Secondary Sex Ratio in Multiple Births

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Attempts have been made to identify factors influencing the sex ratio at birth (number of males per 100 females). Statistical analyses have shown that comparisons between sex ratios demand large data sets. The secondary sex ratio has been believed to vary inversely with the frequency of prenatal losses. This hypothesis suggests that the ratio is highest among singletons, medium among twins and lowest among triplets. Birth data in Sweden for the period 1869–2004 showed that among live births the secondary sex ratio was on average 105.9 among singletons, 103.2 among twins and 99.1 among triplets. The secondary sex ratio among stillbirths for both singletons and twins started at a high level, around 130, in the 1860s, but approached live birth values in the 1990s. This trend is associated with the decrease and convergence of stillbirth rates among males and females. For detailed studies, we considered data for Sweden in 1869–1878 and in 1901–1967. Marital status or place of residence (urban or rural) had no marked influence on the secondary sex ratio among twins. For triplets, the sex ratio showed large random fluctuations and was on average low. During the period 1901–1967, 20 quadruplet, two quintuplet and one sextuplet set were registered. The sex ratio was low, around 92.0.

Keywords: marital status, live births, stillbirths, stillbirth rate, urban and rural regions, $\chi 2$ tests, Sweden

In a long series of papers, attempts have been made to identify factors influencing the sex ratio at birth (males per 100 females), also called the secondary sex ratio (SR). Widespread belief has held that the SR varies inversely with the frequency of prenatal losses (Hawley, 1959). However, Visaria (1967) stressed that available data on late fetal mortality lend at best only weak support for this hypothesis. Visaria discussed the possibility that racial differences exist in the SR. In addition, he noted that the observed SRs are influenced by random errors, and he constructed confidence intervals (CIs) for the SR. Krackow et al. (2002) presented a χ^2 test of the variations in the SRs based on the proportion of males. In this study, we present alternative CIs and a new χ^2 test.

Variations in the SR that have been reliably identified in family data have in general been slight and without notable influence on national birth registers (for references, see Fellman et al., 2002; Fellman & Eriksson, 2008).

Material

Our detailed series of Swedish birth data start with data for the period 1869–1878, published by Berg (1880), where he presented the total number of singletons, the SR and the stillbirth rates (SBRs) among males and females. Based on this information, we estimated the number of live and stillbirths among both male and female singletons. For the multiple maternities, Berg gave observed numbers of the composition of the multiple sets with respect to live and stillbirths and to the sex combinations. In addition, Berg grouped the data according to marital status of mothers and place of residence (rural and urban regions). Similar information published by Statistics Sweden was available for Sweden for the period 1901–1967. Information about the marital status of the mothers was registered for the whole period, but information about the place of residence only up to 1964.

Berg noted 209 triplet sets for the period 1869–1878. For 1901–1967, a total of 989 triplet, 20 quadruplet, two quintuplet and one sextuplet set were registered.

From 1973 onwards 'Socialstyrelsen' (Center for Epidemiology at the National Board of Health and Welfare in Sweden) has been responsible for the registration of stillbirths. However, their published data for 1973–2004 are not as informative as the data of Berg (1880) or Statistics Sweden data. Therefore, we were able to conduct detailed analyses only for the period 1869–1967.

Methods

In the following mathematical analyses, we define for simplicity the SR as

$$SR = \frac{p}{1-p},$$

where p is the proportion of males. In numerical applications, the SRs are usually given as number of

Received 02 June, 2009; accepted 20 November, 2009.

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males per 100 females. In the applications, we return to the traditional formulae

$$SR = 100\frac{p}{1-p} \text{ and } p = \frac{SR}{SR+100},$$

and the theoretical variances obtained should be scaled with 10000 and the estimators and the standard deviations (*SD*s) with 100.

Maximum Likelihood Estimation

If the theoretical proportion of males is p_0, then the observed relative frequency of males p is a maximum likelihood (ML) estimator of p_0 being unbiased, consistent, efficient and asymptotically normal with $E(p) = p_0$ and

$$Var(p) = \frac{p_0(1-p_0)}{N}.$$

According to the ML theory,

$$SR = \frac{p}{1-p}$$

is a ML estimator of the transformed parameter

$$SR_0 = \frac{p_0}{1-p_0},$$

but SR is not unbiased. Consider the difference

$$SR - SR_0 = \frac{p}{1-p} - \frac{p_0}{1-p_0} = \frac{p-p_0}{(1-p)(1-p_0)}.$$

When $N \to \infty$, then $p \to p_0$ and $SR - SR_0 \to 0$ and the estimate SR is consistent and asymptotically unbiased and normally distributed.

Standard Deviations and Confidence Intervals

Visaria (1967) stressed that random errors influence the variation in the SR. Therefore, he presented a numerical table illustrating how the CIs of the SR depend on the observed SR and the number of births. He gave no formula for the intervals, but he stated that 'the standard error of an observed sex ratio can be estimated as the standard error of the proportion 'p' of male births among the total'. We have interpreted his statement to mean that he constructed CIs for p, that is

$$\left(p - k\sqrt{\frac{p(1-p)}{N}},\ p + k\sqrt{\frac{p(1-p)}{N}}\right) = (p_L, p_U), \qquad (1)$$

where k corresponds to the confidence level.

He then defined the CI for the SR, (SR_L, SR_U), such that

$$SR_L = \frac{p_L}{1-p_L} \text{ and } SR_U = \frac{p_U}{1-p_U}.$$

Visaria's attempt is based on SR being a monotonously increasing function of p. Numerical checking of his results confirmed this interpretation.

Visaria's CI has the following properties. If we introduce the following short notations $p_L = p - h$ and $p_U = p + h$, where

$$h = k\sqrt{\frac{p(1-p)}{N}},$$

then the center of the confidence interval is

$$\tfrac{1}{2}\left(\frac{p_L}{1-p_L} + \frac{p_U}{1-p_U}\right) = \tfrac{1}{2}\left(\frac{p-h}{1-p+h} + \frac{p+h}{1-p-h}\right) =$$

$$\frac{p-\left(p^2-h^2\right)}{(1-p)^2-h^2} = \frac{p}{1-p} + \frac{h^2}{(1-p)\left((1-p)^2-h^2\right)} \geq$$

$$\frac{p}{1-p} = SR. \qquad (2)$$

The center is greater than the observed SR, but when $N \to \infty$, then $h \to 0$ and the center converges towards SR.

The length of the CI is

$$CI_1 = \frac{p_U}{1-p_U} - \frac{p_L}{1-p_L} = \left(\frac{p+h}{1-p-h} - \frac{p-h}{1-p+h}\right)$$

$$= \frac{2h}{(1-p)^2-h^2} = \frac{2k\sqrt{\frac{p(1-p)}{N}}}{(1-p)^2 - k^2\frac{p(1-p)}{N}}$$

$$= \frac{2k}{(1-p)}\sqrt{\frac{p}{(1-p)N}}\left(\frac{1}{1-k^2\frac{p}{(1-p)N}}\right). \qquad (3)$$

According to the ML theory, the variance of SR is

$$Var(SR) = \left(\frac{df(p)}{dx}\right)^2 Var(p), \qquad (4)$$

where $f(p) = SR = \frac{p}{1-p}$. We obtain

$$Var(SR) = \left(\frac{d\left(\frac{p}{1-p}\right)}{dp}\right)^2 Var(p)$$

$$= \left(\frac{1}{(1-p)^2}\right)^2 \frac{p(1-p)}{N} = \frac{p}{(1-p)^3 N}. \qquad (5)$$

From (5) follows that $SD(SR) = \frac{1}{1-p}\sqrt{\frac{p}{(1-p)N}}$,

and the CI is

$$\left(SR - \frac{k}{1-p}\sqrt{\frac{p}{(1-p)N}},\ SR + \frac{k}{1-p}\sqrt{\frac{p}{(1-p)N}}\right). \qquad (6)$$

Obviously, the center of the CI is SR. The length of the CI is

$$CI_2 = \frac{2k}{1-p}\sqrt{\frac{p}{(1-p)N}}\,. \tag{7}$$

In addition to the result that the center of the Visaria CI converges toward SR, we obtain

$$\frac{CI_2}{CI_1} = \frac{2k\sqrt{\frac{p}{(1-p)N}}\left((1-p)^2 - k^2\frac{p(1-p)}{N}\right)}{(1-p)2k\sqrt{\frac{p(1-p)}{N}}}$$

$$= \left(1 - k^2\frac{p}{(1-p)N}\right) \le 1\,. \tag{8}$$

Hence, $CI_2 \le CI_1$, but the ratio $\frac{CI_2}{CI_1} \to 1$ when $N \to \infty$. Hence, the CIs are asymptotically the same, and although the observed SRs are biased, both CIs are applicable for large N. Visaria (1967) pointed out the CIs are crucial when differences in the SRs are interpreted.

In Figure 1, we present Visaria's and our CIs with respect to the sample size N given on a logarithmic scale. We note that for small data sets the CIs are broad, and consequently, it is difficult to identify statistically significant differences. In addition, we observe that for small values of N there is a notable upward shift in Visaria's CIs. With increasing N, this shift vanishes.

Testing Differences in Sex Ratios

Fellman and Eriksson (2006) introduced an approximate χ^2 test for monozygotic and dizygotic twinning rates. Analogous procedures will be presented for the SRs. Our test procedures are developed under the assumption that the SRs are asymptotically consistent and normal. Furthermore, we assume in this paragraph that the data sets are large enough so that asymptotic results can be presented without any additional assumptions.

The simultaneous test of several SRs results in a χ^2 test. Let the null hypothesis be that the sets have a common SR_0. According to (5), the variance

$$Var(SR_t) = \frac{p_0}{(1-p_0)^3 N_t}, \text{ where } p_0 = \frac{SR_0}{1+SR_0}$$

and N_t is the sample size for $t = 1,\ldots,T$ and $T \ge 2$. The variable

$$(SR - SR_0)/\sqrt{\frac{p_0}{(1-p_0)N_t}}$$

is a standardized variable, and consequently, $N(0,1)$. Hence,

$$\chi^2 = \frac{(1-p_0)^3}{p_0}\sum_{t=1}^{T} N_t(SR_t - SR_0)^2 \tag{9}$$

is χ^2 distributed with T degrees of freedom. If p_0 is unknown, we introduce the weighted mean

$$\overline{SR} = \sum_t \frac{N_t SR_t}{\sum N_t},$$

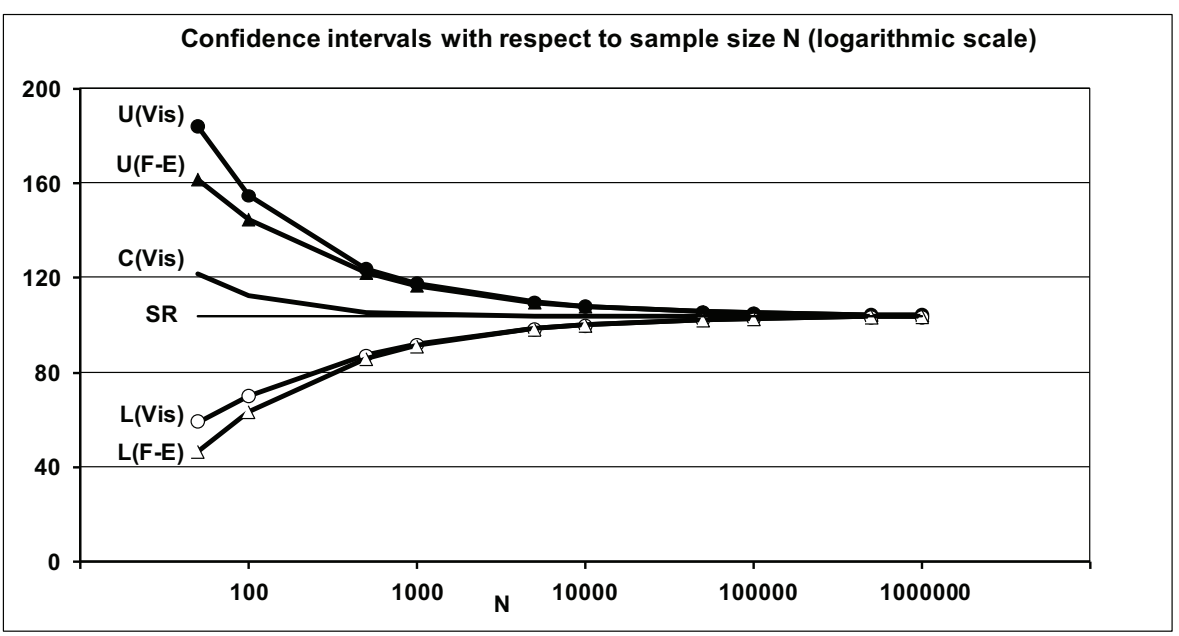

Figure 1

Graphical sketch of the confidence intervals (CIs) for the secondary sex ratio (SR) according to sample size *N* on a logarithmic scale.

Note: The CIs are given by Visaria (1967) and in Eq. (6) of this study. Upper (U) and lower (L) limits of the CIs are denoted U(Vis) and L(Vis) for Visaria CIs and U(F-E) and L(F-E) for our CIs, respectively. The center of the Visaria CI (C(Vis)) and the SR (104.0) are also included in the figure.

which under the null hypothesis is the most efficient estimate of SR_0, and estimate

$$\overline{p}_0 = \frac{\overline{SR}}{1+\overline{SR}}.$$

Consequently, we have estimated one parameter, and

$$\chi^2 = \frac{(1-\overline{p}_0)^3}{\overline{p}_0}\sum_{t=1}^{T} N_t\left(SR_t - \overline{SR}\right)^2 \tag{10}$$

is χ^2 distributed with $T - 1$ degrees of freedom.

Krackow et al. (2002) presented an analogous χ^2 test based on the proportion of males. Their method follows the same ideas as ours based on the SR. They compared the proportions of males in different clutches with variable sizes. Under the assumption that p is common for all clutches, their formula was

$$\chi^2 = \sum_{t=1}^{T}\frac{n_i^2(p_i - p)^2}{n_i pq}. \tag{11}$$

The observed relative frequency p converges rapidly toward normality, and the standardized variables

$$\frac{(p_i - p)}{\sqrt{pq/n_i}}$$

can be assumed $N(0,1)$ also for small data sets. Consequently, the test statistic is χ^2 distributed with T degrees of freedom. If p is unknown, then it is estimated by

$$\hat{p} = \frac{\sum n_i p_i}{\sum n_i},$$

i.e. the proportion of males in the total data set. The χ^2 test is modified to

$$\chi^2 = \sum_{t=1}^{T}\frac{n_i^2(p_i - \hat{p})^2}{n_i\hat{p}(1-\hat{p})}, \tag{12}$$

which has T – 1 degrees of freedom. Our numerical checks show that Krackow's and our methods give similar results.

An alternative χ^2 test based on the contingence table of males and females in the data sets can be applied. However, it yields a mathematically identical χ^2 test as Krackow's test.

Association Between Stillbirth Rate and Secondary Sex Ratio

We use the following notations: let the number of males be $n(M)$, the number of females $n(F)$, the number of liveborn males $n_L(M)$, the number of liveborn females $n_L(F)$, and the number of stillborn males $n_S(M)$ and the number of stillborn females $n_S(F)$. Consequently, the SRs are

$$SR_0 = \frac{n(M)}{n(F)} \text{ among all births,}$$

$$SR_L = \frac{n_L(M)}{n_L(F)} \text{ among the liveborn and}$$

$$SR_S = \frac{n_S(M)}{n_S(F)} \text{ among the stillborn.}$$

The SBR among males is $SBR(M) = \frac{n_s(M)}{n(M)}$

and among females $SBR(F) = \frac{n_s(F)}{n(F)}$.

The SR among the stillborn is

$$SR_s = \frac{n_s(M)}{n_s(F)} = \frac{n_s(M)/n(F)}{n_s(F)/n(F)}$$

$$= SR_0\frac{n_s(M)/n(M)}{n_s(F)/n(F)} = SR_0\frac{SBR(M)}{SBR(F)}. \tag{13}$$

Usually $SBR(M) > SBR(F)$ and $SR_S > 1$.

For the SR among the liveborn, we obtain the formula:

$$SR_L = \frac{N_L(M)}{N_L(F)} = \frac{N(M) - N_s(M)}{N(F) - N_s(F)}$$

$$= \frac{N(M)(1-SBR(M))}{N(F)(1-SBR(F))} = SR_0\frac{(1-SBR(M))}{(1-SBR(F))}. \tag{14}$$

In general, $SBR(M)$ and $SBR(F)$ are markedly less than one, and consequently,

$$\frac{1-SBR(M)}{1-SBR(F)} \approx 1$$

and $SR_L \approx SR_0$. If $SBR(M) > SBR(F)$, then $SR_L < SR_0$.

Results

In Figure 2, we present the SRs for live and still births of singletons and twins in Sweden for 1869–2004. The period is divided into seven subperiods corresponding to the different data sources. The SRs are rather stable during the whole period. Among liveborn singletons, it is on average 105.9 and among liveborn twins 103.2. The temporal variation is tested by the χ^2 test in Eq. (10). For liveborn singletons, χ^2 = 15.045 with 6 degrees of freedom and $P < .05$, indicating slight temporal variations. If we apply the χ^2 test (Eq. (12)) proposed by Krackow et al. (2002), we obtain χ^2 = 15.053, and both test results are comparable. Consequently, the large data sets of liveborn singletons identify statistically significant temporal differences for singletons. In general, the χ^2 tests depend strongly on the sample sizes, and therefore, significant differences cannot be found among the liveborn twins.

The SR among the stillborn starts from a high level of around 130 for both singletons and twins, indicating a surplus of males among stillbirths. After the

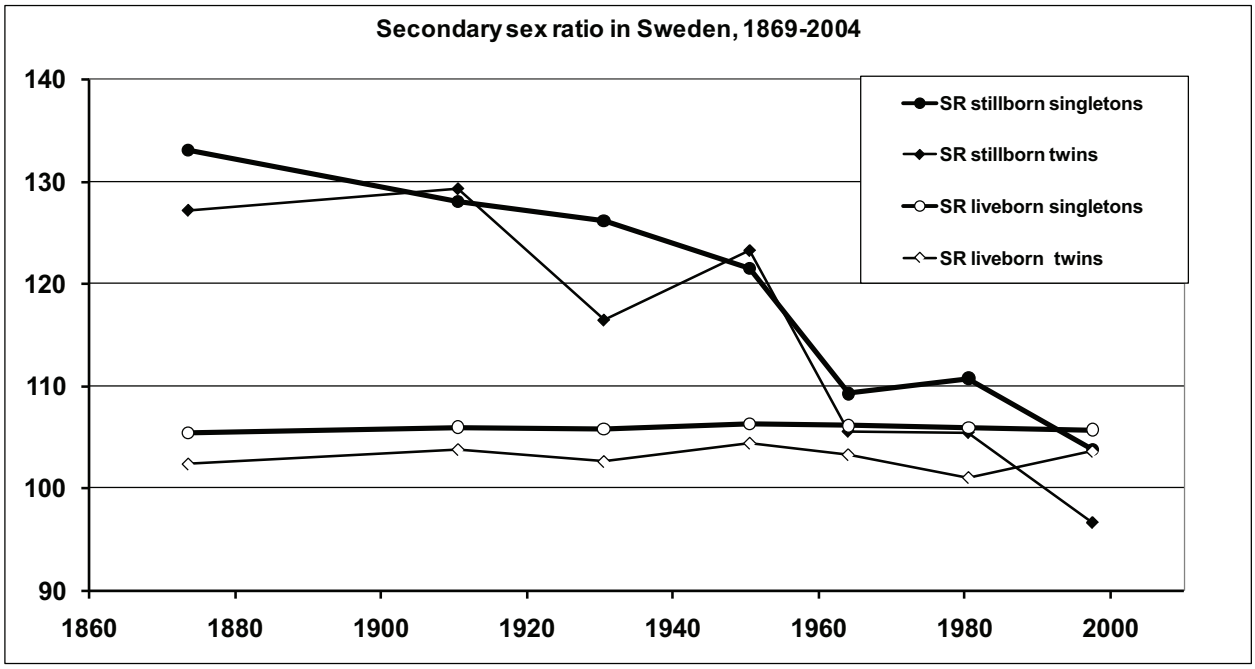

Figure 2

Secondary sex ratio (SR) among live- and stillborn singletons and twins in Sweden, 1869-2004.

Note: The period is divided into seven subperiods (1869–1878, 1901–1920, 1921–1940, 1941–1960, 1961–1967, 1971–1990, 1991–2004). Marked differences can be observed between still and live births, particularly up to the 1960s. The SRs among live births are rather constant. The SR among stillbirths starts from a high level (around 130). After the 1950s, the SRs among the stillborn decrease to a level mainly between 95 and 105, being considered normal. This trend is caused by a convergence of the stillbirth rates among males and females (cf. Figure 3).

1950s, the SRs among the stillborn decreased to a level mainly between 95 and 105, being considered rather normal. The temporal trends in the SRs among the stillborn can be explained by the SBRs among males and females converging, as can be seen in Figure 3. The temporal variation is tested by the χ^2 test in Eq. (10). The large data sets of stillborn singletons reveal significant differences. For stillborn singletons, $\chi^2 = 169.0$ with 6 degrees of freedom and $P < .001$. Krackow's test yields $\chi^2 = 167.0$. The data set for stillborn twins is so small that significance is not obtained despite a strong decrease.

In Figure 4, we compare the SR among live- and stillborn twins in Sweden, 1869–1967, according to marital status. The period is divided into five subperiods, as presented in Figure 4. Among the stillborn to unmarried mothers, the SR is on average almost the same (123.2) as among the stillborn to married mothers (123.9). The SRs are 102.3 among liveborn twins to unmarried mothers and 103.6 among liveborn twins to married mothers. No statistically significant differences were obtained.

In Figure 5, we compare the SR among live- and stillborn twins in urban and rural regions of Sweden, 1869–1964. The period is still divided into five subperiods. The SR among stillborn twins is on average slightly higher in urban regions (129.9) than in rural regions (122.5). Among liveborn twins, the SR is 104.0 in urban and 103.2 in rural regions. No significant regional differences were discernible.

For triplets, the SR showed large random fluctuations during the period 1869–1967 and was on average somewhat lower than among singletons and twins, being 97.6 for live births and 89.9 for stillbirths (cf. Table 1). The SR among stillborn triplets showed no significant temporal variations during the whole period. This result is supported by the SBR being similar for males and females (see Figure 3). During 1869–1967 20 quadruplet, two quintuplet and one sextuplet set were registered. These comprised 46 males and 50 females. Consequently, the SR was rather low, 92.0, but with a broad 95% CI 55.2 – 128.8.

Discussion

The SR in multiple births is known to be low. The reason for this low ratio is unclear, but several hypotheses have been presented, including theories about maternal gonadotrophin level at the time of conception or higher prenatal mortality of twin males (Bulmer, 1970; James, 1980; 1986; Milham, 1964). James (1975) studied the effect of maternal age on the SR among twins. He collected data on over 2.5 million twin births from different countries. Based on his analyses, he stated that the SR is lower in monozygotic (MZ) twins than in dizygotic (DZ) twins or singletons. This finding would also account for the low overall SR in twins. He estimated that the SR

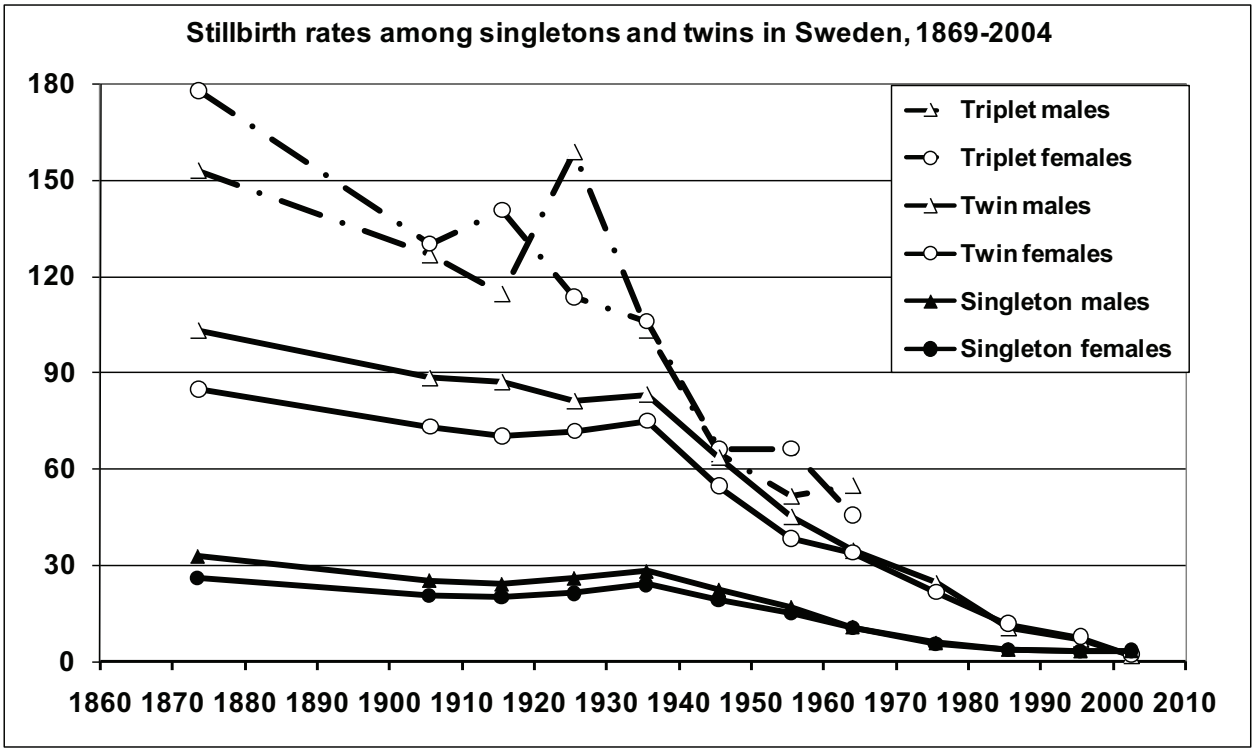

Figure 3

Stillbirth rates (SBRs) among singletons and twins in Sweden, 1869-2004, and among triplets in Sweden, 1869–1967.

Note: The sex differences disappear and the convergence causes a decreasing trend in the secondary sex ratio among the stillborn (cf. Figure 2). The SBRs among triplets are on a higher level, but the temporal decreasing trend is similar. Note that no marked sex difference exists in the SBR among triplets.

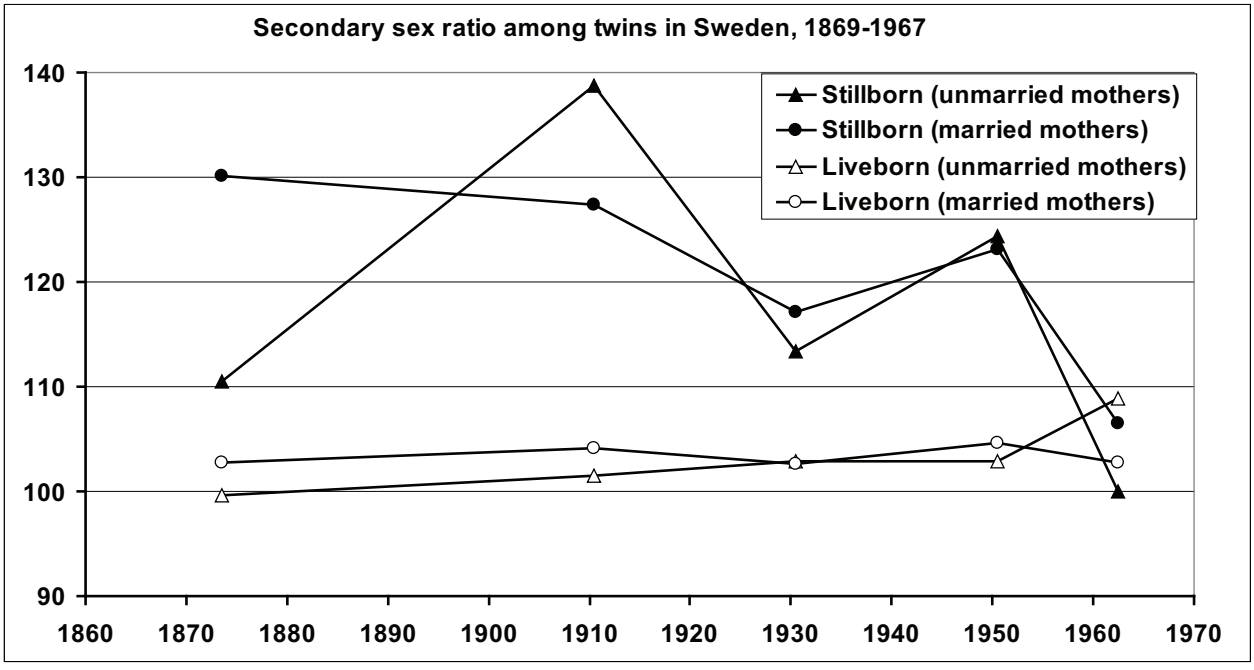

Figure 4

Secondary sex ratio (SR) among live- and stillborn twins in Sweden, 1869–1967, according to mothers' marital status (married or unmarried).

Note: The period is divided into five sub-periods (1869–1878, 1901–1920, 1921–1940, 1941–1960, 1961–1967). Among the stillborn to unmarried mothers, the SR is on average almost the same as among the stillborn to married mothers. The SR among liveborn twins to unmarried mothers is almost the same as that to married mothers.

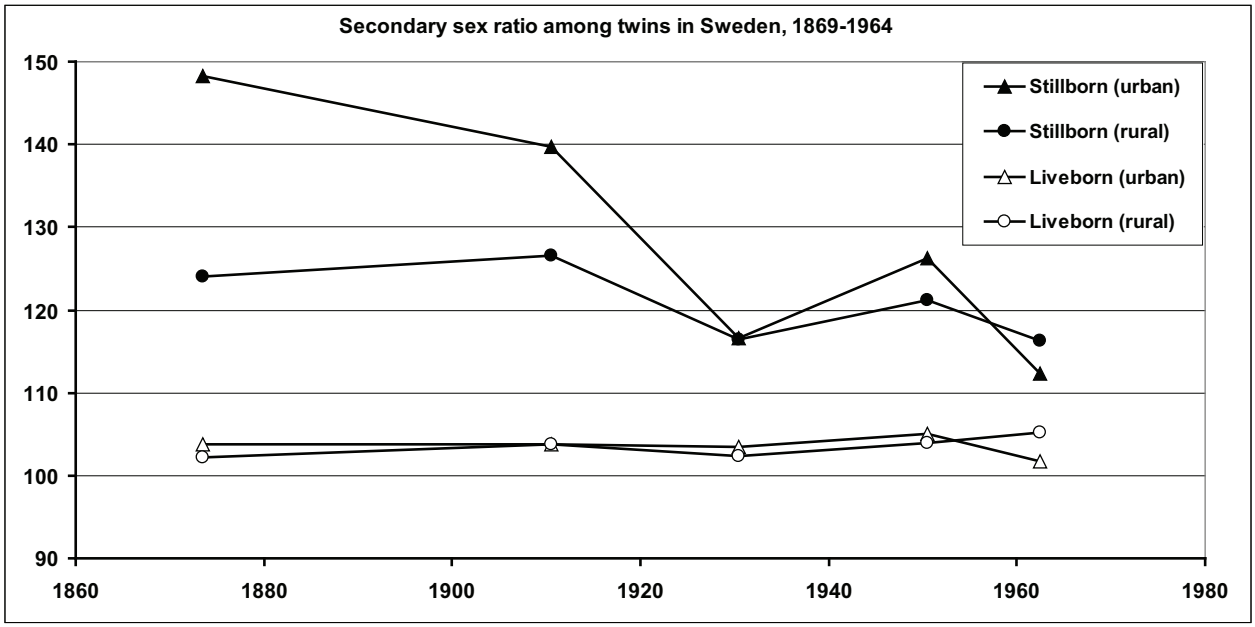

Figure 5

Secondary sex ratio (SR) among live- and stillborn twins in Sweden, 1869–1964 according to place of residence (urban or rural region).

Note: The period is divided into five subperiods (1869–1878, 1901–1920, 1921–1940, 1941–1960, 1961-1964). The SR among stillborn twins is on average slightly higher in urban than in rural regions. Among liveborn twins, no regional differences are discernible.

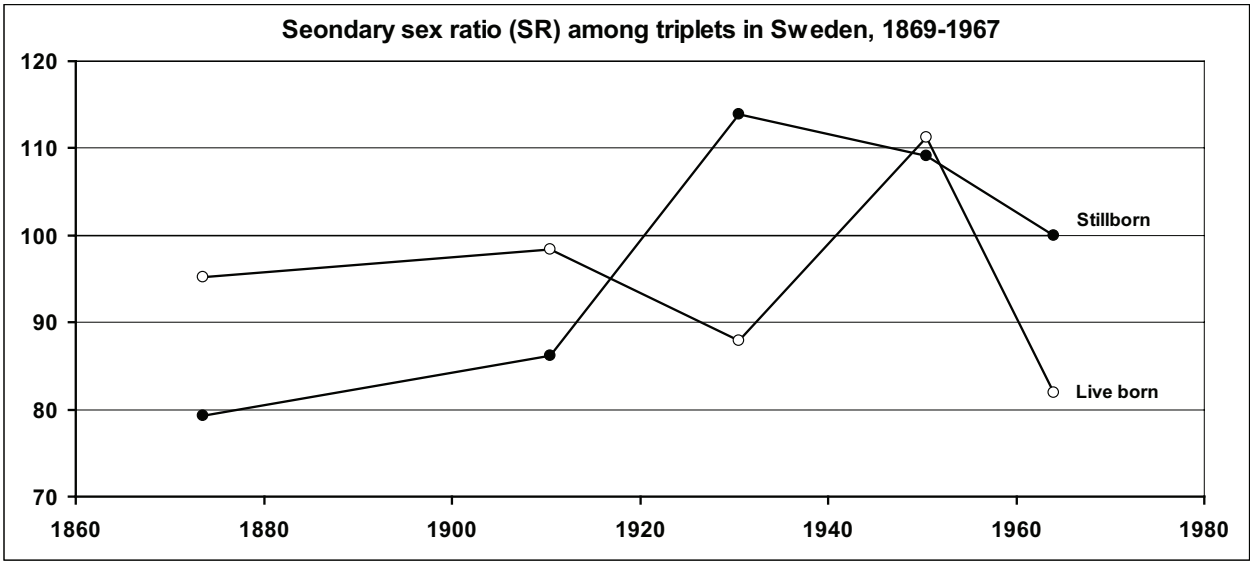

Figure 6

Secondary sex ratio (SR) among triplets in Sweden, 1869–1967.

Note: The SRs show great random fluctuations and that systematic differences in the SR among liveborn and stillborn triplets cannot be identified.

among twins obtains a maximum when the maternal age is between 30 and 40 years. This is in good agreement with the statement that the SR is lower among MZ than DZ twins. The proportion of DZ twins is highest in this maternal age group.

Hawley (1959) stated that where prenatal losses are low, as in the high standard of living in West, the SRs at birth are usually around 105 to 106. On the other hand, in areas with a lower standard of living, where the frequencies of prenatal losses are relatively high, SRs at birth are around 102. Visaria (1967) could not find any correlation between the late fetal death ratios and the SRs of live births. Further, he stated that 'the sex ratio at birth in the negro population of the United States has not increased despite a marked fall in fetal mortality'. Visaria concluded that

Table 1

Secondary Sex Ratio (SR) Among Stillborn, Liveborn and all Singletons, Twins and Triplets in Sweden, 1869–1967

	Singletons		Twins		Triplets	
	N	SR	*N*	SR	*N*	SR
Stillborn	197464	126.20	17604	123.80	414	89.91
Liveborn	8783447	105.97	226370	103.43	3180	97.64
Total	8980911	106.38	243974	104.77	3594	96.72

Note: One observes that the SR is almost the same among all births and live births and consequently, the stillbirth rates have a very slight effect.

there seem to be racial differences appear to exist in the SR.

Logically, decreased SBRs could increase the SR among the liveborn, but according to Eq. (14) the effect is minute. We elucidate the situation with a numerical example. We use the Swedish data for the period 1869–1967, when the SBRs among males and females were known for singletons, twins and triplets. For this period, the SBR is 23.798 per 1000 among singleton males and 20.060 among singleton females, 78.011 among twin males and 66.020 among twin females and 111.488 among triplet males and 117.068 among triplet females. If we apply Eq. (14), we obtain $SR_L = 0.996\ SR_0$ among singletons, $SR_L = 0.987\ SR_0$ among twins and $SR_L = 1.006\ SR_0$ among triplets. Note that among triplets the SBR is slightly higher among females than among males, and consequently, $SR_L > SR_0$. Although the SBR differs markedly between singletons, twins and triplets, the influence on the SR among live births is negligible. The results are summarized in Table 1.

Acknowledgments

This study was in part supported by grants from the Finnish Society of Sciences and Letters and the foundations 'Magnus Ehrnrooths Stiftelse' and 'Liv och Hälsa'.

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