2 (continued)



Appendix 3. Table showing individual risk of bias (MINORS) scores

	MINORS 1	MINORS 2	MINORS 3	MINORS 4	MINORS 5	MINORS 6	MINORS 7	MINORS 8	MINORS 9	MINORS 10	MINORS 11	MINORS 12	Total
Kolz et al, 2020	2	1	2	2	0	1	0	0					8
Romero, 2020	2	2	2	2	0	2	0	0					10
Civinini et al, 2020	2	2	1	2	0	2	1	0					10
Dubin et al, 2019	2	1	2	2	0	1	1	0	2	2	2	2	17
Li et al, 2019	2	2	2	2	0	1	0	1	2	2	1	2	17
Markel et al, 2019	2	0	2	2	0	1	0	0					7
Chalmers et al, 2019	1	2	2	2	0	1	1	0					9
Huang et al, 2019	2	0	2	2	0	1	0	0					7
Nam et al, 2019	2	0	2	2	0	1	0	2					9
Lombardo et al, 2019	1	0	2	2	0	1	0	0	2	0	1	2	11
Diamond et al, 2018	1	2	0	1	0	1	0	0					5
Sutter et al, 2017	1	2	0	2	0	1	0	0					6
Harwin et al, 2017	2	0	1	2	0	1	1	0					7
Tarity et al, 2017	2	1	2	2	0	1	0	0	1	2	1	2	14
Barlow et al, 2017	2	1	1	2	0	1	0	0	1	2	1	2	13
Matsen Ko et al, 2016	1	2	1	1	0	1	2	0					8