Supplementary table 3: Description of included studies

Author, Year, Country	Study design	Population included	Data source and study dates	Sample size & No. centres
Studies on volume and mortality including all CHD conditions				
Arenz, 2011, Germany [8]	Longitudinal	Paediatric CHD surgery	Aristotle database and mortality data (2006-9)	1828 Single centre
Bazzani and Marcin, 2007, USA [9]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	California Office of Statewide Health Planning and Development Discharge (OSHPD) database (1998-2003)	12,801 cases 4 analyses. 13,917 cases 1 analysis.
Benavidez, 2007, USA [10]	Cross-sectional	CHD surgery (0-18 years)	Healthcare Cost and Utilisation Project-KIDS (HCUP-KIDS) Database (2000)	10,032 100 centres
Chang, 2006, USA [11]	Retrospective cohort	Infants and children undergoing Norwood operation, VSD closure, ASD closure	California OSHPD Discharge database (1989-1999)	25402 500 centres
Dinh and Maroulas, 2010 USA and Canada [12]	Retrospective cohort	Paediatric CHD surgery	Paediatric Cardiac Care Consortium Database (1985-2004)	80,000 47 centres
Gray, 2003, Sweden [13]	Cross sectional cohort	Paediatric CHD surgery	Hospital medical records	284 4 centres
Hickey, 2010, USA [14]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	National Association of Children's Hospitals Paediatric Health Information System (PHIS) Database (2005-2006)	19,736 38 centres
Karamlou, 2008, USA [15]	Retrospective observational	Adult CHD open heart or thoracic aorta procedures	Nationwide Inpatient Sample (NIS) (1988-2003)	30,250 operations
Kazui, 2007, Japan [16]	Retrospective cohort	CHD surgery in newborns and infants	Survey data collected by Japanese Association for Thoracic Surgery (2000-2004)	11,197
Mery, 2014, USA [17]	Retrospective cohort	CHD surgery (0-18 years)	PHIS (2004-2011)	77,777 43 centres
Kim, 2011, USA [18]	Retrospective cohort	CHD surgery adults (18-49 years)	PHIS (2000-2008)	3061 42 centres

Author, Year, Country	Study design	Population included	Data source and study dates	Sample size & No. centres
Oster, 2011,USA [19]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	PHIS (2006- 2008)	49792 39 centres
Pasquali, 2012b, United States [20]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	Society of Thoracic Surgeons Congenital Heart Disease (STS –CHD) database	35,7776 patients 68 centres
Sakata, 2012, Japan [21]	Retrospective cohort	CHD surgery in newborns and infants	Survey data collected by Japanese Association for Thoracic Surgery (2005-2009)	13,074 220 centres
Seifert, 2007, USA [22]	Retrospective cohort	Paediatric CHD surgery (0-20 years)	HCUP-KIDS (2000)	10282 patients
Vinocur, 2013, USA [23]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	PCCC Database (1982 – 2007)	109475 operations 85 023 admissions 49 centres
Welke, 2006, USA [24]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	Congenital Heart Surgeon's Society (CHSS) member institutions (2001-2004)	12,672 11 centres
Welke, 2008, USA [25]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	NIS database (1988 -2005)	55,164 307 centres
Welke, 2009, USA [26]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	STS-CHD database (2002- 2006)	32,413 48 centres
Welke, 2010, USA [27]	Retrospective cohort	Paediatric CHD surgery (0-18 years)	NIS (2000 to 2005)	21,709 161 centres
Studies on volume and mortality specific conditions or procedures				
Arnaoutakis, 2012, USA[28]	Retrospective cohort	Adult (>18 years) orthotopic heart transplant (not all CHD)	United Network for Organ Sharing (UNOS) Standard Transplant and Research Dataset database (2000-2010)	18,226 141 centres
Berry, 2006,USA [29]	Retrospective cohort	Children with Hyperplastic Left Heart Syndrome(HLHS) undergoing stage 1, 2 and 3 palliation	HCUP-KIDS Database (1997 and 2000)	754 in 1997 880 in 2000
Berry, 2007, USA, [30]	Retrospective cohort	Children 0-18 years having Ventricular Septal Defect surgery with	HCUP-KIDS database (2003)	2301

Author, Year, Country	Study design	Population included	Data source and study dates	Sample size & No. centres
		cardiopulmonary bypass		
Checcia, 2005, USA [31]	Retrospective cohort	HLHS, age <30 days and Norwood Procedure	PHIS Database (1998-2001)	801 29 centres
Davies, 2011, USA [32]	Retrospective cohort	Heart transplants patients aged <19 years	UNOS Standard Transplant and Research Dataset (1992-2007)	4647 136 centres
Dean, 2013, USA [33]	Retrospective cohort	Children with HLHS undergoing stage 1, 2 and 3 palliation	University Health System Consortium (UHC) Database (1998-2007)	2761 patients
Hirsch, 2008, USA [34]	Cross-sectional	Neonates undergoing Norwood procedure or Arterial Switch Operation (ASO)	HCUP-KIDS database (2003)	Norwood – 624, 60 centres ASO - 547, 74 centres
Hornik, 2012, United States [35]	Retrospective cohort	Infants undergoing Norwood procedure	STS -CHD database (2000-2009)	2,555 53 centres
Karamlou, 2010, Canada/USA [36]	Retrospective cohort	Neonates 1)undergoing Norwood procedure or 2) with Transposition of Great Arteries (TGA) 3) Interrupted Aortic Arch (IAA); 4)Pulmonary Atresisia with Intact Ventricular Septum (PAIVS)	STS-CHD Database. Each group varies using 5 to 10 years of data during 1987-2000	2421 (Norwood 710; TGA 829; IAA 474; PAIVS 408) 24 - 33 CHSS centres
McHugh, 2010, USA [37]	Retrospective cohort	Children with HLHS undergoing stage 1, 2 and 3 palliation	UHC Database (1998 to 2007)	9187 (Stage 1 1949; Stage 2 1279; Stage 3 1084) 118 centres (Stage 1 48; Stage 2 48; Stage 3 47)
Morales, 2010, USA [38]	Retrospective cohort	All patients ≤ 20 years undergoing Ventricular Assist Device (CHD 21%)	HCUP-KIDS Database (2006)	187 67 centres
Pasquali, 2012a, United States [39]	Retrospective cohort	Infants undergoing Norwood procedure	STS -CHD database (2000-2009)	2,557 53 centres
Petrucci, 2011,	Retrospective	Neonates aged ≤ 30 days, weight>1.5kg	STS -CHD database (2002-2009)	1273

Author, Year, Country	Study design	Population included	Data source and study dates	Sample size & No. centres
United States [40]	cohort	receiving modified Blalock-Taussig shunt		70 centres
Tabbutt, 2012, USA [41]	Analysis of randomised controlled trial data	Children undergoing Norwood procedure with right ventricular-pulmonary artery shunt (RVPAS) or modified Blalock-Taussig shunt (MBTS)	RCT clinical and outcome data (2005-2008)	549 15 centres

Supplementary table 4: Summary of results and main findings of included studies

Study	**Risk Adjusted?**	**Mortality/survival endpoint**	**Volume/mortality effect** [OR=risk of dying (95%CI)]	**Main findings**
Studies on volume and mortality including all CHD conditions				
Arenz, 2011, Germany [8]	Yes	In hospital Within 30 days	Performance score (including mortality) increased from 100% baseline to 124.9% and 132.9%	Performance over 3 years maintained despite increasing complexity and volume
Bazzani and Marcin, 2007, USA [9]	Yes	Within 30 days	OR = 0.86/ increase of 100 cases (0.81 to 0.92) OR=0.75 (0.55 to 1.02) >75 cases/year versus < 75 cases	For each 100 patient increase in annual volume there was a 13.9% decrease in the odds of dying. Effect lost by removing single highest volume centre.
Benavidez, 2007, USA [10]	Yes	In hospital	Diagnosed complication v no complication OR=2.4 (1.9 to 3.0) (p< 0.0001)]	Complications are associated with increased risk of death in CHD surgery.
Chang, 2006, USA [11]	Yes	In hospital 30, 90 & 365 days	Total mortality (in hospital and post discharge) OR= 1.23, p<0.01	Lower volume hospitals had higher mortality for all cases. No difference in post discharge only deaths.
Dinh and Maroulas, 2010 USA and Canada [12]	Yes	In hospital	Linear decreasing dependency (mortality and volume) 1985-1989 (p=0.005); 1990-1994 (p =0.016); 1995-1999 (p=0.043); 2000-2004 (p=0.045)	Modelling study. Inverse relationship between volume and mortality. In small and medium sized centres the smaller the volume the higher the risk of dying.
Gray, 2003, Sweden [13]	Yes	30 day post-operative	Volume/Mortality comparing 4 centres OR for each centre compared to highest volume = 0.24, 0.12, 0.32 (p=0.0001)	No consistent relationship of smaller volume centres having lower mortality than the highest volume centre
Hickey, 2010, USA [14]	Yes	In hospital	Volume/Mortality OR = 0.93/increase of 100 cases (0.90 to 0.96)	For each 100 patient increase in annual volume there was a 7% decrease in the odds of dying.

Study	Risk Adjusted?	Mortality/survival endpoint	Volume/mortality effect [OR=risk of dying (95%CI)]	Main findings
Karamlou, 2008, USA [15]	Yes	In hospital	Non-paediatric vs paediatric surgeons OR = 4.5 (2.1 to 9.5); More vs less paediatric CHD experience OR= 0.92 (0.89 to 0.95); More vs less paediatric plus adult CHD experience OR =0.65 (0.43 to 0.99)	Adult patients operated on by paediatric surgeons have lower mortality which decreases further as surgeon volume increases.
Kazui, 2007, Japan [16]	No	In hospital	Volume/Mortality Newborns OR=2.20 (0.95 to 5.09) Infants OR=3.69 (20.2 to 6.73)	Higher mortality in lowest volume centres compared to highest volume centres for subgroup of cardiothoracic procedures. No adjustment for risk
Mery, 2014, USA [17]	Yes	In hospital	Complications – highest-volume quartile lower incidence of chylothorax vs lowest volume OR 0.49 (0.42 to 0.58)	Patients cared for in lowest-volume centres are more likely to develop this specific complication when compared with the highest-volume centres
Kim, 2011, USA [18]	Yes	In hospital	Total CHD volume ≥400 cases vs <200: OR 1.6 (CI not reported)] High vs low adult CHD surgery volume OR= 0.4 (0.2 to 0.7)	No volume mortality relationship for all cases. Adult CHD patients have lower mortality highest volume group compared to two lower volume groups.
Oster, 2011,USA [19]	Yes	In hospital	Volume/Mortality p=0.41 low risk, p=0.067 high risk	Standardised Mortality Ratio calculated from previous performance. Previous hospital mortality was more significantly associated with future mortality than volume indicating factors other than volume have an effect.
Pasquali, 2012b, United States [20]	Yes	In hospital	Volume/Mortality OR= 1.10 [1.04 to 1.17 (p=0.002)]	Complex analysis comparing cases with and without complications. Mortality greatest in low volume centres for all cases and those with complications.
Sakata, 2012, Japan [21]	No	30 days	Volume/Mortality - Pearson correlation co-efficient Newborns: -0.108 (p=0.273); Infants: -0.151 (p=0.149)	No relationship between volume and mortality for subgroup of paediatric cardiothoracic procedures

Study	**Risk Adjusted?**	**Mortality/survival endpoint**	**Volume/mortality effect** [OR=risk of dying (95%CI)]	**Main findings**
Seifert, 2007, USA [22]	Yes	In hospital	Volume/Mortality - Highest vs lowest volume quartile OR =0.5 [CI 0.35 to 0.71 (p<0.001)]; middle quartile vs lowest OR =0.68, [0.46 to 1.00(p=0.049)]	Assessed gender effect on mortality. Volume used as a co-variate. Mortality lower in highest volume centres and may be one factor influencing outcome.
Vinocur, 2013, USA [23]	Yes	In hospital	Volume/Mortality OR= 0.84/increase of 100 cases [0.78 to 0.90 (p<0.0001)]	For each 100 patient increase in annual volume there was a 16% decrease in the odds of dying. Mortality decreased 10 fold over this time period indicating improving care. Individual centre effect contributed more to risk model than volume.
Welke, 2006, USA [24]	Yes	In hospital	Volume not predictor of mortality; c statistic 0.55	Mortality most associated with case-mix and not volume.
Welke, 2008, USA [25]	Yes	In hospital	Volume/Mortality - Small/medium hospital vs. large hospitals OR=1.85 (1.56 to 2.20) and 1.48 (1.24-1.77)	Mortality rates significantly better for hospitals performing >200 operations per year but volume mortality relationship was not linear. Age and complexity better predictors of mortality than volume
Welke, 2009, USA [26]	Yes	In hospital	Volume/Mortality - no effect for low difficulty operations P = 0.29. Difficult operations (Aristotle >3) OR= 2.41 [1.89-3.06 (p< 0.0001)]	An inverse relationship between surgical volume and mortality was found and this was associated with case complexity. No relationship between volume and mortality for low difficulty operations but low volume centres did not perform as well as higher volume for complex procedures.
Welke, 2010, USA [27]	Yes	In hospital	Only 8% hospital had minimum caseload required to detect 5% difference in mortality	Paediatric cardiac surgery operations are performed too infrequently or have very low mortality. Mortality rates are a poor measure for comparing hospital performance.

Study	Risk Adjusted?	Mortality/survival endpoint	Volume/mortality effect [OR=risk of dying (95%CI)]	Main findings
Studies on volume and mortality specific conditions or procedures				
Arnaoutakis, 2012, USA [28]	Yes	30 days, 1 year	30-day mortality: low vs high volume: OR= 1.9 (1.5 to 2.4); medium vs high volume: OR= 1.3 (1.1 to 1.5). 1-year mortality: low vs high volume: OR= 1.6 (1.3 to 1.9); medium vs high volume: OR= 1.2 (1.1 to 1.3).	Heart transplants (CHD only 3% of cases). Mortality lower in high volume centres at 30 days and one year. High risk patients had higher mortality in low volume centres suggesting higher volume moderates the effect of risk.
Berry, 2006,USA [29]	Yes	In hospital	Highest volume vs lowest mortality rate OR= 1.59 (0.2 to 12.7)	Surgery for VSD is a subgroup in a study of common paediatric operations. No relationship between volume and mortality but VSD surgery concentrated in children's hospitals resulted in better outcome.
Berry, 2007, USA, [30]	Yes	In hospital	Low volume vs high volume OR= 3.1 (1.1 to 8.3)	Comparing HLHS mortality in 4 volume groups found mortality was worse in the lowest volume group but no difference between the other 3 groups.
Checcia, 2005, USA [31]	Yes	In hospital	Volume r2 =0.18, p= .02. Survival increased 4% (1% to 7%) per 10 additional procedures	Norwood procedure. Number of cases per surgeon too small to detect an effect. For each additional increase of 10 cases per year there is a 4% improvement in survival.
Davies, 2011, USA [32]	Yes	In hospital, 1 year	Low vs high volume OR = 1.60 (1.13 to 2.24); medium vs high volume OR=1.24 (0.92 to 1.67)	Heart transplants including non-CHD. Low & medium volume centres have worse mortality than expected when compared to high volume centres.
Dean, 2013, USA [33]	Yes	In hospital	Stage 1 palliation large vs small volume: OR= 0.57 (0.45 to 0.71)	HLHS. For stage 1 palliation, mortality was lower in highest volume centres. Mortality in medium volume centres not investigated. No relationship between volume and mortality for stages 2 & 3 palliation.

Study	Risk Adjusted?	Mortality/survival endpoint	Volume/mortality effect [OR=risk of dying (95%CI)]	Main findings
Hirsch, 2008, USA [34]	Yes	In hospital	Significant inverse associations for institutional volume/in-hospital mortality for Norwood procedure ($p \leq 0.001$) and Arterial Switch Operation (ASO) ($p = 0.006$).	Norwood versus ASO. As volume of cases per year increases mortality decreases.
Hornik, 2012, United States [35]	Yes	In hospital	Volume as continuous variable - lower centre volume associated with higher inpatient mortality (p=0.03). Surgeon volume associated with higher inpatient mortality (p=0.02). Volume as categorical variable lowest vs highest volume OR =1.56 [1.05 to 2.3 (p=0.03)]. Lowest vs highest surgeon volume OR= 1.6 [1.12 to 2.27 (p=0.01)].	Both high volume centres and high volume individual surgeon caseload have lower mortality than low volume centres and low caseload surgeons.
Karamlou, 2010, Canada/USA [36]	Yes	In hospital	Centre volume impact on adjusted mortality p<0.001 for TGA and IAA Surgeon total case volume p=0.002 for TGA Centre volume on adjusted mortality p=0.17 for Norwood and p=0.07 for PAIVS Surgeon total case volume p=0.4 Norwood	Good outcomes for one group didn't translate to all groups. No relationship between centre or surgeon volume for Norwood and PAIVS. Higher volume centres had lower mortality for TGA and IAA and higher surgeon volume had lower mortality for TGA only.
McHugh, 2010, USA [37]	Yes	In hospital	Stage 1 small vs high volume OR = 2.49 (1.51 to 4.07); medium vs high volume OR=1.75 (1.23 to 2.49). 1998-2002 vs 2003-7 OR-1.62 (1.16 to 2.27) Stage 2 small vs high volume OR 2.09 (1.06 to 4.1). Stage 3 medium vs high volume OR=1.70 (1.13 to 2.57)	Higher mortality in both small and medium volume centres compared to high volume centres for stage 1 but mixed results for stages 2 and 3. Mortality reduced over time independently of volume.
Morales, 2010, USA [38]	Yes	In hospital	Large volume teaching hospitals v rest OR=0.07 (0.02 to 0.24)	Ventricular Assist Device – not all cases CHD. Placement of VAD at large volume teaching hospitals reduces risk of mortality when compared to lower volume and non-teaching hospitals.

Study	**Risk Adjusted?**	**Mortality/survival endpoint**	**Volume/mortality effect** [OR=risk of dying (95%CI)]	**Main findings**
Pasquali, 2012a, United States [39]	Yes	In hospital	Volume as continuous variable p=0.04; As categorical variable lowest vs. highest volume OR = 1.54 [1.02 to 2.32 (p=0.04)]	Norwood procedure. Overall higher volumes associated with lower mortality but variation in individual centre mortality rates that do not reflect this relationship.
Petrucci, 2011, United States [40]	Yes	In hospital	Per 10-unit increase in average volume OR = 0.98 [0.85 to 1.13 (p= 0.78)]	Total case volume and Blalock Taussig Shunt Procedure volume included. No relationship between volume and mortality was found.
Tabbutt, 2012, USA [41]	Yes	In hospital, 30 days	Morbidity outcomes - Sepsis – Centre volume P=0.003 Renal failure – centre volume P=0.006, surgeon volume p=0.02 Time to extubation – centre & surgeon volume P<0.001 Length of stay – centre volume P<0.001	Norwood. Centre and surgeon volume. No relationship between volume and mortality but lower volume centres and surgeon procedures were associated with higher rates of morbidity outcomes and length of stay.