The role of size at birth and postnatal catch-up growth in determining systolic blood pressure: a systematic review of the literature

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Objective To conduct a systematic review in order to (i) summarize the relationship between birthweight and blood pressure, following numerous publications in the last 3 years, (ii) assess whether other measures of size at birth are related to blood pressure, and (iii) study the role of postnatal catch-up growth in predicting blood pressure.

Data identification All papers published between March 1996 and March 2000 that examined the relationship between birth weight and systolic blood pressure were identified and combined with the papers examined in a previous review.

Subjects More than 444 000 male and female subjects aged 0–84 years of all ages and races.

Results Eighty studies described the relationship of blood pressure with birth weight. The majority of the studies in children, adolescents and adults reported that blood pressure fell with increasing birth weight, the size of the effect being approximately 2 mmHg/kg. Head circumference was the only other birth measurement to be most consistently associated with blood pressure, the magnitude of the association being a decrease in blood pressure by approximately 0.5 mmHg/cm. Skeletal and non-skeletal postnatal catch-up growth were positively associated with blood pressure, with the highest blood pressures occurring in individuals of low birth weight but high rates of growth subsequently.

Conclusions Both birth weight and head circumference at birth are inversely related to systolic blood pressure. The relationship is present in adolescence but attenuated compared to both the pre- and post-adolescence periods. Accelerated postnatal growth is also associated with raised blood pressure. *J Hypertens* 2000, 18:815–831 © Lippincott Williams & Wilkins.

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Introduction

The fetal origins hypothesis proposes that undernutrition during fetal life and infancy can programme the development of risk factors for cardiovascular disease in adulthood, including impaired glucose tolerance, hyperlipidaemia and raised blood pressure. Evidence comes from epidemiological studies, which relate birth measurements, as a proxy for fetal nutrition, with levels of cardiovascular disease risk factors postnatally. The relationship between systolic blood pressure (SBP) and birth weight has been studied in diverse populations in terms of race, gender and age. The literature was previously reviewed in 1996 [1], when an inverse relationship between SBP and birth weight in children and adults was reported by most studies. However, several important issues remain to be clarified.

Firstly, some studies have reported that SBP is associated with other measurements at birth, including head and chest circumference, birth length and placental : birth weight ratio. The proportions of a baby at birth may reflect the timing of a nutritional insult to that baby's growth during gestation. For example, an infant who is thin at birth (i.e. with a low ponderal index) is thought to have sustained a period of undernutrition during the third trimester, whereas a baby with a small head circumference may have grown slowly throughout gestation. If SBP is shown to be related to such measurements, it may provide insight into the timing of the blood pressure 'programming' mechanism.

A further question that has arisen is whether the SBP–birth weight relationship is apparent in adolescents. In the previous review, the relationship in adolescence was found to be inconsistent, with studies reporting positive, inverse or no associations. Finally, the role of postnatal catch-up growth in predicting SBP is unclear. Adults who were born small for gestational age as a result of impaired fetal growth but who experienced accelerated growth in infancy have been proposed to be at increased risk of raised blood pressure [2] and coronary heart disease [3]. If this is true, there are important implications regarding postnatal nutrition of small-for-gestational-age infants.

To address these three questions, we performed a systematic review of the recent literature and integrated this with the information published in the previous systematic review [1].

Methods

A computerized literature search of publications from March 1996 (the cut-off date from the previous review) to March 2000 was performed on Medline. The search was performed on combinations of the keywords 'birth weight', 'blood pressure' and 'hypertension'. The papers identified were examined for further relevant references. All papers that referred to the relationship between birth weight and blood pressure in humans were assessed. Papers were excluded if they performed no statistical analysis on the association between birth weight and blood pressure, or if all of the subjects had a pathological condition such as premature birth, or if studies reported on twins or on hypertension in pregnancy. If more than one paper had been written on one sample, only the paper with the most complete data was included. Case–control studies were included provided the controls came from the general population.

For included studies, the place and method of the study and the number, birth year, age, sex, mean birth weight and mean blood pressure of subjects were recorded. As in the previous review, the relationship between blood pressure and birth weight was described by the linear regression coefficient (with confidence interval or P value) of SBP on birth weight after adjustment for measures of current size (weight, height or body mass index) if available. If not available, other forms of quantitative analysis were used. The relationship was reported regardless of whether it was statistically significant, and was described by sex, unless the results had been combined in the original publication. If blood pressure had been adjusted for variables other than current size, this was reported. Papers reporting longitudinal studies of blood pressure and their relationship with birth weight were analysed separately. Papers that examined 11–18-year-old subjects were included in the main analysis and in a separate analysis on the relationship between birth weight and SBP in adolescence.

This review also aimed to investigate the role of two types of postnatal catch-up growth in childhood, skeletal and non-skeletal growth, on the relationship between birth weight and later SBP. As these two types of catch-up growth were not uniformly described in the papers, we used some measure of relative growth as a measure of catch-up growth. To measure skeletal catch-up growth, we used attained adult height relative to birth weight. To measure non-skeletal catch-up growth, we used either weight gain relative to birth weight or attained body mass index (BMI) relative to birth weight.

Papers included in the previous review are presented in separate sections in the tables describing the association of birth weight with SBP. This enables assessment of any change that might have arisen from publication bias in either direction. Papers from both the previous review and the current review that described the relationships between SBP and birth measurements in adolescence and in association with postnatal skeletal and non-skeletal catch-up growth are presented together, as this is the first review to evaluate studies on these sub-topics.

Results

Relationship of birth weight with systolic blood pressure

A total of 45 papers published between March 1996 and March 2000 described the relationship between SBP or hypertension and birth weight in 46 studies. These papers referred to 37 cohort studies and nine longitudinal studies which had repeated measurements. The previous review had included 32 papers which described 34 studies published up to March 1996.

Studies reporting multiple regression analyses

A total of 24 papers published between March 1996 and March 2000 reported the association of birth weight with SBP in 25 studies. All of the papers described cohort studies. The characteristics of the studies reported in these papers are given in Table 1 for children and adolescents and in Table 2 for adults. The age range of subjects was 3–84 years and the sexes were equally represented in 20 of the 25 studies. The remaining six cohort studies consisted of only men or women, but the numbers of 177 000 women and 188 000 men were similar. Tables 1 and 2 also present equivalent data from the previous review which included 15 papers representing 17 studies. In studies of children, adolescents and adults published since March 1996, a 1 kg increase in birth weight was associated with typically a 1–2 mmHg/kg decrease in SBP. In the previous review, 26 out of 28 studies reported negative associations, typically 2–3 mmHg/kg in children and adolescents and 2–4 mmHg/kg in adults.

Figure 1 shows the regression coefficients (95% con-

Table 1 **Studies reporting multiple regression analyses of systolic blood pressure (SBP) on birth weight (BW), after adjusting for current size, in children and adolescents**

Authors	Year of birth	Place	Sex	*n* (males)	Age (years)	Mean SBP (mmHg)	Mean BW (g)	Regression of SBP on BW (mmHg/kg) after adjustment for current weight (95% CI)
Studies published between 1996 and 2000								
Alves *et al.* [4]	1997	Brazil	Mixed	634 (335)	Newborn	Not given	3198	1.7 (0.92 to 2.48)
Whincup *et al.* [5]	1991–1992	Avon, UK	Mixed	1860 (971)	3	90.4 (M)	3520	−1.91 (−2.60 to −1.22)
						89.2 (F)	3410	
Levitt *et al.* [6]	1990	Soweto, South Africa	Mixed	818 (420)	5	108.2 (M)	3063	−2.2 (−5.2 to 0.6)[a]
						107.7 (F)	3065	
Woelk *et al.* [7]	Not given	Harare, Zimbabwe	Mixed	576	6.5	108.3	3025	−1.73 (−3.28 to −0.182)
Yiu *et al.* [8]	1959–1965	USA	Mixed	2958 (1485)	6–9	103.7	3229	−1.36 (−2.31 to −0.41)[b]
Bergel *et al.* [9]	1987–1990	Argentina	Mixed	518 (274)	7	104.9 (M)	3277	−0.6 (−1.5 to 0.20)[c]
						104.2 (F)	3196	
						105.3 (placebo)		
Donker *et al.* [10]	Not given	Louisiana	Mixed	1446 (745)	7–11	97.5	3291	−0.04 (−0.3 to 0.3)[d]
Rona *et al.* [11]	Not given	England & Scotland	Mixed	1310 (664)	8–9	109.3 (M)	Not given	−4.1 (−6.77 to −1.43)[e]
						110.4 (F)		
Taylor *et al.* [12]	1973–1976	England & Wales	Mixed	3010 (1568)	8–11	112.4	3350	F −2.54 (−3.60 to −1.48)[f]
								M −0.64 (−1.58 to 0.30)[f]
Clark *et al.* [13]	1982–1985	England	Mixed	296	11	104 (white)	3254	−0.7 (−3.2 to 1.8)[g]
						107 (Asian)	3035	
Rabbia *et al.* [14]	1977–1978	Turin, Italy	Mixed	1310 (660)	12–14	114 (M)	3300	*M* −0.07 (−1.6 to 1.53)[h]
						111.2 (F)	3200	−0.27 (−1.9 to 1.33)[h]
Laor *et al.* [15]	1974–1976	Jerusalem	Mixed	10 833 (6684)	17	111.3	Not given	F −0.73 (−1.51 to 0.05)[i]
								M −0.94 (−1.54 to −0.33)[i]
Nilsson *et al.* [16]	1973–1975	Sweden	M	149 378	18	128.8	3543	−0.78 (−0.919 to −0.641)[j]
Walker *et al.* [17]	Not given	Edinburgh	Mixed	452 (231)	16–26	117	3470	−1.71 (−3.85 to 0.43)[k]
Milligan *et al.* [18]	Not given	Australia	Mixed	583 (301)	18	126.7 (M)	Not given	−2.00 (−3.98 to 0.02)[l]
						112.9 (F)		
Stocks *et al.* [19]	Not given	Bristol, UK	Mixed	1355 (572)	18–25	120.3 (M)	Not given	−0.67 (−2.68 to 1.33)[m]
						109.4 (F)		−1.99 (−3.78 to −0.20)[m]
Studies from the review by Law and Shiell [1]								
Hashimoto *et al.* [20]	Not given	Nigata, Japan	Mixed	195	3	97	3200	−6.2 (−11.0 to −1.3)
Fall *et al.* [21][A]	1987–1989	Poona, India	Mixed	200	3–4	96	2700	−0.6 (−4.4 to 3.1)
Vancheri *et al.* [22]	Not given	Santa Caterina, Italy	Mixed	715	3–12	102	Not given	−2.68 (−3.26 to −2.00)
Whincup *et al.* [23]	1983–1985	10 towns in UK	Mixed	3061	5–7	104	3300[B]	−2.05 (−2.70 to −1.4)
Forrester *et al.* [24]	1979–1981	Kingston, Jamaica	Mixed	1610	6–16	106	3100	−2.6 (−3.6 to −1.6)[c]
Zureik *et al.* [25]	Not given	South Lorraine, France	Mixed	52	8–10	112	3300	−3.39 (−9.50 to 2.73)[c]
Godfrey *et al.* [26]	1979–1981	Kingston, Jamaica	Mixed	77	10–12	95	3100	1.8 (−1.2 to 4.9)[d]
Zureik *et al.* [25]	Not given	South Lorraine, France	Mixed	105	11–16	112	3300	−4.20 (−8.12 to −0.28)[c]
Macintyre *et al.* [27]	1971–1972	Clydeside, UK	M	413	15	114	Not given	−1.26 (−3.01 to 0.47)
			F	425		109		0.52 (−1.28 to 2.34)

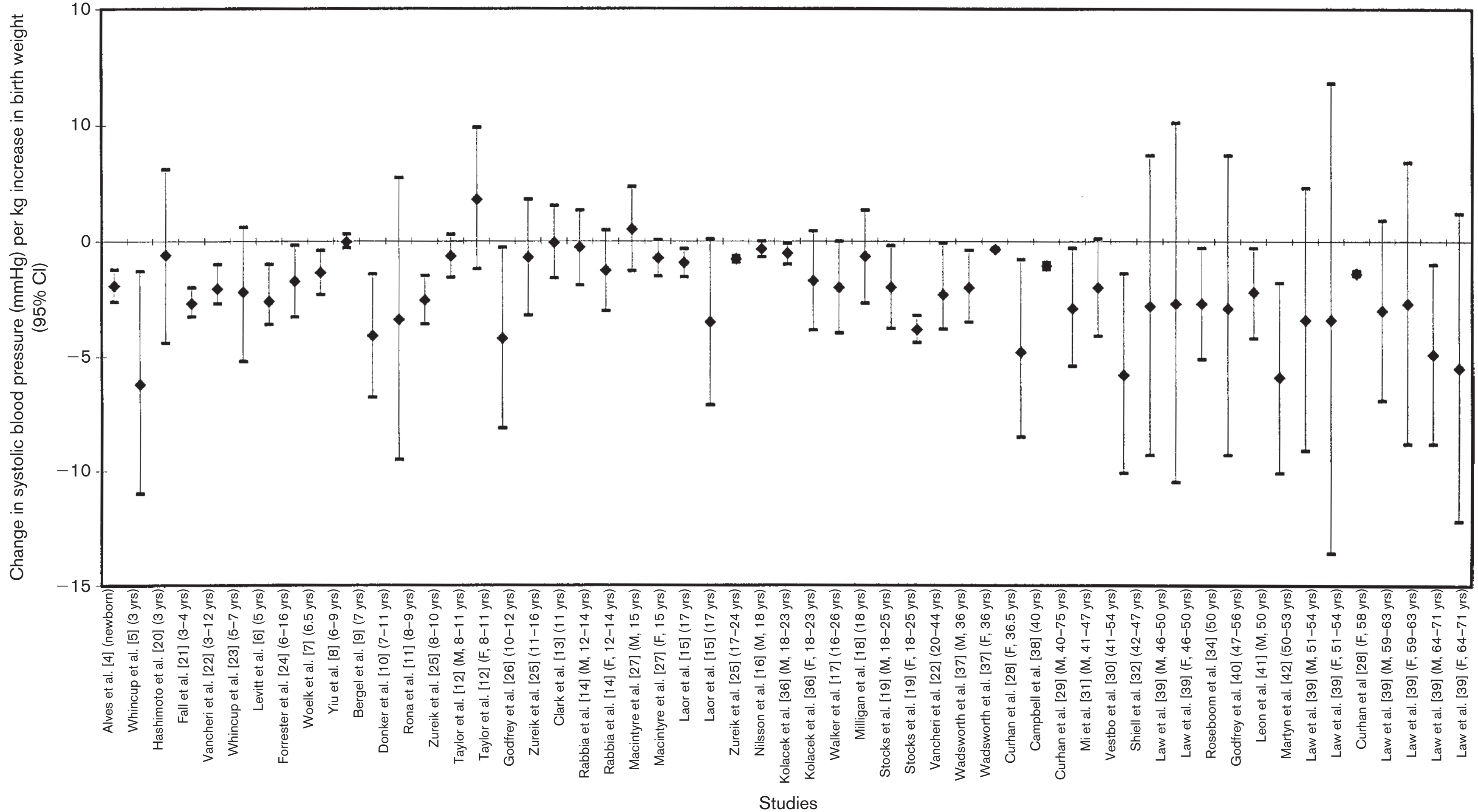
M, male; F, female; Regressions adjustment for: [a] gestational age, maternal age; [b]gestational age, sex, race; [c]sex, age, treatment, maternal blood pressure at follow-up; [d]age, sex, race; [e]race , sex, age, gestation; [f]town, person who measured BP, age, sex; [g]cuff size, time of day, race, sex; [h]heart rate, age, sport, TV, Tanner's stage, familial risk of hypertension, parental cultural level, maternal risk, interaction factors; [i]race, gestation, birth order, social status; [j]gestation, mother's age and parity; [k]parental blood pressure, no adjustment for current size; [l]age, sex, no adjustment for current size; [m]age; [n]sex and age; [o]sex; [A] subjects from normal birth weight group only; [B] estimated; CI, confidence interval; NS, not significant ($P > 0.05$).

Table 2 **Studies reporting multiple regression analyses of systolic blood pressure (SBP) on birth weight (BW), after adjusting for current size in adults**

Authors	Year of birth	Place	Sex	*n* (males)	Age (years)	Mean SBP (mmHg)	Mean BW (g)	Regression of SBP on BW (mmHg/kg) after adjustment for current weight (95% CI)
Studies published between 1996 and 2000								
Curhan *et al.* [28]	Not given	USA	F	92 940	36.5	113.7	Not given	−0.35 (−0.41 to −0.29)[a]
Curhan *et al.* [29]	Not given	USA	M	22 846	40–75	127.7	~ 3470	−1.06 (−1.22 to −0.90)[a]
Vestbo *et al.* [30]	Not known	Denmark	Mixed	620	41–54	M offspring of diabetics = 130	3700	−2.00 (−4.10 to 0.10)[b]
						M controls = 128	3500	
						F offspring of diabetics = 121	3500	
						F controls = 122	3475	
Mi *et al.* [31]	1948–1954	China	Mixed	627(309)	41–47	128 (M)	3196	−2.9 (−5.4 to −0.3)[c]
						121 (F)	3094	
Shiell *et al.* [32]	1948–1954	Aberdeen, Scotland	Mixed	168 (79)	42–47	124	3218	−5.8 (−10.1 to −1.4)[d]
Kumaran *et al.* [33]	1934–1953	India	Mixed	435 (237)	49.5	126 (M)	2785	Regression not presented
Roseboom *et al.* [34]	1943–1947	Netherlands	Mixed	739 (309)	50	125.5	3349	−2.7 (−5.1 to −0.3)[b]
Curhan *et al.* [28]	Not given	USA	F	71 100	58	126.1	Not given	−1.39 (−1.49 to −1.26)[a]
Yarborough *et al.* [35]	Not given	California, USA	F	303	50–84	134.4	Not given	1.41 ($P > 0.10$)[b]
Studies from the review by Law and Shiell [1]								
Zureik *et al.* [25]	Not given	South Lorraine, France	Mixed	53	17–24	112	3300	−3.5 (−7.11 to 0.09)[a]
Kolacek *et al.* [36]	1968–1969	Three regions in Croatia	M	214	18–23	129	3500[A]	−0.34 (−0.69 to 0.0)
			F	251		118	3300[A]	−0.52 (−1 to −0.1)
Vancheri *et al.* [22]	Not given	Santa Caterina, Italy	Mixed	448	20–44	123	Not given	−3.82 (−4.39 to −3.21)
Wadsworth *et al.* [37]	1946	UK National Cohort	M	1396	36	123	Not given	−2.3 (−3.8 to −0.8)
			F	1553		117		−2 (−3.5 to −0.4)
Campbell *et al.* [38]	1948–1954	Aberdeen, UK	Mixed	253	40	137	3200	−4.8 (−8.5 to −0.8)[e]
Law *et al.* [39]	1939–1943	Preston, UK	M	123	46–50	154	3200	−2.8 (−9.3 to 3.7)
			F	116		143	3200	−2.7 (−10.5 to 5.1)
Godfrey *et al.*[B] [40]	1935–1943	Preston, UK	Mixed	139	47–56	141	Not given	−2.9 (−9.3 to 3.7)[c]
Leon *et al.* [41]	1920–1924	Uppsala, Sweden	M	1333	50	133	3600	−2.2 (−4.2 to −0.3)[f]
Martyn *et al.* [42]	1939–1941	Sheffield, UK	Mixed	336	51–54	Not given	3200	−5.9 (−10.1 to −1.8)[g]
Law *et al.* [39]	1935–1938	Preston, UK	M	117		154	3200	−3.4 (−9.1 to 2.3)
			F	103	59–63	149	3200	−3.4 (−13.6 to 6.8)
Law *et al.* [39]	1920–1930	Hertfordshire, UK	M	426		162	3600	−3 (−6.9 to 0.9)
	1923–1930		F	203	64–71	159	3400	−2.7 (−8.8 to 3.4)
Law *et al.* [39]	1920–1930	Hertfordshire, UK	M	418		166	3600	−4.9 (−8.8 to −1)
	1923–1930		F	184		161	3400	−5.5 (−12.2 to 1.2)

M, male; F, female, Regressions adjusted for: [a]sex and parental blood pressures; [b]age and sex; [c]sex; [d]age, sex and cuff size; [e]sex, cuff size and alcohol consumption; [f]age; [g]sex, alcohol consumption, gestational age
[A]Estimated; [B]includes 100 with blood pressure not measured previously; CI, confidence interval.

Fig. 1



Studies reporting multiple regression analyse in children, adolescents and adults. CI. confidence interval.

fidence intervals) for the change (mmHg) in systolic blood pressure per kilogram increase in birth weight after adjustment for current size in children, adolescents and adults from both reviews. Except where specified, the regression coefficients are combined for both males and females. All of the regression coefficients except three [4,25,26], are negative after adjustment for current size.

Other analyses

Twelve papers published between March 1996 and March 2000 described the relationship of birth weight with SBP either using correlation coefficients or in some other quantitative way. All were cohort studies. The characteristics of these studies are shown in Table 3. Three studies, two in children [44,47] and one in adults [54], reported negative associations between blood pressure and birth weight, and one study of adults found an inverse association only in those born before 37 completed weeks of gestation [53]. Six studies spread across the age groups found no association between birth weight and blood pressure [45,46,48,50–52]. Two studies, one in newborns [43] and one in adults [49], reported a positive association of SBP with birth weight.

A total of 12 papers from the previous review examined the relationship of birth weight with SBP. These studies are also presented in Table 3. Four studies in newborns reported positive associations with blood pressure and birth weight [55–58]. Negative associations were reported for both children and adults in five studies [59–61,64,65]. A positive association was reported in one study in adolescents [62] and in one study in adults [66]. One study reported a positive, negative or no relationship in adolescents, depending on whether there was adjustment for current size [63].

Studies with repeated measures

Nine studies presented data that allowed the association of blood pressure with birth weight to be described over a number of years in the same individuals. The characteristics of these studies are given in Table 4. Four studies reported consistent inverse associations between birth weight and SBP [70,72,74,75] and two studies reported no association [67,71]. One study reported an inverse trend in men only at age 17 years, but in both men and women at age 30 years [73]. Two studies reported no association between birth weight and SBP in early infancy but an inverse association in later childhood [68,69].

There were seven studies with repeated measures included in the previous review, all of which were performed in children and adolescents. The characteristics of these studies are also shown in Table 4. Positive associations were reported in the studies of newborns [39] and the one study in adolescents between birth weight and blood pressure [80]. The remaining studies in children reported negative associations [21,76–79].

The association between systolic blood pressure and birth measurements other than birth weight

A total of 39 studies published up to February 2000 provided information on the univariate relationship between blood pressure and other measurements at birth including gestational age (22 studies), placental weight (18 studies), placental : birth weight ratio (eight studies), ponderal index (14 studies), birth length (14 studies), head circumference (11 studies) and chest circumference (three studies). The direction of association for each measurement with SBP is shown in Table 5. Sex appears to have an effect on the relationship between some birth measurements and SBP, such that the association is observed to be present in females but not in males.

The most consistently reported finding is an inverse association between head circumference and SBP. A total of 11 studies examined the association of SBP with head circumference. Six studies reported inverse associations [4,7,12,34,42,77], although in one study it was reported only in females [12]. In one study [73] which examined the relationship between blood pressure and head circumference at two time points, no relationship was observed at age 17 years, but at age 30 years, a negative relationship was reported in females only. Two studies, one in newborn, reported a positive association between head circumference and blood pressure [4,47], and two studies reported no association [9,68]. Overall, SBP was found to decrease by approximately 0.5 mmHg/cm increase in head circumference. Three studies examined the relationship between chest circumference and SBP. One reported an inverse association [42], one study reported a positive association [68] and one study reported no association at age 17 years but an inverse association at age 30 years in females only [73].

The relationship between birth length and SBP was examined in 14 studies. Five studies reported no association [7,20,58,61,68] and five studies reported inverse associations [5,12,34,42,74], although in one of these studies the relationship was present only in females [11]. Three studies reported a positive association between birth length and SBP [4,33,77]. One study reported no association at age 17 years but an inverse association between birth length and blood pressure at age 30 years in females only [73].

Out of a total of 14 studies, six reported no association between ponderal index and SBP in either sex [9,12,41,42,48,67,71]. Five studies reported an inverse association [5,34,74,77,80]. One study reported an in-

Table 3 Studies reporting quantitative analysis other than regression, on the relationship between birth weight (BW) and systolic blood pressure (SBP)

Authors	Year of birth	Place	Sex	*n* (males)	Age (years)	Mean SBP (mmHg)	Mean BW (g)	Direction of association between BW and SBP
Studies published between 1996 and 2000								
O'Sullivan *et al.* [43]	1991	Ireland	Mixed	248 (125)	Newborn	62.8	3493	+
Lurbe *et al.* [45]	Not given	Spain	Mixed	134 (61)	3–19	108.9	3400	−
Ley *et al.* [46]	Not given	Sweden	Mixed	68	8–10	Not given	2159 (SGA, *n* = 32)	0[a]
							2883 (AGA, *n* = 36)	
Pharoah *et al.* [47]	1980–1981	Merseyside, UK	Mixed	139	15	Non-disabled (*n* = 128) 114.7	1249	−[b]
						Controls (*n* = 128) 111.5	3338	
Clausen *et al.* [48]	1961–1973	Denmark	Mixed	331 (162)	18–32	M = 119	Not given	0
						F = 114	Not given	0
Hoy *et al.* [49]	Not given	Australia	Mixed	317 (181)	20–38	LBW = 115	2220	+
						AGA = 119	2960	
Leger *et al.* [50]	1971–1978	France	Mixed	517 (232)	20	SGA (M) = 124.4	SGA 2550 (*n* = 236)	0[b]
						AGA (M) = 125.3	AGA 3410 (*n* = 281)	0[b]
						SGA (F) = 117.0		
						AGA (F) = 115.3		
Hennesey *et al.* [51]	1958	UK	Female	3172	33	Not given	3283	0
Frankel *et al.* [52]	Not given	Caerphilly, Wales	Male	1258	45–59	Not given	Not given	0
Siewart-Delle *et al.* [53]	1926–1927	Goteborg, Sweden	Male	430	49	144	3535	− (PT only)
Martyn *et al.* [54]	1922–1926	Sheffield, UK	Mixed	181 (125)	70	166	Not given	−
Studies from the review by Law and Shiell [1]								
Contis *et al.* [55]	Not given	Stockholm, Sweden	Mixed	32	Newborn	89	3600	+
Versmold *et al.* [56]	1965–1969	San Francisco, USA	Mixed	61	1–12 h	58[A]	2100	+
Hulman *et al.* [57]	1988	Philadelphia, USA	Mixed	552	1–3 days	61	3200	+
Lee *et al.* [58]	1973–1974	Boston, USA	Mixed	206	2–4 days	74	3300	+
Cater & Gill *et al.* [59]	1969–1970	Aberdeen, UK	Mixed	282	10	110	Not given	−
Barker *et al.* [60]	1970	UK national cohort	M	5087	10	98	3400	−[b]
			F	4834		98	3300	−[b]
Himmelman *et al.* [61]	1969–1973	Goteborg, Sweden	Mixed	53	10–15	118	3400	−
Matthes *et al.* [62]	1975–1977	Cardiff, Wales	Mixed	328	15	108	2800	+[b]
Seidman *et al.* [63]	1964–1971	Jerusalem, Israel	M	20 088	17	121	Not given	+−[B,b]
			F	12 492		113		+−[B,b]
Valdez *et al.* [64]	1949–1963	San Antonio, USA	Mixed	541	25–64	114	3300	−
Gennser *et al.* [65]	Not given	Stockholm, Sweden	M	77	28	21% > 145	5% < 2500	−
Brown *et al.* [66]	Not given	East Anglia, UK	Mixed	Not given	40–69	(diastolic ~75)	Not given	+[b]

M, male; F, Female; SGA, small for gestational age; AGA, appropriate for gestational age; LBW, low birth weight; PT, pre-term; +, positive association; −, negative association; 0, no association; Analysis adjusted for; [a]gestational age; [b]current size. [A]Estimated; [B]depending on adjustment used for current size.

Table 4 **Studies with repeated measurements of the relationship between birth weight (BW) and systolic blood pressure (SBP)**

Authors	Year of birth	Place	Sex	*n*	Age (years)	Mean SBP (mmHg)	Mean BW (g)	Regression of SBP on BW (mmHg/kg)
Studies published between 1996 and 2000								
Falkner *et al.* [67]	1959–1965	Philadelphia	M	62	0.3	85	3189	0
			F	64		81	3022	0
			M	70	6.9	101		
			F	66		100		
			M	41	13.2	114		
			F	40		109		
			M	67	14.4	116		
			F	65		111		
			M	61	20.1	116		
			F	63		109		
			M	60	21.1	118		
			F	58		106		
			M	70	28	125		
			F	67		106		
Thame *et al.* [68]	Not given	Jamaica	M	131	1	92.8	3150	0[a]
			F	157				
			M	117	2	93.2		0[a]
			F	164				
			M	63	2.5	91.9		−2.8 (−5.0 to −0.6)[a]
			F	103				
			M	105	3	91.4		−2.6 (−4.2 to −1.0)[a]
			F	145				
			M	64	3.5	91.3		0[a]
Bavdekar *et al.* [69]	1987–89	India	F	74				
			Mixed	201	4	Not given	Not given	0
			M	256	8	111.4	2800	–[a]
			F	221	8	111.2	2700	
Taittonen *et al.* [70]	Not given	Finland	M	246	6	106.1	3602	−1.84 (−2.82 to −0.86)[a]
			F	259	6	106.2	3466	−0.94 (−1.91 to 0.04)[a]
			M	280	9	111	3511	
			F	281	9	110.5	3435	
			M	250	12	112.2	3600	−1.92 (−2.85 to −0.98)[a]
			F	287	12	113.3	3454	−0.58 (−1.58 to 0.41)[a]
			M	203	15	119.5	3537	
			F	239	15	116.8	3431	
			M	148	18	126.5	3547	−2.05 (−3.14 to −0.96)[a]
			F	181	18	118.9	3492	−2.50 (−3.50 to −1.50)[a]
Forsen *et al.* [71]	1981–1982	Finland	Mixed	171	0.5	Not given	Not given	0
				171	1			
				163	2			
				169	3			
				169	5			
				171	7			
Uiterwaal *et al.* [72]	Not stated	Netherlands	Mixed	94	5–9	Not given	M = 3500	−0.61 (−3.23 to 2.02)[b]
				208	10–14		F = 3300	−2.53 (−4.68 to −0.38)[b]
				316	15–19			−3.05 (−4.88 to −1.23)[b]
				298	20–24			−2.72 (−4.57 to −0.87)[b]
				213	25–29			−1.95 (−3.88 to −0.01)[b]
				112	30–37			−1.93 (−4.56 to 0.7)[b]

Berkey *et al.* [73]	Not stated	Boston	M	67	Birth	Not given	3330	Not known
			F	67	Birth	Not given	3250	Not known
			M	67	17	114.09		–
			F	67	17	104.69		0
			M	67	30	120.44		–
			F	67	30	112.92		–
Moore *et al.* [74]	1975–1976	Adelaide, Australia	M	437	8	101	3392	−1.0 (−2.3 to 0.4)[a]
			F	392	8	102		
			M	297	20	125		−2.6 (−4.4 to −0.7)[a]
			F	287	20	115		−4.6 (−6.4 to −2.9)[a]
Koupilova *et al.* [75]	1920–1924	Uppsala, Sweden	M	1335	50	131.4	3588	−2.53 (−5.85 to −1.10)[cd]
				1087	60	140.4		−1.63 (−2.72 to −0.97)[cd]
				736	70	146.4		−1.72 (−2.69 to −1.10)[cd]
Studies from the review by Law and Shiell [1]								
Law *et al.* [39]	1975–1977	Farnborough, UK	M	903	4 days	72	3400	5.8 (4.6 to 7.0)[e]
			F	836		71	3300	5.5 (4.2 to 6.9)[e]
			M	698	1	94		−0.6 (−2.6 to 1.4)
			F	646		93		1.3 (−0.8 to 3.4)
			M	631	3	97		−1.5 (−3.3 to 0.2)
			F	584		96		−1.6 (−3.4 to 0.3)
			M	560	7	92		−1.5 (−3.2 to 0.2)
			F	506		90		−2.1 (−4.0 to −0.3)
			M	227	10	95		−0.8 (−3.1 to 1.5)
			F	218		93		−2.3 (−4.8 to 0.2)
Launer *et al.* [76]	1980	Rotterdam, Netherlands	Mixed	392	1 week	88[f]	3400	10.8 (4.3 to 17.3)[g]
				392	13–25 weeks	113[f]		−4.3 (−7.3 to 1.3)[h]
				374	4	96		Linear −19.7 (−38.9 to 0.6)[i]
								Quadratic 2.6 (−0.1 to 5.3)[i]
Law *et al.* [77]	1984–1985	Salisbury, UK	Mixed	405	4	105	3400	Regressions not presented
Fall *et al.* [21]				239	9	99		–
								−0.5 (−2.6 to 1.6)
Whincup *et al.* [78, 79]	1980–1983	Nine towns in UK	M	1789	5–7	101	3400[b]	−1.6 (−2.3 to −0.8)
			F	1802		101	3300[b]	−2.0 (−2.8 to −1.3)
		Two of the nine towns in UK	Mixed	523	9–11	Not given		−4.0 (−5.7 to −2.2)
Williams *et al.* [80]	1972–1973	Dunedin, New Zealand	Mixed	750	7	102	3400	Regression not presented −
				702	18	121		Regression not presented +

M, male; F, female; [a]regression of SBP on BW after adjustment for current size (mmHg/kg); [b]regression of SBP on BW after adjustment for current size, sex, alcohol consumption and oral contraceptive use; [c]odds ratio for hypertension in men > 176 cm associated with a 1 kg decrease in BW (95% CI); [d]age-adjusted; [e]selected fom 13 time points and not adjusted for current weight; [f]estimated [95% confidence interval (CI)] Regressions adjusted for: [g]length at birth but not for current weight; [h] length at birth and current weight; [i]length at birth, current weight and early blood pressure; [−], negative association, [+], positive association; 0, no association.

Table 5 **Studies in ascending order of age, which investigated the relationship between measurements at birth and systolic blood pressure (SBP)**

	Birth weight	Head circumference	Chest circumference	Birth length	Ponderal index	Placental weight	Placenta : birth weight ratio	Gestational age
Alves *et al.* [4]	+	+		+		0		0
O'Sullivan *et al.* [43]	+					0		
Hulman *et al.* [57]	+							+
Lee *et al.* [58]	+			0				
Falkner *et al.* [67]	0				0			
Forsen *et al.* [71]	0				0	0	0	
Whincup *et al.* [5]	– (stronger in PT)	–		–	–	–	0	–
Hashimoto *et al.* [20]	–			0				0
Whincup *et al.* [23]	–							–
Whincup *et al.* [78]	–					–	0	
Uiterwaal *et al.* [72]	– (no association in PT)							
Woelk *et al.* [7]	–	–		0				0
Yiu *et al.* [8]	–							0
Bergel *et al.* [9]	0	0			0			
Forrester *et al.* [24]	–					–	0	0
Williams *et al.* [80]	+ (7years), – (18 years)				–	–		
Moore *et al.* [74]	–			–	–	0	+	
Thame *et al.* [68]	–	0	+	0		0		0
Rona *et al.* [11]	–							–
Zureik *et al.* [25]	–							0
Ley *et al.* [46]	0							0
Himmelman *et al.* [61]	0			0		0		0
Taylor *et al.* [12]	– (– NS trend in PT)	– (F), 0 (M)		–(F), 0 (M)	0	– (F), + (M)	0 (F), + (M)	
Barker *et al.* [60]	–					+	+	0
Pharoah *et al.* [47]	–	+						
Matthes *et al.* [62]	+							0
Berkey *et al.* [73](17 years)	0 (F), – (M)	0	0	0	– (F), 0 (M)			
Clausen *et al.* [48]	0				0			
Nilsson *et al.* [16]	–							–
Leger *et al.* [50]	0					0		0
Berkey *et al.* [73] (30 years)	– (F), 0 (M)	– (F), 0 (M)	– (F), 0 (M)	– (F), 0 (M)	0			
Campbell *et al.* [38]	–					–		0
Mi *et al.* [31]	–							0
Law *et al.* [77]	–	–		+	–	+		
Godfrey *et al.* [26]	–					+		
Martyn *et al.* [42]	–	–	–	–	0	0		0
Siewert-Delle *et al.* [53]	– (PT only)				– (PT only)	0		– (PT only)
Kumaran *et al.* [33]	0			+				
Roseboom *et al.* [34]	–	–		–	–	0 (PA)		0
Leon *et al.* [4]	– (FT), + (PT)				0	0	0	

0, no association; +, positive association; –, negative association; F, female; M, male; FT, full-term; PT, pre-term; H, hypertension; PA, placental area; NS, not significant ($P > 0.05$).

verse relationship only in those who had been born before term (37 weeks' gestation) [53]. One study reported an inverse association at age 17 years in females only, but the association was no longer apparent at age 30 years in either sex [73].

A total of 18 studies examined the relationship of placental weight with SBP, nine of which reported no association [41–43,50,53,61,68,71,74]. Five studies reported an inverse association of placental weight with SBP [5,24,38,78,80] and three studies reported positive associations [26,60,77]. One study reported a negative association of placental weight with SBP in females and a positive association in males [12]. Placental : birth weight ratio was found to be unassociated with SBP in five out of eight studies [5,24,41,71,78]. Three studies reported a positive association [12,60,74], although in one of these studies the relationship was apparent only in males [12]. One study reported on the relationship of placental area and SBP and found no association [34].

Out of the 22 studies reporting on the relationship between gestational age and SBP, 16 studies found no association [4,7,8,20,24,25,31,34,38,42,46,50,60–62,68]. Four studies reported an inverse association [5,11, 16,23], and one study reported a positive association between gestational age and SBP [57]. One study reported that gestational age was inversely associated with SBP only in those who had been born before term [53].

The relationship of birth weight with systolic blood pressure in adolescence

A total of 20 studies published up to March 2000 investigated the association between birth weight and SBP in adolescence. The characteristics of these studies are given in Table 6. Fourteen studies reported inverse associations [14–19,24,25,44,47,61,70,72,78] and four studies reported positive associations [26,62,63,80]. Two studies reported an inverse association in males but a positive association in females [27,73].

The role of skeletal catch-up growth in the relationship between birth weight and systolic blood pressure

Three studies examined the relationship between postnatal skeletal catch-up growth and SBP in children, adolescents and adults [51,75,80]. The characteristics of these studies are shown in Table 7. All of the studies reported a positive association between catch-up growth and SBP. One study reported that SBP in both childhood and adolescence was higher in intra-uterine growth-retarded subjects who had exhibited an increased growth rate, assessed using attained height with respect to birth weight [80]. One study reported that the inverse relationship between the prevalence of hypertension and birth weight was stronger in men who were above median height with a body mass index in the upper half of the distribution and who were light at birth [75]. The third study reported that the prevalence of hypertension was higher in women of lower birth weight who became tall as adults [51].

The role of non-skeletal catch-up growth in predicting systolic blood pressure

Thirteen studies examined the role that the relative change in non-skeletal size from birth to current size has on SBP in children, adolescents and adults. The characteristics of these studies are presented in Table 7. Six studies used the relative change in weight from birth to current weight to assess non-skeletal catch-up growth [5,46,69,71,76,78]. Seven studies defined catch-up growth by whether the individual was light at birth but had a high body mass index in later life [9,10,15,16,19,36,72]. Seven studies reported a positive association between non-skeletal catch-up growth [9,10,16,36,46,69,71,72,76], and two studies reported a positive association in males only [19,78]. Two studies reported no relationship between non-skeletal catch-up growth and SBP [5,15]. This review, however, cannot determine whether this postnatal catch-up growth predicts blood pressure independently of prenatal growth, as the measures of postnatal catch-up growth described usually incorporated birth weight in their calculation.

Papers excluded from the review

Table 8 presents the 12 papers published between March 1996 and March 2000 which were not included in the review and the reasons for their exclusion [81–92]. The previous review had excluded 18 papers using the same criteria.

Discussion

The evidence from the 80 studies included in this review demonstrates that, in children, adolescents and adults, there is an inverse relationship between birth weight and systolic blood pressure after adjustment for current weight. In neonates, the relationship is positive. This is based on data from over 444 000 individuals in the age range 0–84 years.

In contrast with the previous review, where nearly half of all the 34 studies reviewed were from groups in the UK, only 11 of the 46 studies published from 1996–2000 were from the UK. The others were from western and northern Europe (15 studies), the USA (eight studies) and the remaining twelve studies were from Australia, South America, the Middle East, China or Africa. The finding that the inverse relationship between birth weight and blood pressure is present in many populations of diverse ages and countries, and reported by different academic groups, strengthens the argument for the

Table 6 **Studies investigating the relationship between birth weight (BW) and systolic blood pressure (SBP) in adolescence**

Authors	Year of birth	Place	*n* (males)	Age (years)	Mean SBP (mmHg)	Mean BW (g)	Direction of association
Lurbe *et al.* [45]	Not given	Spain	134 (61)	3–19	108.9	3400	–
Forrester *et al.* [24]	1979–1981	Kingston, Jamaica	1610	6–16	106	3100	–
Taittonen *et al.* [70]	Not given	Finland	2381 (1132)	6–24	(see Table 4)	3511 (M)	–
						3435 (F)	–
Whincup *et al.* [78]	1980–1983	Two of the nine towns in UK	523	9–11	Not given	Not given	–
Godfrey *et al.* [26]	1979–1981	Kingston, Jamaica	77	10–12	95	3100	+
Himmelman *et al.* [61]	1969–1973	Goteborg, Sweden	53	10–15	118	3400	–
Zureik *et al.* [25]	Not given	France	105	11–16	112	3300	–
Rabbia *et al.* [14]	1977–1978	Turin, Italy	1310 (660)	12–14	114 (M)	3300	–
					111.2 (F)	3200	–
Walker *et al.* [17]	Not given	Edinburgh	452 (231)	16–26	117	3470	–
Matthes *et al.* [62]	1975–1977	Cardiff, Wales	328	15	108	2800	+
Macintyre *et al.* [27]	1971–1972	Clydeside, UK	838 (413)	15	114 (M)	Not given	–
					109 (F)		+
Pharoah *et al.* [47]	1980–1981	Merseyside, UK	139	15	114.7 (non–disabled)	1249	–
					112.1 (disabled)	< 1500	–
Uiterwaal *et al.* [72]	Not given	Netherlands	316	15–19	Not given	3400	–
Berkey *et al.* [73]	Not given	Boston	134 (M)	17	114.1 (M)	3300	–
				17	104.7 (F)	3250	+
Laor *et al.* [15]	1974–1976	Jerusalem	10 833 (6684)	17	111.3	Not given	–
Seidman *et al.* [63]	1964–1971	Jerusalem	32 580 (20 088)	17	121 (M)	Not given	+
					113 (F)		+
Nilsson *et al.* [16]	1973–1975	Sweden	149 378 (M)	18	128.8	3543	–
Milligan *et al.* [18]	Not given	Australia	583 (301)	18	126.7 (M)	Not given	–
					112.9 (F)		
Williams *et al.* [80]	1972–1973	New Zealand	702	18	121	3400	+
Stocks *et al.* [9]	Not given	Bristol, UK	1355 (572)	18–25	120.3 (M)	Not given	–
					109.4 (F)		–

M, male; F, female; –, negative association; +, positive association.

Table 7 **Studies investigating the effects of postnatal catch up growth on systolic blood pressure (SBP)**

Author	Year of birth	Place	Sex	*n*	Age (years)	Mean SBP (mmHg)	Mean BW (g)	Measure used to assess catch-up growth	Effect of catch-up on SBP
Skeletal catch-up growth									
Williams *et al.* [80]	1972–1973	Dunedin, New Zealand	Mixed	750	7	102	3400	Height and weight at 7 and 18 years relative to birthweight	+
				702	18	121			
Hennessey *et al.* [51]	1958	UK	Female	3172	33	Not known	3283	Difference in height between subject and mother and rate of fetal growth	+
Koupilova *et al.* [75]	1920–1924	Uppsala, Sweden	Male	1335	50	131.4	3588	Adult height > 176 cm	+
				1087	60	140.4			
				736	70	146.4			
Non-skeletal catch-up growth									
Whincup *et al.* [5]	1991–1992	Avon, UK	Mixed	971	3	90.4 (M)	3520		0
				889		89.2 (F)	3410		0
Launer *et al.* [76]	1980	Rotterdam, Netherlands	Mixed	374	4	96	3400		+
Whincup *et al.* [78]	1980–1983	Nine towns, UK	M	1789	5–7	101	3400		+
			F	1802		101	3300		0
Uiterwaal *et al.* [72]	Not given	Netherlands	Mixed	330	5–37	Not given	3400		+
Forsen *et al.* [71]	1981–1982	Finland	Mixed	342	7	Not given	Not given		+
Bergel *et al.* [9]	1987–1990	Argentina	Mixed	518	7	104.9 (M)	3277		+
						104.2 (F)	3196		
Baudekar *et al.* [69]	1987–89	India	Mixed	477	8	111.4 (M)	2800		+
						111.2 (F)	2700		
Ley *et al.* [46]	Not given	Sweden	Mixed	68	8–10	62.8	3493		+
Donker *et al.* [10]	Not given	Louisiana, USA	Mixed	1446	7–11	97.5	3291		+
Laor *et al.* [15]	1974–1976	Jerusalem	Mixed	10 833	17	111.3	Not given		0
Nilsson *et al.* [16]	1973–1975	Sweden	M	149 378	18	128.8	3543		+
Kolacek *et al.* [36]	1968–1969	Croatia	Mixed	465	18–23	129	3500		+
Stocks *et al.* [19]	Not given	Bristol, UK	Mixed	1355	18–25	120.3 (M)	Not given		+ (NS)
						109.4 (F)			0

M, male; F, female; 0, no association; +, positive association; NS, not significant ($P > 0.05$).

Table 8 Studies excluded from the review

Authors	Year of birth	Place	Sex	*n*	Ethnicity	Age (years)	Reasons for exclusion
Georgieff *et al.* [81]	Not given	USA	Mixed	61	Not given	Newborn	Pathological group
Northern Neonatal Nursing Initiative [82]	1990–1991	England	Mixed	566	Not given	Newborn	Pathological group
Hegyi *et al.* [83]	1984–1987	USA	Mixed	1105	73% white, 26% black	Newborn	Pathological group
Guerra *et al.* [84]	Not given	Portugal	Mixed	39	Not given	0–3 yrs	Non-quantitative analysis
Leeson *et al.* [85]	1986–1988	England	Mixed	333	95% white 3% Indian 1% Afro-Carribean 1% mixed	11	Non-quantitative analysis
Nelson *et al.* [86]	1965–1967	Arizona, USA	Mixed	308	Pima Indians	20–61	Non-quantitative analysis
Goodfellow *et al.* [87]	1975–1977	Cardiff	Mixed	39	Not given	19–20	Non-quantitative analysis
Rudberg *et al.* [88]	Not given	Sweden	Mixed	300	Not given	18–20	Non-quantitative analysis
Klebanoff *et al.* [89]	1959–1961	Denmark	Female	1261	Not given	Not given	Outcome measure was hypertension in pregnancy
Lee *et al.* [90]	1996–1997	Singapore	Mixed	61	Not given	Newborn	Pathological group
Cunningham *et al.* [91]	Not given	Scotland	Mixed	232	Not given	Newborn	Pathological group
Said *et al.* [92]	Not given	France	Mixed	1296	Not given	3–4 yrs	Non-quantitative analysis

existence of a true association between birth weight and blood pressure.

For measurements other than birth weight the most consistent findings are the inverse association between head circumference and blood pressure, the magnitude of the relationship being a decrease in SBP by approximately 0.5 mmHg/cm, and an absence of an association between ponderal index or birth length and SBP. There is no consistent relationship between gestational age, placental weight or placental : birth weight ratio with SBP. Based on data from only three studies, it is not possible to draw a conclusion about the relationship between SBP and chest circumference. Therefore, the evidence indicates that birth weight and head circumference are the only birth measurements that are consistently predictive of SBP in later life.

The relationship between birth weight and blood pressure in adolescents has previously been reported to be inconsistent. However, this review found that the majority of the studies, which included two large cohorts from Jerusalem [15] and Sweden [16], that examined the relationship in adolescence reported that the inverse relationship was visible but was often smaller than that reported in prepubescent children and adults. For example, in the longitudinal study of Finnish children and adolescents [70], it was found that during puberty the inverse relationship between birth weight and blood pressure is smaller but is restored to previous levels after puberty. This change in the birth weight–SBP association may be due to the perturbed tracking of blood pressure during the adolescent growth phase.

The three studies that investigated the association between postnatal skeletal catch-up growth and SBP in adulthood all reported positive associations [51,75,80]. Nine out of the 13 studies, which examined the role of non-skeletal catch-up growth reported positive associations [9,10,16,36,46,69,71,72,76]. This supports the suggestion that small-for-gestational-age infants, who tend to exhibit catch-up growth postnatally, are at increased risk of high blood pressure [93]. However, our review cannot determine whether this postnatal catch-up growth predicts blood pressure independently of prenatal growth, as the many different measures of postnatal catch-up growth described usually incorporated birth weight in their calculation. Moreover, the heterogeneity of measures of postnatal catch-up growth may have represented different biological processes – for example accelerated growth in early childhood or accumulation of fat in adult life. The inter-relationships between pre- and postnatal growth and later blood pressure requires further study [94].

It has been suggested that the relationship between birth weight, postnatal growth and later blood pressure is a consequence of *in utero* programming [60]. More recently, it has been speculated that genetic factors may influence intra-uterine growth and mediate the relationship between fetal growth and adult blood pressure [84]. It is beyond the scope of this review to discuss the possible underlying biological mechanisms linking fetal growth to blood pressure in later life. However, the consistency of the relationship in observational studies suggests that new challenges of research include elucidation of the underlying biological mechanisms and the potential interventions to reduce blood pressure.

Conclusion

The evidence from the literature indicates that there is an inverse association between birth weight and SBP in children, adolescents and adults. In addition, there is evidence for an inverse relationship between head circumference and SBP. In contrast, other birth measurements including ponderal index, placental weight and gestational age are not consistently related to SBP. Skeletal and non-skeletal postnatal catch-up growth were positively associated with blood pressure, with the highest blood pressures occurring in individuals of low birth weight but high rates of growth subsequently.

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