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Abbreviations

HDSS: Health and Demographic Surveillance System

DHS: Demographic and Health Survey

SSA: Sub-Saharan Africa

SDG: Sustainable Development Goals

LMIC: Low- and Middle- Income Countries

Abstract

There is a considerable body of research on the effects of siblings on child mortality through birth intervals. This research commonly focuses on older siblings. We argue that birth intervals with younger siblings may have equal or stronger effects on child mortality, even while the mother is pregnant. Moreover, we contend that birth interval effects need to be considered only when siblings are co-resident. Using longitudinal data from 29 Health and Demographic Surveillance Systems across sub-Saharan Africa, covering over 560,000 children, we examine the role of siblings on child mortality. We find that a minimum 24 month birth interval is advantageous with both older and younger siblings. The effect of a younger sibling on child mortality is more pronounced, and these effects are in addition to those of an older sibling. Child mortality is further found to be particularly low during a mother's pregnancy. Moreover, we find that when a mother or sibling is absent from the household there is a higher risk of mortality, and death of either reduces child survival even up to six months before the death.

Introduction

A central aim of the Sustainable Development Goals (SDGs) is to ensure healthy lives and promote wellbeing for all, including the survival of new-borns and children under age five years in particular (United Nations 2015). Although under-five mortality has declined significantly worldwide, it remains highest in sub-Saharan African (SSA) countries (UN IGME 2018; You et al. 2015). Even older children who have lower mortality risks are disproportionately more likely to die in SSA than in other regions of the world (Masquelier et al. 2018; UN IGME 2018). Understanding the mechanisms that drive high child mortality in SSA is an important step towards achieving the SDG aim of under-five mortality of 25 per 1000 live births by 2030 (United Nations 2015). Identifying these mechanisms – the causal effects of child mortality – underpins targeted healthcare policies.

Included in these mechanisms are the proximate determinants of child health - maternal factors, environmental contamination, nutrition deficiencies, injury and personal illness control (Mosley and Chen 1984). The maternal factor of birth spacing, or birth interval, has long been identified as one of these key proximate determinants of child mortality in low and middle-income countries (LMIC) (Boerma and Bicego 1992; Curtis et al. 1993; Da Vanzo et al. 2008; Kozuki and Walker 2013; Miller et al. 1992; Rutstein 2005; Winikoff 1987). It is recommended that birth intervals be adequately spaced to avoid creating competition for care between children, especially in less developed country contexts (Molitoris et al. 2019; World Health Organization 2005). The new-born should receive full attention from the mother for at least the first two years of life when health risks are the highest.

Further important direct determinants of child survival are maternal age at birth and child rank (Ezeh et al. 2014; Finlay et al. 2011; Gibbs et al. 2012; Rutstein 2000) though mothers

ordinarily do not regulate these deteminants, unlike birth intervals (Boerma and Bicego 1992). The determinants maternal age, child rank and birth interval are not independent of one another. The first birth necessarily occurs at a younger maternal age than subsequent births. The first child does not compete for care with a preceding child, while the last child does not compete with a following child. The interrelationships between birth history and child survival are difficult to disentangle, with the high correlation between the age of the mother and the rank of the child adding to the difficulty (Kravdal 2018).

The mechanisms behind the effect of birth intervals on child health include maternal depletion, competition between siblings, and disease transmission (Boerma and Bicego 1992; Da Vanzo et al. 2008; Hobcraft et al. 1983; Koenig et al. 1990). Maternal depletion suggests that mothers do not fully recover from the physiological and nutritional demands of pregnancy and breastfeeding. Indeed, women may overlap pregnancy and breastfeeding which may not only be demanding on the mothers (Picciano 2003), but in low-income countries can result in spontaneous abortions or low birth weights on the one hand or can alter milk composition and lead to higher child morbidity on the other hand (Ishii 2009; Marquis et al. 2002, 2003; Merchant et al. 1990; Molitoris 2018). Breastfeeding explains the effects of following birth interval on child mortality through direct effects of post-partum amenorrhea, reduced nutrition and higher risk of disease when weaned - particularly among poor populations (Palloni and Millman 1986; Retherford et al. 1989). However, little research considers the pre-birth interval, or "pregnancy effects", on child mortality. Weaning is often initiated during subsequent pregnancies (Boerma and Bicego 1992), reducing child growth and raising the probability of child death within the first year after weaning (Bøhler and Bergström 1996; Cantrelle and Leridon 1971). Although there is some indication that even during a mother's subsequent pregnancy a child's mortality risk increases (Hobcraft et al. 1985), the impact of both the preceding and next birth interval have rarely been studied together.

The mechanism of sibling competition suggests that families have limited resources, including parental attention, and need to divide them among young siblings rather than invest all in one child. Furthermore, a large number of young children may also facilitate the spread of infectious diseases between siblings. Among children under-five, the leading causes of death are communicable diseases, such as measles, diarrhoeal diseases, or pneumonia (Norheim et al. 2015). While the presence of a sibling close in age can increase a child's risk of death, the absence of a sibling can also be detrimental. While absence of a sibling due to his/her migration may reduce sibling competition and spread of diseases, the death of a sibling may be associated with higher child mortality risk within families, as evident with death clustering. A small proportion of families account for the majority of child deaths within populations (Das Gupta 1990; van Dijk 2018). Children within the same family share genetics, are exposed to the same environment and the same maternal abilities, and are therefore more likely to die if one of their siblings dies.

Another major determinant of child wellbeing and mortality is maternal death (Anderson et al. 2007; Becher et al. 2004; Chikhungu et al. 2017; Clark et al. 2013; Houle et al. 2015). A child's risk of death is especially high when the mother's death takes place in the first year of the child's life (Chikhungu et al. 2017), though this effect has been noted even up to age twelve (Anderson et al. 2007; Houle et al. 2013). The risk of child death is particularly high in regions with high HIV prevalence, when the maternal cause of death is HIV/AIDS or TB-related (Clark et al. 2013; Houle et al. 2013). Indeed, when mothers are HIV positive and suffer drawn-

out periods of illness, they are less capable of caring for their children. As such, there is a critical period leading up to the mother's death during which young children are more likely to die (Clark et al. 2013).

The relationship between maternal death and child mortality is partially explained by lower immunization rates and malnutrition following a mother's death (Anderson et al. 2007). For younger children, it is also explained by the termination of breastfeeding - abrupt weaning (Palloni and Millman 1986). These explanations are equally valid when the mother is absent due to migration. Compared with children unaffected by migration, children's chances of dying increase around the period before, during and after a mother's migration, whether they accompany their mothers or remain behind (Brockerhoff 1994). This may be attributed to a disruption effect of migration resulting in altered circumstances for mothers and their children.

Longitudinal data are necessary to disentangle the effects of birth spacing, maternal age, child rank, maternal mortality, and maternal migration on child mortality. Data detailing dates of children's births and deaths are essential to establish the order of events. To date, Demographic and Health Surveys (DHS) have provided the bulk of comparative data on child mortality in LMICs (Deribew et al. 2016; Kravdal 2018). However, event dates in DHS are not always accurately recorded due to a "moral hazard" associated with fieldwork. Interviewers tend to displace the time of births and deaths occurring in the five-year period before the survey, or to omit them altogether, to avoid completing the lengthy questionnaires pertaining to this period (Pullum and Becker 2014). In addition, since precise dates of migration are not provided or are at best available only for the mother's last migration before the survey, the co-residence of mothers and children cannot be ascertained except for at the time of the survey (Bocquier 2016). Although the DHS are a valuable data source, these concerns over the quality and precision of the order of events invite complementary analyses from alternative sources.

Health and Demographic Surveillance Systems (HDSS) provide valuable longitudinal data alternatives to DHS. The International Network for the Demographic Evaluation of Populations and Their Health (INDEPTH) represents a group of research centres operating HDSSs in LMICs (Sankoh and Byass 2012). The HDSS method continuously captures all births, deaths and in- and out-migrations within a geographically defined population. The data have the necessary temporal accuracy to allow for the analysis of the individual-level events of interest, and for linking children to mothers and siblings. Since 2016, standardised HDSS data have been made available through the INDEPTH iShare repository (INDEPTH 2017). To date, longitudinal data from 29 HDSS located in SSA are available on iShare. Although HDSSs do not cover all populations on the continent since the populations under surveillance are not randomly selected from national populations, the HDSS sites are sufficiently diverse to illustrate heterogeneous contexts across SSA, and convergence at the continental level (Byass 2016; Utazi et al. 2016, 2018).

Considering the paucity of longitudinal population data in SSA with dated events, HDSS data represent a unique opportunity to address maternal and sibling-related proximate determinants of child mortality.[1] In particular, we aim to examine birth interval effects and co-residence of older and younger siblings on child survival, controlling for maternal effects of age, death or migration. This study also demonstrates how complex variable effects on

[1] These proximate determinants can also be easily evaluated by public health systems. For example, a nurse can assess a mother's age more readily than her wealth.

under-five mortality can be derived from readily available HDSS data on birth, death, and migration events for children and their mothers, with precise timing of these events.

In line with available literature, we hypothesise that a sibling's death has a negative effect on child survival since siblings share genetics and are often exposed to similar diseases. That said, we expect a positive effect on child survival where the lack of sibling competition would overcome these circumstances. We further hypothesise that preceding and subsequent birth intervals do not have the same effect on child survival, rather we expect a stronger negative effect of birth interval with a younger sibling since it also includes the pregnancy period before birth of the younger sibling which may compromise childcare. Birth interval effects may begin before the birth of a following child, that is, when the mother is pregnant, especially when the birth interval is short. Finally, we anticipate an effect on survival of a child whose mother or sibling is absent due to migration. The direction of the effect may be positive in the face of less competition for mother's care between children, or negative since migration may be indicative of family dissolution or detrimental socio-economic circumstances.

Materials and Methods

Health and Demographic Surveillance System Data

Data employed in this paper were obtained from the INDEPTH iShare data repository which provides standardised and documented HDSS longitudinal datasets known as "Core Datasets" (INDEPTH 2017; Sankoh and Byass 2012). These downloadable datasets are freely available and consist of key demographic events (birth, death, in- and out-migration, as well as enumeration and last date of observation). The 2018 release includes data for 29 HDSS populations situated in 13 SSA countries (see Table 1). The Core Datasets were produced following a set of procedures that are outlined in a manual of longitudinal data management (Bocquier et al. 2017). This comprehensive guide has become a standard for HDSS data management and provides analysts with a step-by-step description of the process of structuring and preparing an HDSS dataset for event history analysis. Each dataset underwent quality checks which reduced to a minimum inconsistencies in the logical order of events, such as a birth after death or two consecutive out-migrations. The resulting "core residency files" are standardised micro-datasets which follow changes in residency status in the corresponding HDSS area following a birth, death or migration, and are structured for event history analysis.

Table 1 Descriptive statistics of HDSS sites included in this study

Site	Country	Start and end of HDSS (from 1 Jan- 31 Dec)	Number of children under-five	Person-years at risk (under-five child exposure)	Number of deaths under-five	Urbanicity	Annual rainfall in mm (2014)	Average monthly temperature (1980-2008)	Travel-time in minutes to nearest city of 50,000 residents of more (2000)	Average years of educational attainment for women aged 15-49 (2010)	DPT vaccine coverage as % for children aged 12-23 months (2010)	HIV prevalence as % in adults aged 15-49 (2010)	Gross cell product in US$ at purchase power parity exchange rates (2005)
						West Africa							
Nanoro	Burkina Faso	2009-2014	11,344	27,214	471	Rural	705	28.71	255	0.8	95.7	1.0	1.015
Nouna	Burkina Faso	1998-2015	42,290	143,028	3,748	Mostly rural	729	29.09	320	0.4	97.9	0.8	0.182
Ouagadougou	Burkina Faso	2009-2015	15,938	45,801	523	Urban	772	28.61	11	4.5	94.3	1.7	2.132
Taabo	Cote d'Ivoire	2009-2016	11,041	30,842	792	Mostly rural	1455	26.93	300	2.4	92.8	3.9	0.944
Navrongo	Ghana	1994-2014	38,606	141,480	3,868	Mostly rural	900	27.13	103	2.9	92.1	1.4	0.111
Kintampo	Ghana	2006-2014	32,885	97,319	1,540	Semi-urban	1000	27.70	456	3.2	95.3	1.6	0.275
Dodowa	Ghana	2006-2011	14,884	35,344	348	Mostly rural	794	27.15	29	10.2	96.9	2.3	1.222
Farafenni	Gambia	1990-2015	27,912	101,835	2,051	Mostly rural	509	28.19	125	1.3	97.1	1.8	1.306
Nahuche	Nigeria	2011-2014	23,075	46,344	3,608	Rural	935	27.56	254	0.5	10.5	1.4	1.996
Bandafassi	Senegal	1990-2016	13,538	50,946	2,129	Rural	1129	28.07	338	1.2	95.4	1.4	0.073
Mlomp	Senegal	1990-2016	5,036	18,379	315	Rural	1443	26.28	77	4.8	99.5	1.6	0.559
Niakhar	Senegal	1990-2016	37,080	136,814	3,844	Rural	393	28.19	69	2.7	99.2	0.4	1.306
						East Africa							
Gilgel Gibe	Ethiopia	2006-2015	17,851	59,422	1,357	Semi-urban	1806	16.70	906	0.7	31.6	0.5	1.237
Kilte Awulaelo	Ethiopia	2010-2014	7,350	17,337	227	Mostly rural	674	18.30	119	1.5	94.7	1.2	0.553
Kersa	Ethiopia	2008-2016	19,469	55,566	1,597	Semi-urban	1377	22.16	556	1.0	51.0	1.0	0.740
Harar Urban	Ethiopia	2012-2016	2,999	4,980	31	Urban	813	22.16	235	0.8	49.5	1.0	0.740
Dabat	Ethiopia	2009-2015	7,586	22,576	187	Semi-urban	1275	21.73	135	1.7	46.0	1.2	0.590
Arba Minch	Ethiopia	2010-2015	10,818	27,665	327	Mostly rural	1435	17.96	118	2.5	74.6	1.1	2.029
Nairobi	Kenya	2003-2015	23,078	60,304	1,373	Urban	779	18.65	52	9.6	90.5	6.2	2.502
Kombewa	Kenya	2011-2015	7,708	17,088	274	Rural	1203	21.66	364	5.9	98.2	4.4	4.386
Ifakara Rural	Tanzania	1997-2014	47,133	146,875	3,767	Rural	1480	23.61	145	5.7	99.5	5.3	0.476
Rufiji	Tanzania	1999-2014	33,867	114,288	2,310	Mostly rural	1247	26.27	386	3.7	98.9	4.6	1.176
Magu	Tanzania	1994-2013	13,993	42,518	1,207	Rural	926	23.34	51	5.7	98.8	5.8	0.816

Iganga/Mayuge	Uganda	2005-2015	18,364	56,443	1,159	Semi-urban	1415	22.70	31	4.9	98.5	4.8	3.017
Southern Africa													
Karonga	Malawi	2003-2016	7,112	23,493	384	Mostly rural	1023	17.32	375	7.0	97.6	9.0	0.360
Chokwe	Mozambique	2010-2015	14,146	32,502	589	Semi-urban	633	24.30	93	3.8	97.9	25.8	0.473
Agincourt	South Africa	1993-2016	44,757	159,776	1,949	Rural	827	22.24	343	9.4	78.4	22.3	1.070
Dimamo	South Africa	1996-2016	6,402	22,647	99	Rural	532	22.01	47	10.6	74.1	12.9	3.400
Hlabisa	South Africa	2000-2016	26,879	100,270	1,319	Semi-urban	531	22.82	232	9.1	75.6	26.1	0.334

Sources: Geo-coordinates for sites (Utazi et al. 2018), *rainfall, travel time* (Lloyd et al. 2017), *temperature, GCP* (Nordhaus et al. 2006), *education, DPT, HIV* (IHME 2019)

The pooled dataset of 29 HDSS sites included in this study contains information on more than 560 000 children born in an HDSS and follows them until their death or time of censoring. The number of children per site varies widely across HDSS, from less than 5 000 children (Harar Urban, Mlomp) to more than 40 000 children (Nouna, Agincourt, Ifakara Rural), with an average of 20 000 children per site (Table 1). These figures depend on the size of the population followed in each HDSS and on the duration of follow-up. The iShare database contains data as far back as 1990 (Farafenni, Bandafassi, Mlomp, Niakhar) with more recent HDSS providing data from 2011 (Nahuche, Kombewa) or even 2012 (Harar Urban), with the median starting year being 2005. Right-censoring may occur at age five or at last observation date, which varies across sites from 1 January 2013 to 1 January 2017 (median: 1 January 2016). In the pooled data, the total number of person-years exceeds 1.8 million and the number of under-five deaths is over 41 000. The under-five mortality rate ($_5q_0$: probability for a newborn to die before the age of 5) varies from less than 30 (Harar Urban, Dikgale, Dabat) to more than 120 (Niakhar, Bandafassi, Nahuche) per 1000, and its median is 73 per 1000.

These under-five mortality estimates do not represent a true average of under-five mortality in sub-Saharan Africa because some regions in the continent, including central Africa, are not represented by the HDSS included in this study. However, the pooled $_5q_0$ mortality estimate (weighted: 87.3 per 1000, 95% CI: 86.5 – 88.2; unweighted: 77.2 per 1000, 95% CI: 72.0 – 83.5) is very close to that based on DHS for the relevant years in the same countries (weighted: 87.2 per 1000, 95% CI: 79.0 – 95.4; unweighted: 79.6 per 1000, 95% CI: 71.2 – 87.9)[2]. The countries

[2] DHS estimates computed using StatCompiler, accessed 13-06-2019. Weighted estimates using population aged 0-4 two years before DHS surveys obtained from United Nations Population Division data query, accessed 13-06-2019.

represented by HDSS have on average lower mortality than sub-Saharan Africa as a whole, which declined from 115 per 1000 in 2000-2004 to 95 per 1000 in 2010-2014[3].

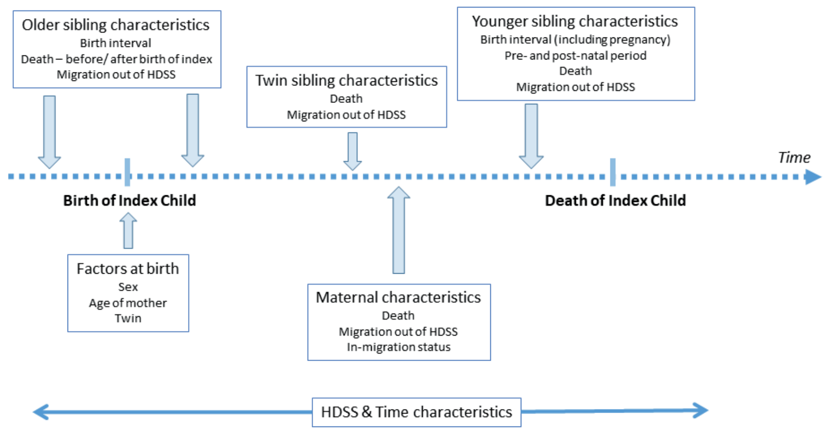
The sites represented in the present study offer a range of settings across the continent, from very high HIV prevalence in South African sites, to very low female educational attainment in rural Burkina Faso sites, and from relatively low vaccination coverage in Ethiopian sites to sites prone to malaria (where rainfall and temperatures are high) as in Senegal. Details of environmental, socioeconomic and health indicators are presented by site in Table 1.

Data Management Methods

The covariates included in our analysis are summarised in the framework depicted in Figure 1. These variables may be fixed (such as age of mother at birth) or time-varying (such as death of sibling). Construction and use of time-varying covariates' implies careful data handling as their inclusion involve creating new observation lines in the event history of the index child corresponding to each event related to the mother or siblings. In addition, a calendar period variable to capture mortality trends was created at five-year intervals. Since we rely heavily on the timing of events, we examine the accuracy of the dates of child and mother-related events – specifically dates of death and out-migration, and date of child's birth. We find that there is some heaping of these dates around specific months but not to an extent that raises concern as to the data quality at this temporal scale (see Appendix Figure 5). No single HDSS site clearly heaps dates and no particular month stands out across all dates examined. Similarly, by examining child age of death we find negligible signs of age heaping around favoured numbers (see Appendix Figure 6).

[3] Estimates obtained from United Nations Population Division data query, accessed 13-06-2019.

Fig. 1 Framework for the analysis of role of siblings on child mortality



The methods used to compute the birth, death, and migration events related to mother and siblings are detailed below. These solely make use of the Core Datasets readily available on INDEPTH iShare.[4] We demonstrate here that even with fairly simple data structures, quite sophisticated covariates can be constructed.

Mother Covariates: Age, Migration and Death

The age-group of the mother at the time of the index child's birth (fixed covariate) is easily computed from her date of birth. The possible effect of the mother's death is accounted for following the method proposed by Houle et al (2015). This involves introducing events 6 months, 3 month and 15 days before the mother's death, as well as 15 days, 3 months and 6

[4] The data from Agincourt available through iShare under-estimates migration. We prefer to still use the readily available data, but we check using the updated and fixed data to see whether our results change once more migration is accounted for. We find that our results are consistent.

months after. Corresponding time-varying indicators for periods between events control for the periods before and after the death of the mother and not just after her death, as is usually done. This is based on the hypothesis that a mother's death may be anticipated because most of these deaths are preceded by a period of illness (sudden or external deaths are rare in the female reproductive age-group) during which time she is less able to care for her children. Also a mother's illness might be more detrimental to child health in the period immediately before or at the time of her death rather than later. In other words, we expect, as in Houle et al (2015), that the relative risk of child mortality around the time of the mother's death will be bell-shaped.

The co-residence of a mother and index child in the HDSS is controlled for with the dates of out- and in-migration of the mother (when the index child remains in the HDSS). Migration refers to moves that cross the boundary of the HDSS site. This time-varying indicator of non-co-residence with a mother signifies that the child is left behind, and does not include cases where the mother may move to a different household within the site boundaries. It is possible that the mother shifts household within a site, but we do not account for such a move since she is still likely present in the child's day-to-day life. Once the mother is no longer a co-resident, her possible death is not accounted for, that is, only the death of a co-resident mother is taken into account. Maternal in-migration to the HDSS site is also accounted for, since child mortality often differs according to mother's migration status (Antai et al. 2010; Bocquier et al. 2011; Omariba and Boyle 2010; SSengonzi et al. 2002). Maternal migration status is defined as having in-migrated 6-24 months ago, or 2-5 years ago. Migration durations of less than 6 months, representing more temporary short-term moves, are less reliable and

therefore are not included in analysis. Migrants from over five years ago are considered as permanent residents.

Twin Covariates: Migration and Death

The co-residence of a twin sibling and index child is controlled for in the analysis as a time-varying covariate, using the same approach as for the mother. Similarly, a twin's death and co-residence is accounted for as is described for the mother.

Older Sibling Covariates: Birth Interval, Migration, and Death

The duration of the birth interval between an index child and an older sibling is computed using the difference between the respective dates of birth. This covariate is fixed, i.e. defined at the time of the index child's birth. Note that the data do not include dates of miscarriages, abortions, or stillbirths, but only live births, thus limiting our analysis. Nonetheless, birth interval effects have been found to be strongest with live births (Da Vanzo et al. 2008). Duration of birth interval in months, based on similar categories proposed by Kravdal (2018), used five-month periods, except the last periods as follows: less than 12 months (essentially 9-12), 12-17, 18-23, 24-29, 30-35, 36-41, 42-47, 48+.

The migration or death of an older sibling is controlled for in the same way as for mothers, using time-varying covariates. In addition, the effect of a death of an older sibling before the birth of the index child is separately examined.

Younger Sibling Covariates: Birth Interval, Pre- and Post-Natal Period, Migration, and Death

As with the older sibling, the duration of the birth interval with the younger sibling is computed using the difference between the index child's date of birth and the younger sibling's date of birth. The birth interval categories are the same as for the older sibling's birth interval but with the younger sibling the birth interval is a time-varying covariate. With younger siblings, we account for the period around the birth of the younger sibling, since there may be an effect of their birth on the health of the index child. This period includes the pregnancy period before the younger sibling's birth. This was done by introducing a "confirmed pregnancy" indicator for the six months before the younger sibling's birth date, assuming the first three months of pregnancy will have no bearing on the index child's survival. Therefore, the period around the birth, a time-varying indicator, is controlled for from when the mother is three months pregnant with the younger sibling, and then for the first six months after the younger sibling's birth, followed by periods of 6-to-11, and 12+ months after the birth. This covariate is based on the hypothesis that the younger sibling's birth is anticipated by pregnancy and that negative effects on child health may be greater in the months immediately after the younger sibling's birth.

The set of birth interval indicators are constructed with reference to the period around the younger sibling's birth, therefore an interaction term is used between period around birth and birth interval. For all these covariates, the reference category is the index child of the same age with no younger sibling. Therefore, there is no collinearity between age of the index child and time-varying covariates controlling for younger sibling effects.

As with older siblings, the co-residence of a younger sibling and index child, and the death of a younger sibling are controlled for using time-varying covariates.

Data analysis

A proportional hazard semi-parametric (Cox) model is used for the analysis of the pooled data from 29 HDSS. HDSS dummy variables are used to control for the difference in the overall level of under-five mortality. The combination of a calendar period variable and HDSS dummy

variables control for the contextual factors that may affect child mortality. Using mothers as clusters we partially account for unobserved heterogeneity between mothers – an important factor that, if ignored, may cause bias in estimates (Molitoris et al. 2019). We are unable to use mother's fixed effects in the model since we have over 350,000 mothers creating too large a matrix for existing software to handle. We are not aware of other means of controlling for maternal heterogeneity. However, we expect that by clustering on mother in the variance-covariance matrix, as well as by including the HDSS dummies, we account for most heterogeneity between mothers. Indeed, the HDSS sites are relatively homogenous in educational attainment and socio-economic status. What we lose with HDSS data in terms of representativeness, we gain in terms of the large number of cases and statistical power, and an understanding of the complex mechanisms leading to child death (Bocquier, Sankoh and Byass 2017).

Based on the framework depicted in Figure 1, we model under-five mortality, and we also test a model of infant mortality to allow for comparison to other studies (notably Molitoris et al. 2019). Examining under-five mortality allows us to move beyond the age of weaning to examine sibling effects based on competition unrelated to breastfeeding. Moreover, the causes of death between infants and 1-4 year olds differ, so in addition to infant mortality we model mortality of 1-4 year olds. Finally, we test for robustness of our results by running our principal model on under-five mortality without younger siblings. These models can be found in the Appendix.

The strength in our analysis lies in the use of time-varying covariates, which allows us to examine family dynamics from the time of birth of the index child, rather than all covariates being set at birth of the child. Results of the model presented in Table 2 indicate time-varying covariates with “TVC”. Our results are interpreted according to the width of confidence intervals and their bounds, rather than using the often arbitrary dichotomization of “significance” based on the p-value (Wasserstein et al. 2019). As such, we test the compatibility of our hypotheses with the data by discussing the upper and lower limits of the interval.

Results

The main variables of interest relate to siblings (birth intervals, death and co-residence with the index child), and mothers (age, death and migration). We describe results successively for mothers, twins, older siblings, and younger siblings. Other variables are considered as control variables and are therefore only briefly commented on. It is sufficient to say that their effects go in the expected direction: lower mortality for female children, mortality decline over calendar time (to a lesser extent in high HIV prevalence sites), and important mortality differences by site. Results of our principal model are displayed in Table 2, excluding the site-year effects which are available in Appendix Table 3. In this section “significant” means that the 95% confidence interval range does not include the value of one, but we are cautious in this and refer additionally to the bounds of the confidence interval, whereby a wide interval suggests a less certain conclusion. We refer to the lower bound of the interval as the minimum effect, when the value is above one.

Table 2 Mother’s and sibling’s effect on under-five mortality in 29 sub-Saharan African HDSS (Cox model)

	Hazard Ratio	*Confidence Intervals*		*P-value*
Sex (ref=male)				
Female	0.909***	0.891	0.927	0.000
Mother's age at birth (ref=21–23)				
15-17	1.167***	1.118	1.218	0.000
18–20	1.061**	1.024	1.099	0.001
24–26	0.975	0.941	1.010	0.165
27–29	0.976	0.941	1.012	0.193
30–32	1.011	0.973	1.050	0.575
33–35	1.016	0.975	1.058	0.450
36–38	1.098***	1.050	1.148	0.000
39–41	1.117***	1.051	1.187	0.000
42+	1.245***	1.175	1.320	0.000
Maternal residence (ref=mother permanent resident or 5yr+ in-migrant)				
Mother non resident	1.512***	1.439	1.589	0.000
-6m to -3m mother's death	3.656***	2.965	4.508	0.000
-3m to -15d mother's death	5.239***	4.395	6.245	0.000
+/- 15d mother's death	11.810***	8.655	16.100	0.000
15d to 3m mother's death	12.560***	10.850	14.550	0.000
+3m to +6m mother's death	6.982***	5.680	8.583	0.000
6m+ mother's death	2.955***	2.521	3.463	0.000
In-migrant 6-24m	0.953**	0.919	0.988	0.009
In-migrant 2y-5y	0.898***	0.867	0.931	0.000
Twin (ref=twin is resident)				
Twin non resident	0.970	0.639	1.473	0.887
-6m to -3m Twin's death	1.755**	1.238	2.488	0.002
-3m to -15d Twin's death	3.123***	2.462	3.961	0.000
+/- 15d Twin's death	27.160***	23.730	31.070	0.000
15d to 3m Twin's death	4.310***	3.399	5.464	0.000
+3m to +6m Twin's death	2.169***	1.561	3.015	0.000
6m+ Twin's death	1.275*	1.045	1.555	0.017
No Twin	0.604***	0.571	0.639	0.000
Older sibling died before birth of index child	2.428***	2.145	2.750	0.000
Older sibling (ref= birth interval 24-29m)				
No Older Sibling	1.199***	1.151	1.249	0.000
O sib non resident	1.396***	1.320	1.476	0.000
O int <12m	1.434***	1.176	1.750	0.000
O int 12-17m	1.168**	1.049	1.300	0.004
O int 18-23m	1.118**	1.044	1.196	0.001
O int 30-35m	1.030	0.979	1.083	0.262
O int 36-41m	1.029	0.971	1.091	0.329
O int 42-47m	0.993	0.927	1.065	0.852
O int 48m +	1.003	0.949	1.060	0.927
Older sibling death (ref=older sibling alive)				
-6m to -3m death	1.559**	1.160	2.096	0.003

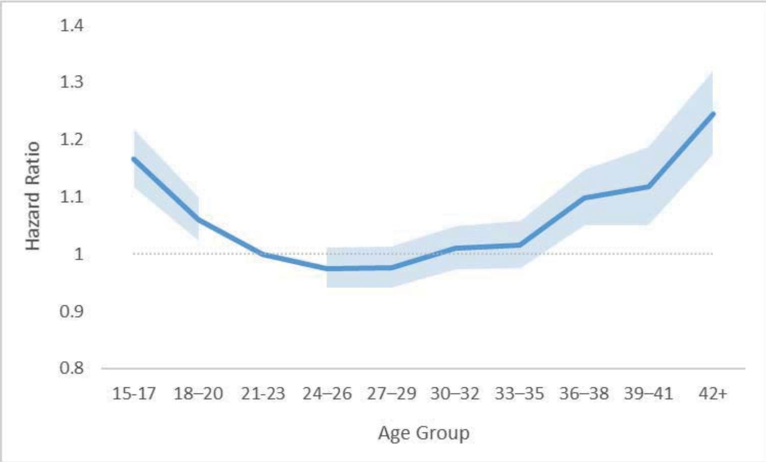
-3m to -15d death	1.200	0.881	1.634	0.248
+/- 15d death	6.038***	4.828	7.551	0.000
15d to 3m death	1.762***	1.405	2.208	0.000
3m to 6m after death	1.090	0.854	1.391	0.488
6m+ death	1.776***	1.522	2.074	0.000
Younger sibling (ref= birth interval 24-29m 0-6m)				
No Younger Sibling	0.948	0.840	1.070	0.386
Int <12m & pregnant	0.143***	0.046	0.447	0.001
Int 12-17m & pregnant	0.279***	0.181	0.428	0.000
Int 18-23m & pregnant	0.479***	0.379	0.607	0.000
Int 24-29m & pregnant	0.562***	0.471	0.670	0.000
Int 30-35m & pregnant	0.658***	0.553	0.783	0.000
Int 36-41m & pregnant	0.813	0.648	1.019	0.073
Int 42-47m & pregnant	1.360*	1.026	1.802	0.032
Int >=48m+ & pregnant	2.163***	1.632	2.866	0.000
Younger sibling non-resident	1.971***	1.472	2.641	0.000
Int <12m & 0-6m	2.781***	2.029	3.814	0.000
Int 12-17m & 0-6m	2.368***	1.923	2.917	0.000
Int 18-23m & 0-6m	1.449***	1.222	1.717	0.000
Int 30-35m & 0-6m	1.039	0.869	1.242	0.673
Int 36-41m & 0-6m	1.175	0.928	1.486	0.180
Int 42-47m & 0-6m	1.281	0.921	1.782	0.141
Int >=48m+ & 6m+	1.193	0.851	1.673	0.305
Int <12m & 6-12m	1.370	0.813	2.307	0.236
Int 12-17m & 6-12m	1.140	0.850	1.529	0.383
Int 18-23m & 6-12m	1.063	0.858	1.317	0.577
Int 24-29m & 6-12m	0.986	0.814	1.194	0.885
Int 30-35m & 6-12m	0.961	0.767	1.203	0.728
Int 36-41m & 6-12m	1.071	0.791	1.452	0.656
Int 42-47m & 6-12m	1.085	0.720	1.635	0.697
Int <12m & 12m+	0.629	0.353	1.121	0.116
Int 12-17m & 12m+	1.028	0.788	1.342	0.836
Int 18-23m & 12m+	0.917	0.741	1.134	0.425
Int 24-29m & 12m+	1.232*	1.031	1.471	0.021
Int 30-35m & 12m+	1.304**	1.068	1.592	0.009
Int 36-41m & 12m+	1.245	0.945	1.641	0.119
Int 42-47m & 12m+	1.532	0.960	2.443	0.074
Younger sibling death (ref=younger sibling alive)				
-6m to -3m death	1.493*	1.036	2.150	0.032
-3m to -15d death	2.453***	1.825	3.297	0.000
+/- 15d death	5.624***	4.242	7.455	0.000
15d to 3m death	1.395	0.961	2.025	0.080
3m to 6m after death	1.795***	1.268	2.541	0.001
6m+ death	1.247	0.951	1.634	0.110
Observations	2,248,767			
Chi2	25,936			
Log likelihood	- 530,210			
N children	583,287			
Person-years at risk	1,819,663			
N failures (child deaths)	41,541			

*Note: Exponentiated coefficients; * p<0.05, ** p<0.01, *** p<0.001; 95% confidence intervals*

Mother's Age Effect is Marginal Compared to Mother's Death and Co-Residence

Mother's age at the birth of the index child displays a flat U-shape with only age-groups below 20 and above 36 being significant (Figure 2). The upper bounds of the confidence interval suggests that if a mother is very young, aged 15-17, it could increase the risk of child death by up to 22% and if the mother is over 42 years old it could increase the risk of child death by up to 32%. When a mother is an in-migrant we find a lower risk of child's death, especially when she moved to the site between two to five years ago (HR: 0.90, 95% CI: 0.87 – 0.93). In contrast, when she leaves the site and no longer resides with the child, the risk of death for the child increases by half (HR: 1.51, 95% CI: 1.44 – 1.59). Moreover, when a mother no longer resides with her child due to death, we find a bell-shaped effect on the index child's risk of death (Figure 3), peaking between 15 days to three months after the mother's death when the risk is more than ten times higher than for a co-resident living mother (HR: 12.56, 95% CI: 10.85 – 14.55).

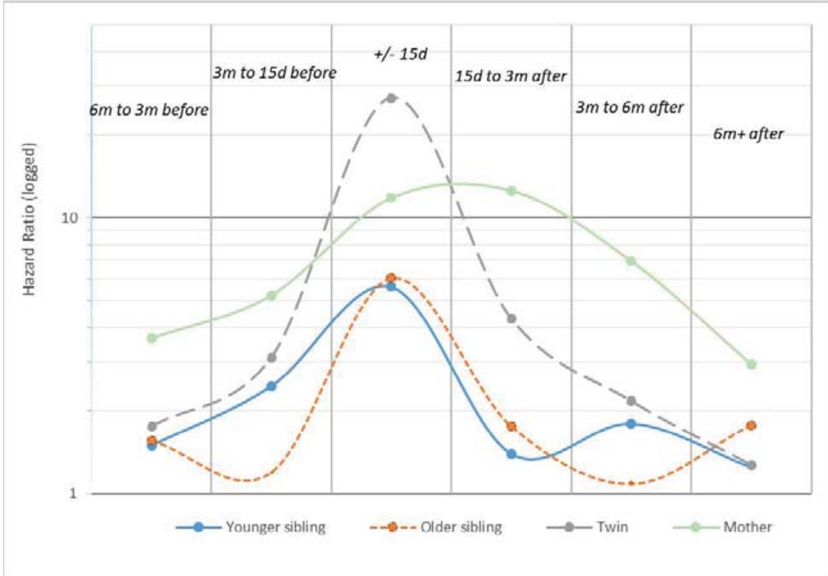
Fig. 2 Effect of mother's age at birth of index child on under-five mortality



Twin Effect in the Expected Direction

Having a twin sibling increases the index child's risk of death. In other words, not having a twin sibling lowers mortality risk by 40% (HR: 0.60, 95% CI: 0.57– 0.64). There is not enough evidence to determine whether non-co-residence with this twin changes the effect. There is a pronounced bell-shape around a twin's death, and despite the limited person-years at risk, the confidence intervals around the hazard ratios are relatively narrow, which indicates that the death of a twin is detrimental to child survival (Figure 3).

Fig. 3 Effect of mother's and siblings' death on under-five mortality



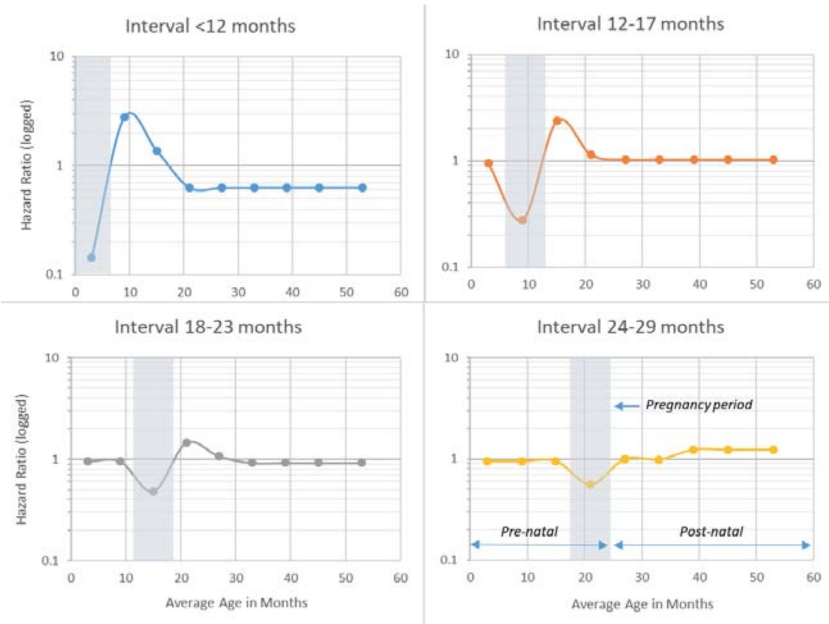
** Markers indicate significant hazard ratios (p>=.05)*

Younger Sibling Effects are More Pronounced than Older Sibling Effects

Risk of mortality is higher when the index child has no older siblings (HR: 1.2, 95% CI: 1.15 – 2.25) pointing to a 'first-child' effect. Among those who have an older sibling, shorter birth intervals with the older sibling, of up to 23 months, significantly increases the risk of index child death. A birth interval with an older sibling of less than 12 months can increase risk of death by 18% to 75% (HR: 1.43, 95% CI: 1.18-1.75). Additionally, the death of an older sibling before the birth of the index child has a significant effect on child mortality, more than doubling the risk of death (HR: 2.43, 95% CI: 2.15-2.75). A bell-shape is found around an older sibling's death (HR: 6.04, 95% CI: 4.83-7.55), after an index child's birth (Figure 3). Similarly, a bell-shape is found around a younger sibling's death, with a similar peak, around the time closest to the younger sibling death (HR: 5.62, 95% CI: 4.24 – 7.45).

The pregnancy period with the younger sibling is the most favourable for child survival, when a child's risk of death is actually reduced compared to children born after an older sibling, within the standard birth interval (24-29 months). The effect of pregnancy with a younger sibling depends on the birth interval with that sibling, as shown in the Figure 4 below, crossing birth intervals with younger sibling and index child's age intervals. Intervals of over four years more than doubles the risk of death with a pregnant mother, with the lower bound of the confidence interval suggesting an effect of at least 63% higher risk (HR:2.16, 95% CI: 1.63-2.87). For small birth intervals, of less than two years, there is a clear pattern whereby a child's risk of death is reduced during the pregnancy period, while in the first six months after the younger sibling's birth there are higher risks of death. After six months, the effects of a younger sibling's birth declines, even with short birth intervals.

Fig. 4 Combined effects of index child's age and birth intervals with younger sibling



** Reference is birth interval of 24-29 months, period of 0-6 months after birth*

Sensitivity of Results

We consider a further set of models to test whether our results are robust to the model specification. Firstly, a model based on Table 2, but without the younger sibling effects (see appendix Table 4), suggests that the effect of younger and older sibling birth intervals on index child mortality are independent of each other. The younger sibling effects operate in addition to older sibling effects. The model excluding younger siblings does not considerably affect the coefficients or associated confidence intervals of the other covariates included in the model.

Secondly, considering that the causes of death among infants under 12 months differ to those among 1-4 year olds (Liu et al. 2012; Lozano et al. 2012), we also examined the independent sibling effects on mortality within these two age groups. We find no important differences between the models (see appendix Table 4). Essentially our model examining infant mortality replicates Molitoris et al.'s (Molitoris et al. 2019) models, albeit using different data, and our findings are consistent. Smaller birth intervals (up to 18 months) with older siblings increase the risk of death of children under 12 months. The effects of mother's death on infant mortality are even stronger for 15 days to six months after her death, compared to the effect on overall under-five mortality. Additionally, the period of 15 days before or after the death of an older sibling has a lower effect on the survival of infants than on 1-4 year olds. The model examining 1-4 year old mortality only indicates a stronger effect of mother's death around the time of her death (HR: 16.19, 95% CI: 12.41-21.11). This model differs to our principal model in the effect of mother's age at birth, which has no significant effect on 1-4 year old's mortality, and in the effect of an older sibling birth interval over 48 months, which is found to lower the risk of child mortality (HR:0.88, CI 95%: 0.80-0.96).

Discussion

This study uses longitudinal data from 29 HDSS sites across SSA to explore the effects of maternal and sibling mortality and migration, and sibling birth intervals, on child mortality. We posit that to examine birth intervals one needs foremost to consider a child's co-residence with their sibling, which can be severed through death or migration. Birth interval effects are relevant when siblings reside together because they may compete for care or have elevated risk of infectious disease transmission. An original contribution of this study is to analyse the effect of a younger sibling on child survival, and to take into consideration the pregnancy period before the birth of the younger child. Consistent with studies using DHS data (Boerma and Bicego 1992; Kravdal 2018; Molitoris et al. 2019; Rutstein 2005), our results indicate that

shorter birth intervals between an older sibling and an index child are associated with a higher risk of mortality, with highest risk observed in birth intervals of less than 12 months. Elevated risk of mortality is also observed following an older sibling's death, which is consistent with an effect of disease transmission being clustered at the family level (van Dijk 2018). This may be the results of environmental factors, inadequate healthcare within the home, or less competent parenting (Das Gupta 1990). In the case of both younger and older siblings, non-co-residence as a result of migration is associated with a higher risk of mortality, which is likely indicative of a dispersed family unit which may affect child care. In short, surviving co-resident siblings are associated with better survival chances.

The present study sheds light on the effects of birth spacing of a younger sibling on child mortality, and reveals a more pronounced effect compared to those observed with an older sibling. This younger sibling effect is present in addition to that of an older sibling. The risk of mortality is highest with a birth interval of under 23 months, though the period corresponding to the mother's pregnancy is associated with lower risk. These findings confirm our hypotheses concerning birth interval, and are likely explained as the result of reduced nutritional intake associated with weaning, or changes in the composition of breast-milk associated with a subsequent pregnancy (Marquis et al. 2003; Molitoris 2018; Palloni and Millman 1986). In contrast to our hypotheses, a mother's pregnancy with a younger sibling is found to benefit the index child. It is possible that a lower risk of mortality during pregnancy is related to breastfeeding during pregnancy – rather than early weaning. Based on regional estimates from the DHS, the median duration of breastfeeding across HDSS is 21 months (ICF International 2018). Thus, the index child may continue to breastfeed while the mother is pregnant with a younger sibling, even if she falls pregnant when the child is already over 12 months old. In some contexts there may be a taboo regarding continued breastfeeding during pregnancy (Bøhler and Bergström 1996; Ishii 2009; Madarshahian and Hassanabadi 2012; Oliveros et al. 1999), and this may affect the accuracy of reporting on breastfeeding, suggesting potentially longer duration of breastfeeding. Whereas we posit that the lower risk during pregnancy could be because of an overlap of breastfeeding and pregnancy, and because mothers may receive ante-natal care during this period. Visiting a medical facility, accompanied by their young children, can be directly (child is examined) or indirectly (mother is advised about healthcare) beneficial to the young child's health. Expectant mothers may also be given attention and help from family members and friends, "protecting the womb". Thus the index child may receive extra care and attention during a mother's pregnancy, but then experience a shock with the birth, through weaning, less dedicated time from caregivers, and no direct health care in contrast to the period before birth. The authors are unaware of any research on a spill-over effect on child health from antenatal clinic visits, nor of extra care pregnant mothers may receive. Qualitative studies aimed at exploring maternal health seeking behaviour and support structures during pregnancy are needed to fully understand whether this could explain our results.

We explored the birth interval and death effects of the sibling by also examining whether the sex of the sibling matters (results are in Appendix Table 5). Our main results suggest that a female index child has lower risk of death – however, by considering at the sex of the sibling too, we find that when interacted with sibling death, the death of a brother increases the risk of death more than the death of a sister. Additionally, having an older or younger sister seems to be driving the short birth interval effects. This exploratory analysis suggests that the role of sex of the sibling needs further unpacking, and should be given attention in future research.

In addition to the crucial role of siblings on child mortality, maternal factors have important effects on child's survival. A mother's age at birth significantly affects mortality when she is very young, under age 20, or over age 36. These results are similar to Kravdal's "augmented standard" model (Kravdal 2018), albeit our estimates are smoother (with no significant differences between the 18-41 age interval), and consistent with Houle et al.'s (Houle et al. 2015) study on Agincourt HDSS that showed a similar peak . The effect of maternal death is strongest from 15 days before to three months after her death. However, it is likely that pre-death effects may differ according to cause of death, which we are not able to examine here. In particular a HIV or TB related death of a mother may have a strong effect before her death since she may suffer prolonged illness (Houle et al. 2015). Additionally, a mother may transmit the disease she dies from to her child, increasing the likelihood of child mortality. Such an effect is not expected when the mother does not reside with the index child.

An innovation of the present study is the use of readily available core HDSS datasets to analyse maternal and sibling effects on child survival, embedding a precise temporal dimension. These results extend the DHS findings, and present scope for expanding analyses to other household-level factors. HDSS data offer detailed data on events, and while not nationally representative, the 29 sites analysed cover a diverse set of sub-populations in locations across SSA. The heterogeneity across sites suggests that patterns of child mortality are contrary to expectation and intra-country differences are higher than between-country differences. This indicates that effects of inequalities within countries and health care access disparities within countries are often overlooked. For example, our analysis indicates that Bandafassi in Senegal is a relatively high mortality site (averaging across all years 157/1000) – and indeed Bandafassi has higher mortality when compared to the country average under-five mortality of 121/1000 in 2005 based on DHS (59/1000 in 2015). Bandafassi is a rural site, characterised by high malaria prevalence, very low female education attainment and is relatively far from a major city (see Table 1). In contrast, Mlomp, also in Senegal, has relatively low mortality (63/1000), much lower than in Bandafassi. Mlomp, is a rural site but with lower temperatures (and therefore less malaria), is closer to a major city, and has much higher vaccination coverage. These contrasting sites exemplify the inequalities within countries. All the same, pooled together, the HDSS are illustrative of SSA.

Our study is not without limitations, mostly due to data constraints. The data available for all 29 sites through iShare do not include socioeconomic factors such as maternal education or household wealth which serve as distal determinants of child mortality (Mosley and Chen 1984). These factors, all the same, most likely work through the proximate determinants we include in our model. Moreover, consideration of these factors would help to control for maternal heterogeneity, which, as discussed in the methods section, we are unable to do. Nonetheless, the populations within each site are relatively homogenous, and including the site-period covariates in our model captures some of the variation between sites geographically and over time. A further limitation is that still-births or abortions are not recorded, and there is evidence that inter-pregnancy intervals are important to consider (Da Vanzo et al. 2008). In addition, the association between short birth intervals and mortality has been shown to be strongest among women with high fertility – that is, among high parity births (Kozuki and Walker 2013; Molitoris et al. 2019), but these data do not allow us to consider birth ranks or parity. These limitations are not trivial, but considering the number of children included and the person-years at risk analysed, as well as the accurate temporal

order of events, the findings offer a valuable and unique contribution to the literature. Furthermore, these findings are robust, and comparable to similar analysis based on DHS.

Our findings have clear policy implications, specifically in guiding mothers on how to optimise the survival of their young children. Firstly, birth spacing is largely important up to age two. While Rutstein (Rutstein 2005) determined that the optimal birth interval is at least 36 months, but not greater than 60 months, we find that for both younger and older siblings, a birth interval greater than 24 months is sufficient. Secondly, we find that the risk of child mortality during a mother's pregnancy with a younger sibling is considerably lower. This period has not been considered in previous studies, and mothers as well as health professionals should be aware that this period can be beneficial to child health. Special attention should also be given to the transition from pregnancy to birth of a younger sibling as it may be a shock for the child whether due to less care or weaning. Addressing these points can help drive under-five mortality reduction in SSA, and thus contribute towards achieving the 2030 Sustainable Development Goal 3 to "Ensure healthy lives and promote well-being for all at all ages" (United Nations 2015).

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Appendix

Fig. 5 Monthly heaping of dates for child and mother’s events as used in this analysis

**Data point labels refer to the country and code of the HDSS site*

Fig. 6 Age heaping in months of children's age at death by HDSS site

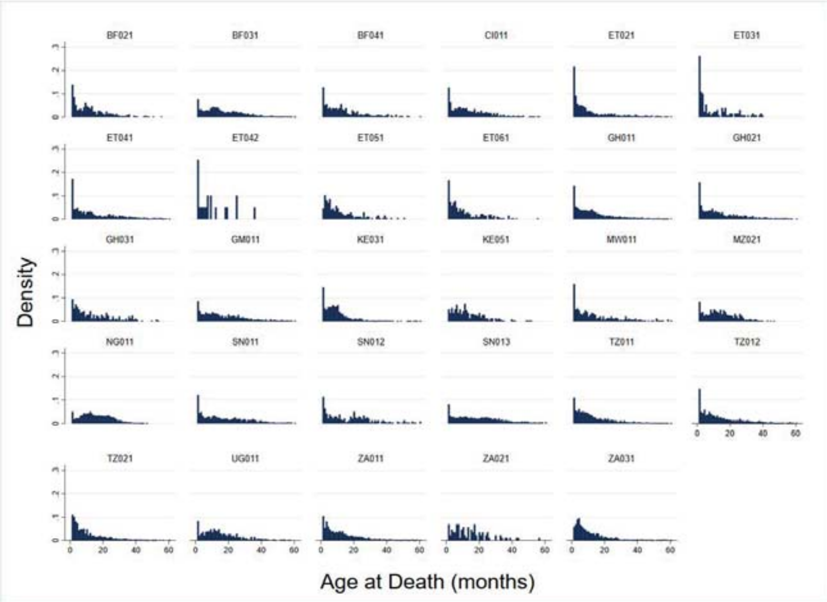

Table 3 Site-period effects on under-five mortality (based on model in Table 2)

Site-period	*Hazard ratio*	*Confidence Intervals*	
BF021 2005	1.103	0.715	1.701
BF021 2010	1.154	0.999	1.333
BF031 1995	2.072***	1.65	2.602
BF031 2000	2.855***	2.515	3.242
BF031 2005	2.354***	2.082	2.661
BF031 2010	1.750***	1.547	1.979
BF031 2015	1.901***	1.621	2.23
BF041 2005	0.66	0.429	1.013
BF041 2010	0.854*	0.738	0.987
BF041 2015	0.768*	0.596	0.99
CI011 2005	2.161***	1.569	2.975
CI011 2010	1.814***	1.579	2.085
CI011 2015	1.989***	1.692	2.337
ET021 2005	2.409***	2.096	2.767
ET021 2010	1.720***	1.509	1.961
ET021 2015	1.403**	1.139	1.728
ET031 2010	0.859	0.722	1.022
ET041 2005	2.328***	1.939	2.795
ET041 2010	2.221***	1.954	2.524
ET041 2015	1.941***	1.686	2.236
ET042 2010	0.385**	0.209	0.708
ET042 2015	0.310***	0.193	0.496
ET051 2005	0.773	0.431	1.388
ET051 2010	0.651***	0.538	0.788
ET051 2015	0.418***	0.27	0.647
ET061 2010	0.824*	0.697	0.974
ET061 2015	0.888	0.696	1.133
GH011 1990	3.799***	3.22	4.482
GH011 1995	3.632***	3.22	4.096
GH011 2000	2.646***	2.337	2.995
GH011 2005	1.712***	1.498	1.957
GH011 2010	1.016	0.874	1.18
GH021 2005	1.187*	1.031	1.365
GH021 2010	1.178*	1.04	1.335
GH031 2005	0.566***	0.469	0.683
GH031 2010	0.737**	0.612	0.889
GM011 1990	3.197***	2.749	3.717
GM011 1995	3.618***	3.139	4.169
GM011 2000	2.361***	2.04	2.732
GM011 2005	1.156	0.992	1.346
GM011 2010	1.047	0.901	1.215
GM011 2015	0.837	0.636	1.101
KE031 2000	1.990***	1.646	2.406
KE031 2005	1.638***	1.428	1.879

KE031 2010	1.730***	1.511	1.98
KE031 2015	0.978	0.734	1.302
KE051 2010	0.971	0.812	1.162
KE051 2015	0.982	0.765	1.26
MW011 2000	1.237	0.765	1.998
MW011 2005	1.194	0.983	1.45
MW011 2010	0.911	0.753	1.103
MW011 2015	0.607**	0.448	0.823
MZ021 2010	1.103	0.955	1.274
MZ021 2015	1.097	0.902	1.334
NG011 2010	4.321***	3.854	4.845
SN011 1990	6.158***	5.343	7.097
SN011 1995	5.092***	4.425	5.859
SN011 2000	4.057***	3.522	4.674
SN011 2005	3.160***	2.702	3.696
SN011 2010	2.047***	1.717	2.441
SN011 2015	1.451**	1.117	1.887
SN012 1990	2.922***	2.326	3.672
SN012 1995	2.198***	1.725	2.8
SN012 2000	1.726***	1.328	2.241
SN012 2005	1.136	0.83	1.554
SN012 2010	0.673	0.449	1.008
SN012 2015	0.215**	0.0689	0.67
SN013 1990	4.664***	4.06	5.356
SN013 1995	4.865***	4.306	5.497
SN013 2000	3.015***	2.652	3.428
SN013 2005	1.527***	1.326	1.76
SN013 2010	1	1	1
SN013 2015	0.762*	0.607	0.957
TZ011 1995	3.192***	2.76	3.692
TZ011 2000	2.599***	2.294	2.944
TZ011 2005	2.085***	1.843	2.359
TZ011 2010	1.599***	1.412	1.81
TZ012 1995	3.588***	2.902	4.437
TZ012 2000	2.020***	1.774	2.3
TZ012 2005	1.641***	1.441	1.868
TZ012 2010	1.202**	1.048	1.379
TZ021 1990	1.465	0.607	3.536
TZ021 1995	3.095***	2.662	3.598
TZ021 2000	3.012***	2.614	3.471
TZ021 2005	1.641***	1.401	1.924
TZ021 2010	0.846	0.665	1.076
UG011 2005	1.682***	1.458	1.94
UG011 2010	1.655***	1.447	1.892
UG011 2015	1.370**	1.093	1.718
ZA011 1990	0.78	0.593	1.026
ZA011 1995	0.812**	0.693	0.95
ZA011 2000	1.397***	1.214	1.609

ZA011 2005	1.389***	1.212	1.593
ZA011 2010	0.771***	0.665	0.895
ZA011 2015	0.547***	0.441	0.678
ZA021 1995	0.819	0.495	1.357
ZA021 2000	0.463**	0.284	0.753
ZA021 2005	0.757	0.518	1.105
ZA021 2010	0.175***	0.113	0.272
ZA021 2015	0.201***	0.113	0.357
ZA031 2000	1.866***	1.626	2.141
ZA031 2005	1.136	0.986	1.309
ZA031 2010	0.612***	0.517	0.725
ZA031 2015	0.357***	0.262	0.487

*Note: Exponentiated coefficients; * p<0.05, ** p<0.01, *** p<0.001; 95% confidence intervals*

Table 4 Sensitivity analysis

	No younger sibling (under five year olds)			*Under 12 months*			*1-4 year olds*		
	Hazard Ratio	Confidence Intervals		Hazard Ratio	Confidence Intervals		Hazard Ratio	Confidence Intervals	
Female	0.909***	0.891	0.927	0.890***	0.867	0.913	0.938***	0.91	0.967
15-17	1.167***	1.118	1.218	1.274***	1.206	1.345	1.001	0.933	1.074
18–20	1.061**	1.024	1.099	1.112***	1.062	1.164	0.981	0.928	1.038
Mother's age at birth (ref=21–23)									
24–26	0.975	0.941	1.01	0.986	0.942	1.033	0.949	0.898	1.003
27–29	0.975	0.94	1.012	0.975	0.929	1.023	0.98	0.925	1.038
30–32	1.01	0.972	1.049	1.038	0.988	1.091	0.961	0.906	1.019
33–35	1.015	0.974	1.057	1.044	0.99	1.101	0.977	0.916	1.042
36–38	1.096***	1.048	1.145	1.156***	1.092	1.224	1.006	0.938	1.08
39–41	1.113***	1.047	1.183	1.169***	1.081	1.264	1.035	0.954	1.124
42+	1.240***	1.17	1.315	1.355***	1.258	1.459	1.084	0.99	1.187
Maternal residence (ref=mother permanent resident or 5yr+ in-migrant)									
Mother non resident	1.512***	1.439	1.589	1.307***	1.223	1.397	1.795***	1.666	1.934
-6m to -3m mother's death	3.657***	2.964	4.511	4.205***	3.242	5.454	2.667***	1.825	3.897
-3m to -15d mother's death	5.275***	4.423	6.292	5.934***	4.789	7.354	3.767***	2.68	5.294
+/- 15d mother's death	11.96***	8.746	16.35	11.24***	8.209	15.39	16.19***	12.41	21.11
15d to 3m mother's death	13.00***	11.22	15.06	16.65***	13.82	20.06	7.255***	5.532	9.514
+3m to +6m mother's death	7.177***	5.834	8.828	10.27***	7.828	13.46	4.415***	3.179	6.133
6m+ mother's death	2.917***	2.49	3.418	3.303***	2.439	4.472	2.896***	2.402	3.49
In-migrant 6-24m	0.953**	0.919	0.988	0.914***	0.877	0.952	0.968	0.894	1.048
In-migrant 2y-5y	0.899***	0.867	0.931	0.930**	0.887	0.976	0.912***	0.864	0.963
Twin (ref=twin is resident)									
Twin non resident	0.973	0.641	1.478	0.961	0.467	1.979	1.247	0.747	2.083
-6m to -3m Twin's death	1.753**	1.236	2.487	1.722**	1.188	2.497	1.54	0.637	3.723
-3m to -15d Twin's death	3.113***	2.453	3.951	2.566***	1.965	3.352	5.680***	3.587	8.992
+/- 15d Twin's death	27.10***	23.68	31.02	24.61***	21.46	28.23	27.08***	16.99	43.16
15d to 3m Twin's death	4.315***	3.403	5.471	3.799***	2.894	4.987	5.105***	3.131	8.326
+3m to +6m Twin's death	2.168***	1.56	3.013	2.018***	1.366	2.981	2.251**	1.223	4.142
6m+ Twin's death	1.292*	1.06	1.574	1.698**	1.178	2.448	1.423**	1.119	1.81
No Twin	0.604***	0.571	0.639	0.523***	0.49	0.559	0.812***	0.732	0.9
Older sibling died before birth of index child	2.433***	2.148	2.756	2.717***	2.285	3.23	2.036***	1.696	2.444
No Older Sibling	1.201***	1.153	1.252	1.261***	1.194	1.332	1.073*	1.006	1.144
O sib non resident	1.400***	1.324	1.481	1.472***	1.367	1.584	1.282***	1.184	1.389
O int <12m	1.442***	1.182	1.759	1.634***	1.289	2.073	1.117	0.779	1.6
O int 12-17m	1.174**	1.055	1.307	1.184*	1.033	1.357	1.142	0.96	1.357
O int 18-23m	1.119**	1.046	1.198	1.091	0.998	1.193	1.173**	1.06	1.299
Older sibling (ref= birth interval 24-29m)									
O int 30-35m	1.031	0.98	1.084	1.031	0.964	1.104	1.006	0.93	1.087
O int 36-41m	1.032	0.973	1.093	1.034	0.957	1.118	0.985	0.9	1.078
O int 42-47m	0.996	0.929	1.068	1.032	0.943	1.129	0.899	0.804	1.005

O int 48m +	1.005	0.95	1.062	1.047	0.975	1.125	0.880**	0.804	0.963
Older sibling death (ref=older sibling alive)									
-6m to -3m death	1.560**	1.16	2.096	1.713**	1.208	2.431	1.553	0.893	2.702
-3m to -15d death	1.199	0.88	1.633	1.205	0.837	1.736	1.725	0.981	3.033
+/- 15d death	6.032***	4.823	7.544	4.001***	2.911	5.5	14.37***	10.56	19.57
15d to 3m death	1.761***	1.405	2.208	1.828***	1.408	2.373	2.560***	1.649	3.973
3m to 6m after death	1.089	0.853	1.39	1.194	0.91	1.567	1.282	0.746	2.205
6m+ death	1.786***	1.53	2.085	2.054**	1.311	3.219	1.479***	1.249	1.75
Younger sibling (ref= birth interval 24-29m 0-6m)									
No Younger Sibling							1.03	0.914	1.159
Int <12m & pregnant							83.77***	24.11	291.1
Int 12-17m & pregnant							0.521**	0.329	0.826
Int 18-23m & pregnant							0.394***	0.305	0.509
Int 24-29m & pregnant							0.483***	0.404	0.578
Int 30-35m &&pregnant							0.535***	0.447	0.64
Int 36-41m & pregnant							0.646***	0.509	0.822
Int 42-47m & pregnant							1.155	0.858	1.554
Int >=48m+ & pregnant							1.773***	1.312	2.398
Younger sibling non-resident							1.740***	1.296	2.335
Int <12m & 0-6m							2.807***	1.906	4.133
Int 12-17m & 0-6m							2.646***	2.148	3.259
Int 18-23m & 0-6m							1.463***	1.236	1.731
Int 30-35m & 0-6m							0.946	0.793	1.128
Int 36-41m & 0-6m							1.11	0.878	1.403
Int 42-47m & 0-6m							1.25	0.9	1.738
Int >=48m+ & 6m+							1.186	0.843	1.67
Int <12m & 6-12m							1.439	0.853	2.426
Int 12-17m & 6-12m							1.231	0.919	1.647
Int 18-23m & 6-12m							1.043	0.843	1.291
Int 24-29m & 6-12m							0.895	0.741	1.082
Int 30-35m & 6-12m							0.855	0.684	1.069
Int 36-41m & 6-12m							0.991	0.732	1.342
Int 42-47m & 6-12m							1.038	0.689	1.565
Int <12m & 12m+							0.644	0.361	1.147
Int 12-17m & 12m+							1.073	0.821	1.402
Int 18-23m & 12m+							0.878	0.71	1.086
Int 24-29m & 12m+							1.096	0.917	1.309
Int 30-35m & 12m+							1.126	0.921	1.376
Int 36-41m & 12m+							1.108	0.836	1.468
Int 42-47m & 12m+							6.01E-63	6.01E-63	6.01E-63
Younger sibling death (ref=younger sibling alive)									
-6m to -3m death							1.4	0.972	2.017
-3m to -15d death							2.302***	1.707	3.103
+/- 15d death							5.250***	3.949	6.981
15d to 3m death							1.327	0.915	1.925
3m to 6m after death							1.669**	1.18	2.361
6m+ death							1.129	0.86	1.483

Observations	2248767	905267	1813940
Chi2	25044	17689.7	54848.5
Log likelihood	-530549.3	-322179.6	-209013.5
N children	583287	579130	479854
Person-years at risk	1819663	522840.5	1296822.5
N failures (child deaths)	41541	24971	16545

*Note: Exponentiated coefficients; * p<0.05, ** p<0.01, *** p<0.001; 95% confidence intervals*

Table 5 Exploration of effects of sex of sibling on under-five mortality

	Hazard Ratio	**Confidence Intervals**	
Male (ref)			
Female	0.899***	0.865	0.935
Mother's age at birth (ref=21–23)			
15-17	1.017	0.831	1.246
18–20	0.976	0.896	1.063
24–26	0.922*	0.862	0.987
27–29	0.968	0.905	1.036
30–32	1.011	0.943	1.084
33–35	1.090*	1.014	1.173
36–38	1.187***	1.092	1.291
39–41	1.289***	1.156	1.436
42+	1.535***	1.334	1.767
Maternal residence (ref=mother permanent resident or 5yr+ in-migrant)			
Mother non resident	1.1	0.93	1.301
-6m to -3m mother's death	3.11e-14***	2.63E-14	3.67E-14
-3m to -15d mother's death	4.041**	1.487	10.98
+/- 15d mother's death	4.051*	1.006	16.32
15d to 3m mother's death	2.935	0.908	9.484
+3m to +6m mother's death	2.191	0.552	8.691
6m+ mother's death	1.259	0.389	4.074
In-migrant 6-24m	1.005	0.902	1.12
In-migrant 2y-5y	0.986	0.92	1.056
Twin(ref= twin is resident)			
Twin non resident	0.918	0.393	2.144
-6m to -3m Twin's death	1.575	0.778	3.187
-3m to -15d Twin's death	2.752***	1.717	4.411
+/- 15d Twin's death	25.56***	19.93	32.79
15d to 3m Twin's death	3.748***	2.307	6.089
+3m to +6m Twin's death	1.532	0.746	3.144
6m+ Twin's death	1.093	0.762	1.568
No Twin	0.566***	0.502	0.638
Older sibling died before birth of index child	2.405***	2.104	2.748
Older sibling (ref= birth interval 24-29m Male)			
Older sib non resident Male	1.338***	1.224	1.464
Older sib non resident Female	2.403***	1.82	3.172
O int <12m Male	1.158	0.796	1.685
O int <12m Female	2.600***	1.682	4.019
O int 12-17m Male	0.976	0.795	1.197
O int 12-17m Female	2.253***	1.638	3.098
O int 18-23m Male	1.064	0.947	1.194
O int 18-23m Female	1.984***	1.496	2.63
O int 24-29m Female	1.678***	1.293	2.177
O int 30-35m Male	1.005	0.923	1.093
O int 30-35m Female	1.754***	1.333	2.308

O int 36-41m Male	1.045	0.946	1.153
O int 36-41m Female	1.963***	1.484	2.597
O int 42-47m Male	0.987	0.871	1.118
O int 42-47m Female	1.661***	1.239	2.228
O int 48m + Male	1.023	0.92	1.137
O int 48m + Female	1.967***	1.484	2.607
Older sibling death (ref=older sibling alive Male)			
Older sibling alive and Female	0.553***	0.426	0.718
-6m to -3m death Male	1.249	0.709	2.201
-6m to -3m death Female	1.104	0.663	1.837
-3m to -15d death Male	1.504	0.923	2.451
-3m to -15d death Female	0.593	0.321	1.096
+/- 15d death Male	6.004***	4.03	8.945
+/- 15d death Female	3.836***	2.451	6.003
15d to 3m death Male	1.433	0.908	2.261
15d to 3m death Female	1.318	0.868	1.999
3m to 6m after death Male	1.015	0.648	1.59
3m to 6m after death Female	0.547*	0.333	0.899
6m+ death Male	1.726***	1.358	2.193
6m+ death Female	1	1	1
Younger sibling (ref= birth interval 24-29m 0-6m Male)			
No Younger Sibling Male	1.091	0.857	1.39
No Younger Sibling Female	1.823*	1.011	3.285
Int <12m & pregnant Male	0.229	0.0314	1.675
Int <12m & pregnant Female	6.04e-14***	3.25E-14	1.12E-13
Int 12-17m & pregnant Male	0.555	0.264	1.167
Int 12-17m & pregnant Female	0.636	0.22	1.839
Int 18-23m & pregnant Male	0.794	0.517	1.22
Int 18-23m & pregnant Female	0.59	0.267	1.308
Int 24-29m & pregnant Male	0.693*	0.495	0.969
Int 24-29m & pregnant Female	1.145	0.61	2.152
Int 30-35m & pregnant Male	0.625**	0.447	0.873
Int 30-35m & pregnant Female	1.206	0.652	2.23
Int 36-41m & pregnant Male	0.989	0.659	1.486
Int 36-41m & pregnant Female	0.949	0.455	1.98
Int 42-47m & pregnant Male	1.435	0.808	2.549
Int 42-47m & pregnant Female	2.658*	1.169	6.045
Int >=48m+ & pregnant Male	4.327***	2.579	7.262
Int >=48m+ & pregnant Female	5.284***	2.271	12.3
Younger sibling non-resident Male	3.289***	1.797	6.023
Younger sibling non-resident Female	4.272**	1.748	10.44
Int <12m & 0-6m Male	3.387***	1.749	6.56
Int <12m & 0-6m Female	3.572*	1.319	9.672
Int 12-17m & 0-6m Male	2.942***	1.879	4.608
Int 12-17m & 0-6m Female	2.763*	1.267	6.029
Int 18-23m & 0-6m Male	1.402	0.986	1.992
Int 18-23m & 0-6m Female	2.231*	1.171	4.249
Int 24-29m & 0-6m Female	1.577	0.926	2.687

Int 30-35m & 0-6m Male	0.88	0.616	1.256
Int 30-35m & 0-6m Female	1.415	0.736	2.717
Int 36-41m & 0-6m Male	1.142	0.7	1.862
Int 36-41m & 0-6m Female	2.560*	1.242	5.275
Int 42-47m & 0-6m Male	2.017*	1.111	3.663
Int 42-47m & 0-6m Female	3.004*	1.269	7.112
Int >=48m+ & 6m+ Male	1.563	0.772	3.162
Int >=48m+ & 6m+ Female	2.757*	1.114	6.823
Int <12m & 6-12m Male	2.538*	1.011	6.375
Int <12m & 6-12m Female	3.017	0.845	10.77
Int 12-17m & 6-12m Male	0.602	0.242	1.495
Int 12-17m & 6-12m Female	1.248	0.462	3.374
Int 18-23m & 6-12m Male	0.812	0.509	1.296
Int 18-23m & 6-12m Female	1.266	0.612	2.619
Int 24-29m & 6-12m Male	1.053	0.732	1.514
Int 24-29m & 6-12m Female	1.317	0.671	2.585
Int 30-35m & 6-12m Male	1.262	0.829	1.922
Int 30-35m & 6-12m Female	1.264	0.599	2.666
Int 36-41m & 6-12m Male	0.745	0.361	1.539
Int 36-41m & 6-12m Female	2.466*	1.098	5.539
Int 42-47m & 6-12m Male	1.973	0.937	4.154
Int 42-47m & 6-12m Female	1.861	0.616	5.621
Int <12m & 12m+ Male	3.97e-14***	2.91E-14	5.40E-14
Int <12m & 12m+ Female	1.475	0.409	5.314
Int 12-17m & 12m+ Male	1.929**	1.211	3.072
Int 12-17m & 12m+ Female	0.858	0.314	2.348
Int 18-23m & 12m+ Male	0.906	0.578	1.422
Int 18-23m & 12m+ Female	2.114*	1.058	4.225
Int 24-29m & 12m+ Male	1.738**	1.213	2.489
Int 24-29m & 12m+ Female	1.964	0.979	3.942
Int 30-35m & 12m+ Male	1.522*	1.005	2.305
Int 30-35m & 12m+ Female	2.698**	1.317	5.528
Int 36-41m & 12m+ Male	1.541	0.876	2.712
Int 36-41m & 12m+ Female	2.620*	1.162	5.908
Int 42-47m & 12m+ Male	1.098	0.333	3.616
Int 42-47m & 12m+ Female	5.044**	1.883	13.51
Younger sibling death (ref=younger sibling alive Male)			
Younger sibling alive Female	0.606	0.356	1.031
-6m to -3m death Male	0.401	0.1	1.605
-6m to -3m death Female	1.525	0.685	3.395
-3m to -15d death Male	2.636***	1.484	4.68
-3m to -15d death Female	2.433*	1.201	4.927
+/- 15d death Male	7.150***	4.303	11.88
+/- 15d death Female	3.672***	1.743	7.734
15d to 3m death Male	1.446	0.693	3.019
15d to 3m death Female	0.939	0.391	2.255
3m to 6m after death Male	1.981*	1.016	3.861
3m to 6m after death Female	1.282	0.578	2.843

6m+ after death Male	1.455	0.86	2.46
6m+ after death Female	1	1	1
Observations	633674		
Chi2	779278.1		
Log likelihood	-116554.2		
N children	100968		
Person-years at risk	422947.8		
N failures (child deaths)	10430		

*Note: Exponentiated coefficients; * p<0.05, ** p<0.01, *** p<0.001; 95% confidence intervals*

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