

Outcomes of neonatal hypoxic-ischaemic encephalopathy in centres with and without active therapeutic hypothermia: a nationwide propensity score-matched analysis

Lara Shipley , Aarti Mistry, Don Sharkey 

► Additional supplemental material is published online only. To view, please visit the journal online (<http://dx.doi.org/10.1136/archdischild-2020-320966>).

Academic Child Health, School of Medicine, University of Nottingham, Nottingham, UK

Correspondence to

Dr Don Sharkey, Academic Child Health, School of Medicine, University of Nottingham, Nottingham, UK; don.sharkey@nottingham.ac.uk

Received 15 October 2020

Accepted 12 May 2021

Published Online First

27 May 2021

ABSTRACT

Objective Therapeutic hypothermia (TH) for neonatal hypoxic-ischaemic encephalopathy (HIE), delivered mainly in tertiary cooling centres (CCs), reduces mortality and neurodisability. It is unknown if birth in a non-cooling centre (non-CC), without active TH, impacts short-term outcomes.

Design Retrospective cohort study using National Neonatal Research Database and propensity score-matching.

Setting UK neonatal units.

Patients Infants ≥ 36 weeks gestational age with moderate or severe HIE admitted 2011–2016.

Interventions Birth in non-CC compared with CC.

Main outcome measures Primary outcome was survival to discharge without recorded seizures.

Secondary outcomes were recorded seizures, mortality and temperature on arrival at CCs following transfer.

Results 5059 infants were included with 2364 (46.7%) born in non-CCs. Birth in a CC was associated with improved survival without seizures (35.1% vs 31.8%; OR 1.15, 95% CI 1.02 to 1.31; $p=0.02$), fewer seizures (60.7% vs 64.6%; OR 0.84, 95% CI 0.75 to 0.95, $p=0.007$) and similar mortality (15.8% vs 14.4%; OR 1.11, 95% CI 0.93 to 1.31, $p=0.20$) compared with birth in a non-CC. Matched infants from level 2 centres only had similar results, and birth in CCs was associated with greater seizure-free survival compared with non-CCs. Following transfer from a non-CC to a CC ($n=2027$), 1362 (67.1%) infants arrived with a recorded optimal therapeutic temperature but only 259 (12.7%) of these arrived within 6 hours of birth.

Conclusions Almost half of UK infants with HIE were born in a non-CC, which was associated with suboptimal hypothermic treatment and reduced seizure-free survival. Provision of active TH in non-CC hospitals prior to upward transfer warrants consideration.

INTRODUCTION

Moderate or severe hypoxic-ischaemic encephalopathy (HIE) is the leading cause of mortality and neurodisability in infants ≥ 36 weeks gestational age (GA) affecting an estimated 1.5–2.0/1000 births.^{1,2} Active therapeutic hypothermia (TH) started within the first 6 hours postinsult is safe^{3,4} and significantly improves survival and neurodisability.^{5,6} Active TH for moderate/severe HIE has been successfully established within regional cooling centres (CCs),⁷ that are mainly tertiary neonatal centres in

What is already known on this topic?

- Hypoxic-ischaemic encephalopathy (HIE) remains the leading cause of mortality and neurodisability in term infants.
- Active therapeutic hypothermia started within the first 6 hours posthypoxic insult is safe and significantly improves survival and severe neurodisability.
- Infants who subsequently develop seizures secondary to HIE have worse neurodevelopmental outcomes, independent of HIE severity.

What this study adds?

- Infants with moderate or severe HIE who are born in centres without immediate access to active therapeutic hypothermia are less likely to survive without seizures.
- Infants who are transferred into cooling centres frequently arrive beyond the optimal 6-hour therapeutic window and with temperatures outside of treatment range.
- Infants transferred to tertiary cooling centres from level 2 centres with active therapeutic hypothermia are more likely to arrive in target temperature range.

the UK. Infants born in non-cooling centres (non-CCs), typically non-tertiary centres where equipment to undertake active TH is not available, are usually passively cooled prior to upward transfer to a regional CC. Although many neonatal transport teams use active TH during transportation,⁸ their availability, despatch time and travelling distance can delay achieving target temperature for babies in non-CCs with delays beyond 6 hours of age potentially reducing the benefits of TH.⁹ Furthermore, early TH (<3 hours of age) has been associated with better neurodevelopmental outcomes^{9,10} although not universally.^{11,12}

High seizure burden in HIE, based on their number, frequency and treatment required, is associated with more severe brain injury and adverse neurodevelopmental outcomes^{13–18} and this may be independent of HIE severity.^{15,19} Furthermore,



► <http://dx.doi.org/10.1136/fetalneonatal-2021-322563>



© Author(s) (or their employer(s)) 2022. No commercial re-use. See rights and permissions. Published by BMJ.

To cite: Shipley L, Mistry A, Sharkey D. *Arch Dis Child Fetal Neonatal Ed* 2022;**107**:F6–F12.

Table 1 Demographic and clinical variables of infants ≥ 36 weeks gestational age with moderate or severe hypoxic-ischaemic encephalopathy both prepropensity and postpropensity score-matching

Variables	Unmatched infants				Propensity score-matched infants			
	Born in non-CC n=2364*	Born in CC n=2695*	SMD	P value†	Born in non-CC n=2165*	Born in CC n=2165*	SMD	P value†
Gender (male)	1354 (57.3)	1417 (52.6)	-0.095	0.002	1203 (55.6)	1225 (56.6)	0.02	0.49
Birth weight (g)	3340 (2957–3760)	3332 (2940–3750)	0.014	0.7	3340 (2944–3760)	3340 (2970–3775)	-0.018	0.23
Gestation (weeks)	40 (38–41)	40 (38–41)	-0.015	0.47	40 (38–41)	40 (38–41)	-0.006	0.85
Birth year	2014 (2012–2015)	2014 (2012–2015)	-0.089	0.02	2014 (2012–2015)	2014 (2012–2015)	0.026	0.4
Pre-eclampsia	113 (4.8)	120 (4.5)	0.016	0.58	98 (4.5)	97 (4.5)	0.003	0.92
Maternal infection	555 (23.5)	559 (20.7)	0.066	0.02	480 (22.2)	480 (22.2)	0	0.99
Mode of delivery‡								
Em CS no labour	405 (17.1)	449 (16.7)	0.013	0.66	375 (17.3)	357 (16.5)	0.022	0.48
Em CS in labour	682 (28.9)	787 (29.2)	-0.008	0.78	639 (29.5)	630 (29.1)	0.008	0.8
El CS no labour	20 (0.9)	28 (1.0)	-0.02	0.48	21 (0.95)	18 (0.81)	0.014	0.64
El CS in labour	7 (0.3)	6 (0.2)	0.014	0.61	7 (0.33)	6 (0.27)	0.011	0.72
Instrumental	358 (15.1)	514 (19.1)	-0.104	<0.001	355 (16.4)	310 (14.3)	0.06	0.05
Missing	100 (4.2)	84 (3.1)	0.059	0.04	80 (3.7)	74 (3.4)	0.014	0.65
Presentation								
Cephalic	1833 (77.5)	2206 (81.9)	-0.107	<0.001	1753 (81.0)	1734 (80.1)	0.022	0.47
Breech	154 (6.5)	205 (7.6)	-0.043	0.13	142 (6.6)	162 (7.5)	-0.036	0.2
Transverse	11 (0.5)	12 (0.5)	0.003	0.91	11 (0.62)	11 (0.5)	0.003	0.92
Other	20 (0.9)	17 (0.6)	0.025	0.37	15 (0.7)	15 (0.68)	0.004	0.9
Missing	346 (14.6)	255 (9.5)	0.16	<0.001	244 (11.3)	244 (11.3)	0	1
Intrapartum events	276 (11.7)	349 (13.0)	-0.039	0.17	265 (12.2)	257 (11.9)	0.011	0.72
Significant resuscitation	1364 (57.7)	1703 (63.2)	-0.112	<0.001	1312 (60.6)	1278 (59.0)	0.033	0.28
Apgar at 5 min	4 (2–5)	4 (2–6)	-0.01	0.56	4 (2–5)	4 (2–6)	-0.003	0.72
Grade of HIE								
Grade 2	811 (34.3)	1068 (39.6)	0.11	<0.001	779 (36.0)	760 (35.1)	-0.018	0.55
Grade 3	1553 (65.7)	1627 (60.4)			1386 (64.0)	1405 (64.9)		
Place of birth level§								
Level 1	670 (28.3)	0	-		615 (28.4)	0	-	-
Level 2	1546 (65.4)	701 (26.0)	0.861	<0.001	1425 (65.8)	566 (26.2)	0.868	<0.001
Level 3	18 (0.8)	1938 (71.9)	-2.198	<0.001	16 (0.8)	1551 (71.6)	-2.183	<0.001
Home	96 (4.1)	56 (2.1)	0.094	<0.001	82 (3.8)	48 (2.2)	0.094	0.002
Midwife led unit	34 (1.4)	0	-		27 (1.2)	0	-	-
Interhospital transfers§								
L1–L3 transfer	632 (26.7)	0	0.854	<0.001	578 (26.7)	0	-	<0.001
L2–L3 transfer	1386 (58.6)	452 (16.8)	0.957	<0.001	1283 (59.3)	358 (16.5)	0.981	<0.001

*Data are n (%) or median (IQR).

†Categorical data analysed using χ^2 test; non normally distributed continuous data analysed using Mann-Whitney U test; matched data by paired t-test for continuous data or McNemar's test or extensions thereof for binary and categorical data.

‡Compared with baseline – NVD.

§Variables not included in propensity score matching.

CC, cooling centre; El CS, elective caesarean section; Em CS, emergency caesarean section; HIE, hypoxic-ischaemic encephalopathy; L2, level 2; L3, Level 3; NVD, normal vaginal delivery; SMD, Standardised mean difference.

studies have suggested that TH for HIE suppresses and reduces the overall burden of seizures,^{6 13 20 21} leading some to conclude that seizures exacerbate the underlying brain injury and is potentially one of the mechanisms by which TH protects the brain.^{21 22} Parents of infants with seizures associated with HIE have more mental health problems with symptoms of anxiety and depression.²³

Centralisation of CCs has resulted in many infants requiring transportation soon after their insult and potentially during a period of increased susceptibility to secondary brain injury. It is unclear if the transport of newborns with HIE impacts on their outcomes.²⁴ No study has explored the impact of a nationwide

approach to centralised TH for infants with HIE and the impact on outcomes.

The primary aim of this study was to evaluate the relationship between birth in a non-CC and seizure-free survival to discharge in infants ≥ 36 weeks GA with moderate/severe HIE. The secondary aims were to compare mortality, seizures only and admission temperatures for infants transported to a CC.

METHODS

Study population

We performed a retrospective cohort study using the validated UK National Neonatal Research Database (NNRD).²⁵ The NNRD

Table 2 Outcomes of infants with moderate or severe hypoxic-ischaemic encephalopathy who were born in either a non-CC or CC after propensity score matching

Outcome variable	Born in non-CC	Born in CC	OR (95% CI)	P value
	n=2165*	n=2165*		
Survival without seizures	693 (31.8)	764 (35.1)	1.15 (1.02 to 1.31)	0.02
Seizures	1399 (64.6)	1314 (60.7)	0.84 (0.75 to 0.95)	0.007
Death	312 (14.4)	343 (15.8)	1.11 (0.93 to 1.31)	0.2
Day of death (hours)				
<24	65 (3.0)	81 (3.7)	–	0.06
24–72	87 (4.0)	116 (5.4)	1.08 (0.70 to 1.66)	
>72	160 (7.4)	145 (6.7)	0.72 (0.49 to 1.08)	
Anticonvulsants†‡				
None	349 (25.0)	296 (22.5)	–	–
1 drug	668 (47.3)	663 (50.5)	1.17 (0.96 to 1.42)	0.1
≥2 drugs	382 (27.2)	355 (27.0)	1.09 (0.88 to 1.36)	0.4
Respiratory support†				
Ventilated	1454 (67.2)	1515 (70.0)	1.15 (0.94 to 1.42)	0.17
HFOV	388 (17.9)	340 (15.7)	0.97 (0.76 to 1.24)	0.81
CPAP	95 (4.4)	104 (4.8)	1.21 (0.85 to 1.72)	0.28
Hypotension	983 (45.4)	982 (45.4)	0.99 (0.88 to 1.12)	0.96
PPHN	260 (12.0)	236 (10.9)	0.90 (0.74 to 1.08)	0.25
Nitric oxide	214 (9.9)	236 (10.1)	1.02 (0.84 to 1.25)	0.79
Length of stay (days)	11.3 (7.3–18.9)	10.0 (6.5–16.4)	0.14 (0.05 to 0.36)	<0.001

*Data are n (%) or median (IQR).

†Compared with baseline – no anticonvulsant/No respiratory support.

‡Data are n (%) of infants with seizures.

CC, cooling centre; CPAP, continuous positive airway pressure; HFOV, high frequency oscillatory ventilation; PPHN, persistent pulmonary hypertension.

contains prospectively recorded demographic and clinical data. It uses a designated approved dataset (National Neonatal Data Set) within the NHS Data Dictionary with all data items searchable²⁶ and approved by the Standardised Committee for Care Information. Anonymised data are cleaned prior to entry into the database; erroneous entries are amended by the Neonatal Data Analysis Unit.

Data collection

Data were extracted on all infants 36–42 weeks' GA, admitted to neonatal units in the UK between 2011 and 2016, with a diagnosis of moderate/severe HIE and underwent TH. Infants who died within the first 48 hours of life with moderate/severe HIE but did not undergo TH were also included within the study population. Infants were identified using data fields from the NNRD (online supplemental table 1); the most severe grade of HIE recorded was allocated for each infant. Infants were excluded if their birth weight was >2 SD above the 99.6th weight centile (to avoid erroneous data, n=5), those born in private hospitals or with missing birth hospital codes. Identification of CCs and their date of active TH start was cross-checked using the TOBY trial register⁵ and via direct communication with centres.

Outcomes

The primary outcome was seizure-free survival to neonatal discharge in infants ≥36 weeks GA with moderate/severe HIE. Seizures were as recorded by the attending clinical team within the database. Secondary outcomes were mortality, seizures alone, anticonvulsant use and admission temperature from time of birth to arrival at a CC following transfer.

Statistical analysis

Clinical variables between infants born in non-CCs and CCs were compared using χ^2 test for categorical data and Mann-Whitney U test for non-normally distributed data.

Propensity score-matching was used to provide balanced groups of infants matched on demographic and clinical covariates within treatment groups.^{27–28} Propensity score analysis entailed fitting a logistic regression model using a priori variables followed by a stepwise process and evaluation of potential interactions to determine covariates to include in the propensity score model (online supplemental eMethods).

Balancing of the groups postmatching was evaluated by the standardised difference and mean bias between control and treatment groups (online supplemental eMethods, online supplemental figure 1 and table 1).^{29–30} Matched groups of infants from non-CC and CC were identified and the effect of birth in a CC on outcomes was described using ORs.³¹ Data were statistically analysed using Stata SE (Stata, V.16).

Sensitivity analyses

We performed two further paired, matched analyses between infants born in level 2 non-CCs and CCs and between infants born in a non-CC and CC but excluding those born either at home or in midwife led units. The propensity-matching methodology was undertaken as previously described (online supplemental eMethods and online supplemental figures 2 and 3). These additional analyses were performed to evaluate the reliability of our findings by minimising potential bias through differences in intrapartum and early neonatal care between different level centres.

Table 3 Demographic and clinical variables of infants with moderate or severe hypoxic-ischaemic encephalopathy born in level 2 centres post propensity score-matching

Variables	Unmatched infants				Propensity score matched infants			
	Born in non-CC n=1546*	Born in CC n=701*	SMD	P value†	Born in non-CC n=696*	Born in CC n=696*	SMD	P value†
Gender (male)	877 (56.7)	373 (53.2)	-0.07	0.12	366 (52.6)	373 (53.6)	0.02	0.71
Birth weight (g)	3332 (2929–3760)	3370 (2960–3730)	-0.033	0.42	3372 (3004–3764)	3370 (2953–3730)	0.036	0.5
Gestation (weeks)	40 (38–41)	40 (38–41)	-0.047	0.28	40 (39–41)	40 (38–41)	0.032	0.56
Birth year	2014 (2012–2015)	2014 (2012–2015)	-0.134	0.003	2014 (2013–2015)	2014 (2012–2015)	0.01	0.86
Pre-eclampsia	71 (4.6)	38 (5.4)	-0.04	0.4	31 (4.5)	38 (5.5)	-0.046	0.39
Maternal Infection	383 (24.8)	173 (24.7)	0.002	0.96	176 (25.3)	172 (24.7)	0.013	0.8
Mode of delivery‡:								
Em CS no labour	263 (17.0)	118 (16.8)	0.005	0.92	115 (16.5)	118 (17.0)	-0.012	0.83
Em CS in labour	494 (32.0)	205 (29.2)	0.059	0.2	200 (28.7)	205 (29.5)	-0.016	0.77
El CS no labour	13 (0.8)	7 (1.0)	-0.017	0.71	7 (1.0)	6 (0.9)	0.015	0.78
El CS in labour	6 (0.4)	3 (0.4)	-0.006	0.89	4 (0.6)	3 (0.4)	0.02	0.71
Instrumental	240 (15.5)	144 (20.5)	-0.131	0.003	137 (19.7)	140 (20.1)	-0.011	0.84
Missing	57 (3.7)	19 (2.7)	0.055	0.24	28 (4.0)	19 (2.7)	0.072	0.18
Presentation:								
Cephalic	1231 (79.6)	586 (83.6)	-0.103	0.03	588 (84.5)	582 (83.6)	0.024	0.66
Breech	84 (5.4)	42 (6.0)	-0.024	0.59	34 (4.9)	41 (5.9)	-0.044	0.41
Transverse lie	10 (0.7)	4 (0.6)	0.01	0.83	4 (0.6)	4 (0.6)	0	1
Other	11 (0.7)	5 (0.7)	0	1	3 (0.4)	5 (0.7)	-0.038	0.48
Missing	210 (13.6)	64 (9.1)	0.141	0.003	67 (9.6)	64 (9.2)	0.015	0.78
Intra-partum events	187 (12.1)	89 (12.7)	-0.018	0.69	93 (13.4)	89 (12.8)	0.017	0.75
Significant resuscitation	935 (60.50)	434 (61.9)	-0.029	0.52	440 (63.2)	432 (62.1)	0.023	0.66
Apgar at 5 min	4 (2–5)	4 (2–6)	-0.07	0.09	4 (3–6)	4 (2–6)	0.018	0.74
Grade of HIE								
Grade 2	521 (33.7)	243 (34.7)	0.02	0.66	236 (33.9)	240 (34.5)	0.012	0.82
Grade 3	1025 (66.3)	458 (65.3)			460 (66.1)	456 (65.5)		

*Data are n (%) or median (interquartile).

†Categorical data analysed using χ^2 test; non-normally distributed continuous data analysed using Mann-Whitney U test; matched data by paired t-test for continuous data or McNemar's test or extensions thereof for binary and categorical data.

‡Compared with baseline – normal vaginal delivery.

CC, cooling centre; El CS, elective caesarean section; Em CS, emergency caesarean section; HIE, hypoxic-ischaemic encephalopathy; NVD, normal vaginal delivery; SMD, standardised mean difference.

RESULTS

Population

There were 5120 infants ≥ 36 weeks GA admitted to UK neonatal units with moderate/severe HIE and treated with TH. An additional 127 infants with moderate/severe HIE died within the first 48 hours of life without TH treatment were also included. In total, 188 infants were excluded (online supplemental figure 1) leaving 5059 infants for analysis. Prior to matching, 2364 (46.7%) infants were born in a non-CC (table 1). In the unmatched groups, 65.4% of infants in the non-CC group were born in level 2 units; 71.9% of CC infants were born in a level 3 unit.

Propensity matched groups

Propensity score-matching (online supplemental figure 2) yielded a total of 4330 infants (n=2165/group, table 1). Infants born in a CC had significantly higher rates of seizure-free survival prior to discharge compared with infants born in a non-CC (35.1% vs 31.8%; OR 1.15, 95% CI 1.02 to 1.31; p=0.02) and significantly lower odds of recorded seizures overall (60.7% vs 64.6%; OR 0.84, 95% CI 0.75 to 0.95; p=0.007). Mortality prior to discharge was similar between the groups (table 2).

In matched infants, 76.2% (n=2068) of infants recorded as having seizures received anticonvulsant medication, and 27.1%

of these infants received escalation of treatment with additional anticonvulsant agents but there was no difference between groups (table 2). Compared with CC infants, those born in a non-CC received similar amounts of cardiorespiratory support but did require a longer length of hospital stay (table 2).

Level 2 births only

Propensity score-matching yielded 1392 infants (n=696/group, tables 3 and 4, online supplemental figure 3). Matched infants born in a level 2 CC had significantly higher seizure-free survival (38.8% vs 32.3%; OR 1.33, 95% CI 1.06 to 1.65; p=0.01), less recorded seizures (57.6% vs 63.9%; OR 0.77, 95% CI 0.61 to 0.95; p=0.02) and fewer anticonvulsants compared with infants born in level 2 non-CC. Mortality was not significantly different between the groups.

Admission temperature following transfer

A total of 2027 infants (85.7%) transferred from a non-CC to a CC had an admission temperature recorded after arrival. Of these, 259 (12.7%) had an admission temperature within the optimal therapeutic range of $33.5 \pm 0.5^\circ\text{C}$ ³² before 6 hours of age (figure 1 and online supplemental table 2). Overall, 1362 (67.1%) of infants arrived at the CC following transfer with an

Table 4 Outcomes of infants with moderate or severe hypoxic-ischaemic encephalopathy who were born in either a level 2 non-CC or CC after propensity score-matching

Outcome variable	Born in non-CC	Born in CC	OR (95% CI)	P value
	n=696*	n=696*		
Survival without seizures	225 (32.3)	270 (38.8)	1.33 (1.06 to 1.65)	0.01
Seizures	445 (63.9)	401 (57.6)	0.77 (0.61 to 0.95)	0.02
Death	105 (15.1)	90 (12.9)	0.84 (0.62 to 1.13)	0.25
Day of death (hours)				
≤24	25 (3.6)	22 (3.2)	–	0.84
24–72	28 (4.0)	27 (3.9)	1.10 (0.50 to 2.40)	
>72	52 (7.5)	41 (5.9)	0.90 (0.44 to 1.82)	
Anticonvulsants†‡				
None	97 (21.8)	116 (28.9)	–	–
1 drug	222 (49.9)	206 (51.4)	0.90 (0.71 to 1.13)	0.67
≥2 drugs	126 (28.3)	79 (19.7)	0.57 (0.42 to 0.78)	<0.01
Respiratory support†				
Ventilated	493 (70.8)	454 (65.2)	0.92 (0.64 to 1.32)	0.66
HFOV	108 (15.5)	145 (20.8)	1.34 (0.88 to 2.04)	0.17
CPAP	29 (4.2)	30 (4.3)	1.03 (0.56 to 1.91)	0.91
Hypotension	326 (46.8)	303 (43.5)	0.88 (0.71 to 1.08)	0.22
PPHN	97 (13.9)	95 (13.8)	0.98 (0.72 to 1.32)	0.88
Nitric oxide	66 (9.5)	67 (9.6)	1.01 (0.71 to 1.45)	0.93
Transferred L2–L3	615 (88.4)	449 (64.5)	0.24 (0.18 to 0.32)	<0.001
Length of stay (days)	10.6 (7.0–17.5)	10.5 (6.8–17.7)	0.55 (0.13 to 2.40)	0.41

*Data are n (%).

†Compared with baseline – no anticonvulsants/no respiratory support.

‡Data are n (%) of infants with seizures.

CC, cooling centre; CPAP, continuous positive airway pressure; HFOV, high frequency oscillatory ventilation; PPHN, persistent pulmonary hypertension.

admission temperature within target range (online supplemental table 2). There was no significant difference between time of admission for infants who arrived with their temperature within and outside of optimal therapeutic range (7 hours 40 min vs 7 hours 44 min, $p=0.77$). Following transfer to a level 3 centre, infants born in a level 2 CC were significantly more likely to arrive with a temperature in therapeutic range compared with those born in a level 2 non-CC (78.3% vs 67.4%, respectively, OR 0.57; 95% CI 0.43 to 0.76, $p<0.001$) and were less likely to be overcooled ($<33^{\circ}\text{C}$) on arrival (8.1% vs 14.9%, OR 0.51; 95% CI 0.34 to 0.76, $p<0.001$) (table 4, figure 1 and online supplemental table 3).

DISCUSSION

In the UK, the management of HIE with active TH remains mostly in centralised centres within geographical networks and therefore is not currently available in every birthing hospital. This nationwide UK study, of over 5000 infants with HIE, evaluated the relationship between birth in a non-CC and important short-term outcomes using propensity-score matched groups. We found that almost half of infants were born in non-CCs and were less likely to survive without seizures at discharge compared with those born in CCs. This association appears to be driven by a higher rate of recorded seizures in non-CC infants as the mortality rates were similar. Importantly, the association remained significant when comparing only infants born in level 2 centres and following exclusion of those born at home or midwifery led units.

There is increasing evidence that seizures, and the seizure burden relating to HIE, can have an additive effect on the initial brain injury, independent of HIE severity.^{15–17 22 33} Neonatal seizures occur in 50%–60% of infants with HIE³⁴ and are

associated with an increased risk of adverse neurodevelopment outcome, cerebral palsy and epilepsy compared with those without seizures.³⁵ We found fewer recorded seizures in those with access to immediate active TH in CCs supporting evidence from several smaller studies^{21 36} and a systematic review which found a borderline risk reduction of seizures.⁶ There was no increase in the use of anticonvulsants between the groups in the main analysis; the subgroup of level 2 non-CC births was exposed to more treatment with multiple anticonvulsants, some potentially neurotoxic with adverse additive effects on long-term neurodevelopment.³⁷

Specialist neonatal transport teams transferred 53.1% of infants with HIE during the study period at a time when many transport services transitioned from mainly passive cooling to active, servo-controlled TH.³⁸ Only 12.7% of infants transferred to a CC had an admission temperature within the optimal therapeutic range by 6 hours of age. A further 48.3% arrived between 6 and 12 hours of age in target range. There could be delay in deciding to initiate TH in some of the infants which could account for those in the normothermic range. Brain injury following hypoxic-ischaemic injury is progressive consisting of primary, latent and secondary phase.³⁹ The latent period is considered the optimal time for TH through reduction of cellular injury,^{40 41} although TH started within the late latent phase resulted in reduced cell survival compared with earlier use.⁹ Furthermore, TH started after the latent phase postseizure activity did not improve cell survival.⁴² It is plausible that these infants only receive partial protection from TH through passive cooling, which is more likely to occur during the late latent phase or beyond and result in decreased dampening of excitatory neurotransmitters.⁹ Studies have suggested that this reduction in excitatory transmitter release, along with alterations in neuronal

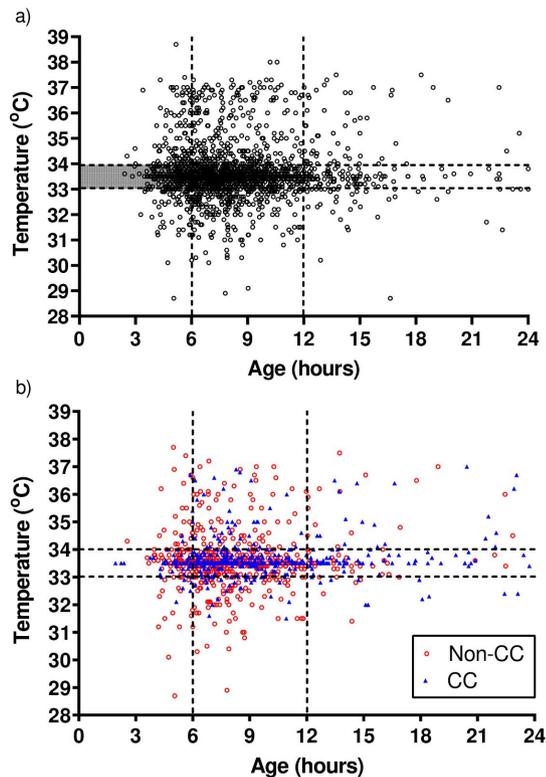


Figure 1 Admission temperature and arrival time following transfer to a CC of infants ≥ 36 weeks gestational age with moderate or severe HIE (A) who were born in a non-cooling hospital ($n=277$) (shaded area optimal temperature in the 6-hour optimal therapeutic window), (B) who were born level 2 centres with immediate access to active TH or non-CC and transferred to a level 3 CC. CC, cooling centre; HIE, hypoxic-ischaemic encephalopathy; TH, therapeutic hypothermia.

membrane potentials as a result of TH, could contribute to the potential of this treatment to directly reduce epileptiform activity, either alone or synergistically with other agents.^{43 44} This could also support our findings that infants born in a CC with immediate access to TH had fewer reported seizures.

Comparing infants born in level 2 centres, a greater proportion of CC infants arrived with a temperature in optimal range compared with non-CC infants, with more overcooling in the latter group. Immediate access to active TH reduces the risk of complications associated with overcooling or potential lack of neuroprotection due to undercooling and mitigates the time critical burden placed on the transport team to commence TH within 6 hours of birth. This could explain the later admission time to tertiary CCs of infants born within level 2 centres CCs.

The transport process itself exposes the infant to noxious stimuli which could contribute to ongoing brain injury.⁴⁵ Preterm infants transferred in early life have an increased risk of brain injury.⁴⁶ It is unclear if exposure to significant levels of vibration and noise during interhospital transport, beyond that deemed safe for healthy adults, is a contributory mechanism to the additional seizures identified in this study.

Strengths and limitations

This study is one of the largest population studies in the TH era using routinely recorded patient data from over 180 centres, overcoming single-centre study weakness and allowing variation in management across a national healthcare service. The use of robust propensity matching with well-balanced groups is also a

significant strength, especially as undertaking a clinical trial of this nature may not be ethical or feasible. The large dataset has allowed identification of a reduced risk of infants recorded as having seizures that may not have been possible with smaller studies.

The main limitation of our study is the use of seizures as a proxy of brain injury due to the lack of neuroimaging results or long-term follow-up as these are not universally recorded in the NNRD dataset. However, previous work has demonstrated an association with seizures, MRI findings and later development.^{36 47} Another limitation is the lack of details on seizure diagnostic criteria or alternative aetiology, such as hypoglycaemia, fetal and neonatal drug exposure, as these are not recorded in sufficient detail within the database. Diagnosis of seizures was determined and coded by the attending clinical team and could be either clinical or electrical in nature. We did try to mitigate this by reporting the use of anticonvulsant therapy.

We could not account for differences in antenatal or neonatal care within the model which may be different between non-CCs and CCs, although subanalysis of level 2 births only minimised bias due to variation in clinical practice. Criteria for TH in infants with HIE are clearly defined by national guidance³² but the database had significant numbers of missing data such as 10 min Apgar and cord/admission pH values. We therefore assumed if the diagnostic classification was recorded and an infant underwent TH they met the criteria for treatment. We also acknowledge that the database does not allow differentiation of equipment used by transport teams or the exact time that target temperatures are achieved, which could be before admission to the CC.

CONCLUSION

This study demonstrates that almost half of infants with moderate/severe HIE in the UK are born in non-CCs and are less likely to have seizure-free survival compared with infants born in CCs, even when comparing level 2 centre births only. Furthermore, many infants transferred to CCs have admission temperatures outside the optimal TH time and temperature windows. The disparity of immediate access to active TH, a treatment known to reduce mortality and disability, could delay optimal therapy and impact on outcomes. With the increasing recognition of the relative safety of TH,⁶ consideration should be given for training, equipping and supporting non-CCs with active TH, minimising delays in initiating and achieving optimal target temperature prior to upward transfer to a specialised CC. Further work is also required to explore any potential adverse effects of interhospital transport on infants at risk of brain injury and suitable mitigation strategies.

Twitter Don Sharkey @DrDonSharkey

Acknowledgements We thank Professor Carol Coupland (Professor of Medical Statistics in Primary Care, University of Nottingham), who reviewed and advised on data analysis, propensity score-matching and the draft manuscript. We would like to acknowledge the contribution of the UK Neonatal Transport Research Collaborative for collecting centre specific data on therapeutic hypothermia. Electronic patient data recorded at participating neonatal units that collectively form the United Kingdom Neonatal Collaborative (UKNC) are transmitted to the Neonatal Data Analysis Unit (NDAU) to form the National Neonatal Research Database (NNRD). Don Sharkey had full access to all the data in the study and takes full responsibility for the integrity of the data and accuracy of the data analysis. We are grateful to all the families that agreed to the inclusion of their baby's data in the NNRD, the health professionals who recorded data and the NDAU team.

Contributors LS and DS made substantial contributions to the concept, planning, design of the study and acquisition of data. AM and DS collated access to TH data. LS and DS analysed and interpreted the data with support from Professor C Coupland (acknowledgement).

Funding This study was partly supported by a University of Nottingham, School of Medicine Impact Funding award.

Competing interests None declared.

Patient consent for publication Not required.

Ethics approval The study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by London-City and East Research Ethics Committee (REC: 17/LO/1822).

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. All data relevant to the study are included in the article or uploaded as supplementary information. All data were extracted and supplied by the NDAU and are available from the corresponding author on reasonable request and with permission of the study team and NDAU.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

ORCID iDs

Lara Shipley <http://orcid.org/0000-0002-8538-9531>

Don Sharkey <http://orcid.org/0000-0002-4989-8697>

REFERENCES

- Kurinczuk JJ, White-Koning M, Badawi N. Epidemiology of neonatal encephalopathy and hypoxic-ischaemic encephalopathy. *Early Hum Dev* 2010;86:329–38.
- Shipley L, Gale C, Sharkey D. Trends in the incidence and management of hypoxic-ischaemic encephalopathy in the therapeutic hypothermia era: a national population study. *Arch Dis Child Fetal Neonatal Ed* 2021;106:F529–34.
- Shankaran S, Pappas A, Laptook AR, et al. Outcomes of safety and effectiveness in a multicenter randomized, controlled trial of whole-body hypothermia for neonatal hypoxic-ischemic encephalopathy. *Pediatrics* 2008;122:e791–8.
- Sarkar S, Barks JD. Systemic complications and hypothermia. *Semin Fetal Neonatal Med* 2010;15:270–5.
- Azzopardi DV, Strohm B, Edwards AD, et al. Moderate hypothermia to treat perinatal asphyxial encephalopathy. *N Engl J Med* 2009;361:1349–58.
- Jacobs SE, Berg M, Hunt R, et al. Cooling for newborns with hypoxic ischaemic encephalopathy. *Cochrane Database Syst Rev* 2013;Cd003311.
- Azzopardi D, Strohm B, Linsell L, et al. Implementation and conduct of therapeutic hypothermia for perinatal asphyxial encephalopathy in the UK—analysis of national data. *PLoS One* 2012;7:e38504.
- Austin T, O'Hare SS. Neurocritical care for hypoxic-ischaemic encephalopathy: cooling and beyond 2013;9:135–8.
- Roelfsema V, Bennet L, George S, et al. Window of opportunity of cerebral hypothermia for postischemic white matter injury in the near-term fetal sheep. *J Cereb Blood Flow Metab* 2004;24:877–86.
- Thoresen M, Tooley J, Liu X, et al. Time is brain: starting therapeutic hypothermia within three hours after birth improves motor outcome in asphyxiated newborns. *Neonatology* 2013;104:228–33.
- Guillot M, Philippe M, Miller E, et al. Influence of timing of initiation of therapeutic hypothermia on brain MRI and neurodevelopment at 18 months in infants with HIE: a retrospective cohort study. *BMJ Paediatr Open* 2019;3:e000442.
- Kwon JM, Guillot R, Shankaran S, et al. Clinical seizures in neonatal hypoxic-ischemic encephalopathy have no independent impact on neurodevelopmental outcome: secondary analyses of data from the neonatal research network hypothermia trial. *J Child Neurol* 2011;26:322–8.
- Wang Y, Liu P-P, Li L-Y, et al. Hypothermia reduces brain edema, spontaneous recurrent seizure attack, and learning memory deficits in the kainic acid treated rats. *CNS Neurosci Ther* 2011;17:271–80.
- Dzhala V, Ben-Ari Y, Khazipov R. Seizures accelerate anoxia-induced neuronal death in the neonatal rat hippocampus. *Ann Neurol* 2000;48:632–40.
- Glass HC, Glidden D, Jeremy RJ, et al. Clinical neonatal seizures are independently associated with outcome in infants at risk for hypoxic-ischemic brain injury. *J Pediatr* 2009;155:318–23.
- Caravale B, Allemand F, Libenson MH. Factors predictive of seizures and neurologic outcome in perinatal depression. *Pediatr Neurol* 2003;29:18–25.
- Miller SP, Latal B, Clark H, et al. Clinical signs predict 30-month neurodevelopmental outcome after neonatal encephalopathy. *Am J Obstet Gynecol* 2004;190:93–9.
- Srinivasakumar P, Zempel J, Trivedi S, et al. Treating EEG seizures in hypoxic ischemic encephalopathy: a randomized controlled trial. *Pediatrics* 2015;136:e1302–9.
- Shah DK, Wusthoff CJ, Clarke P, et al. Electrographic seizures are associated with brain injury in newborns undergoing therapeutic hypothermia. *Arch Dis Child Fetal Neonatal Ed* 2014;99:F219–24.
- Orbach SA, Bonifacio SL, Kuzniewicz MW, et al. Lower incidence of seizure among neonates treated with therapeutic hypothermia. *J Child Neurol* 2014;29:1502–7.
- Low E, Boylan GB, Mathieson SR, et al. Cooling and seizure burden in term neonates: an observational study. *Arch Dis Child Fetal Neonatal Ed* 2012;97:F267–72.
- Glass HC, Grinspan ZM, Shellhaas RA. Outcomes after acute symptomatic seizures in neonates. *Semin Fetal Neonatal Med* 2018;23:218–22.
- Franck LS, Shellhaas RA, Lemmon M, et al. Associations between infant and parent characteristics and measures of family well-being in neonates with seizures: a cohort study. *J Pediatr* 2020;221:64–71.
- Natarajan G, Pappas A, Shankaran S, et al. Effect of inborn vs. outborn delivery on neurodevelopmental outcomes in infants with hypoxic-ischemic encephalopathy: secondary analyses of the NICHD whole-body cooling trial. *Pediatr Res* 2012;72:414–9.
- Battersby C, Statnikov Y, Santhakumaran S, et al. The United Kingdom national neonatal research database: a validation study. *PLoS One* 2018;13:e0201815.
- NHS. Nhs data dictionary. Available: www.datadictionary.nhs.uk [Accessed 01 June 2018].
- Imbens G, Rubin D. *Causal inference for statistics, social and biomedical sciences: an introduction*. Cambridge University Press, 2015.
- Imbens G. Matching methods in practice. *J Hum Resour* 2015;50:373–419.
- Rosenbaum PR. Constructing a control group using multivariate matched sampling methods that incorporate the propensity score. *Am Statist* 1985;39:33–9.
- Caliendo M, Kopeinig S. Some practical guidance for the implementation of propensity score matching. *J Econ Surv* 2008;22:31–72.
- Austin PC. Comparing paired vs non-paired statistical methods of analyses when making inferences about absolute risk reductions in propensity-score matched samples. *Stat Med* 2011;30:1292–301.
- National Institute for Health and Care Excellence. Therapeutic hypothermia with intracorporeal temperature monitoring for hypoxic perinatal brain injury (NICE guideline IPG347), 2010. Available: <https://www.nice.org.uk/guidance/ipg347>
- Wirrell EC, Armstrong EA, Osman LD, et al. Prolonged seizures exacerbate perinatal hypoxic-ischemic brain damage. *Pediatr Res* 2001;50:445–54.
- Weeke LC, Groenendaal F, Toet MC, et al. The aetiology of neonatal seizures and the diagnostic contribution of neonatal cerebral magnetic resonance imaging. *Dev Med Child Neurol* 2015;57:248–56.
- Ramantani G. Neonatal epilepsy and underlying aetiology: to what extent do seizures and EEG abnormalities influence outcome? *Epileptic Disord* 2013;15:365–75.
- Srinivasakumar P, Zempel J, Wallendorf M, et al. Therapeutic hypothermia in neonatal hypoxic ischemic encephalopathy: electrographic seizures and magnetic resonance imaging evidence of injury. *J Pediatr* 2013;163:465–70.
- Maitre NL, Smolinsky C, Slaughter JC, et al. Adverse neurodevelopmental outcomes after exposure to phenobarbital and levetiracetam for the treatment of neonatal seizures. *J Perinatol* 2013;33:841–6.
- Bhat P. Neonatal transport group. Available: <https://ukntg.net> [Accessed 05 Jan 2020].
- Shalak L, Perlman JM. Hypoxic-ischemic brain injury in the term infant-current concepts. *Early Hum Dev* 2004;80:125–41.
- Globus MY, Alonso O, Dietrich WD, et al. Glutamate release and free radical production following brain injury: effects of posttraumatic hypothermia. *J Neurochem* 1995;65:1704–11.
- Edwards AD, Yue X, Squier MV, et al. Specific inhibition of apoptosis after cerebral hypoxia-ischaemia by moderate post-insult hypothermia. *Biochem Biophys Res Commun* 1995;217:1193–9.
- Gunn AJ, Bennet L, Gunning MI, et al. Cerebral hypothermia is not neuroprotective when started after postischemic seizures in fetal sheep. *Pediatr Res* 1999;46:274–80.
- Schmitt FC, Buchheim K, Meierkord H, et al. Anticonvulsant properties of hypothermia in experimental status epilepticus. *Neurobiol Dis* 2006;23:689–96.
- Gano D, Orbach SA, Bonifacio SL, et al. Neonatal seizures and therapeutic hypothermia for hypoxic-ischemic encephalopathy. *Mol Cell Epilepsy* 2014;1.
- Gupta N, Shipley L, Goel N, et al. Neurocritical care of high-risk infants during inter-hospital transport. *Acta Paediatr* 2019;108:1965–71.
- Shipley L, Gyorkos T, Dorling J, et al. Risk of severe intraventricular hemorrhage in the first week of life in preterm infants transported before 72 hours of age. *Pediatr Crit Care Med* 2019;20:638–44.
- Dunne JM, Wertheim D, Clarke P, et al. Automated electroencephalographic discontinuity in cooled newborns predicts cerebral MRI and neurodevelopmental outcome. *Arch Dis Child Fetal Neonatal Ed* 2017;102:F58–64.