DEMOGRAPHIC RESEARCH
A peer-reviewed, open-access journal of population sciences

DEMOGRAPHIC RESEARCH

VOLUME 38, ARTICLE 65, PAGES 2053−2072
PUBLISHED 26 JUNE 2018
http://www.demographic-research.org/Volumes/Vol38/65/
DOI: 10.4054/DemRes.2018.38.65

Research Article

A synthetic measure of mortality using skeletal data from ancient cemeteries: The d index

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Demographic Research: Volume 38, Article 65
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A synthetic measure of mortality using skeletal data from ancient cemeteries: The d index

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Abstract

BACKGROUND
Due to the scarcity of written sources in ancient historical periods, and thanks to the development of increasingly sophisticated methods of excavation, recognition, publication, and interpretation, archaeology has played an important role in the understanding of demographic mechanisms. It is in this context that the last decade has seen important developments in paleodemography, the use of skeletons to reconstruct the demographic dynamics of the past.

OBJECTIVES
In this study we show how skeletal data can be used to determine mortality regimes, enlarging the demographic meaning of the **d** index proposed by Bocquet-Appel in 2002. We apply the **d** index to Italian cemeteries dating from the 1st to the 15th century AD.

CONTRIBUTION
Our study contributes to the development of paleodemography, a particularly valuable method that uses large osteological samples to understand mortality trends in ancient historical periods. In this study we extend and develop the **d** index, introduced by Bocquet-Appel in 2002, and demonstrate its usefulness in a range of plausible demographic scenarios. By applying this method to the study of mortality in Italy from the 1st to the 15th centuries AD, we show its reliability in tracing mortality trends in periods of both normal mortality and mortality crisis.

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1. Paleographic analyses and the study of mortality in the past

Only after the Council of Trent (1545–1563) made ecclesiastical records mandatory did baptism, marriage, and burial records and Parish family books start being produced with any regularity, only becoming reliable in the mid-17th century. Although many recent studies have focused on the Black Death, shining new light on the demographic dynamics of the 14th and 15th centuries, sources are sporadic for earlier periods. Censuses, tax declarations, and death records (mainly in cities) are few and far between, allowing for reconstruction of fertility and mortality rates only in rare cases (Leverotti 1982; Alfani and Bonetti, in press). Ancient and medieval European demography is therefore largely a matter of speculation. Due to the scarcity of written sources and thanks to the development of increasingly sophisticated methods of excavation, recognition, publication, and interpretation, archaeology has played an important role in the understanding of demographic mechanisms. Methodological advances in biomolecular archaeology (DNA and isotopic analyses) have opened up innovative ways of studying ancient human remains, contributing to the understanding of living standards in the past (Barbiera, Castiglioni, and Dalla-Zuanna 2016a).

This is the context in which paleodemography, the use of skeletons to reconstruct the demographic dynamics of the past, has seen important developments over the last decade, while previously collected and published information on skeletons has been reconsidered (Hoppa 2002; Bocquet-Appel and Bacro 2008; Ségui and Buchet 2013). We reconstruct Imperial Roman and medieval mortality trends in Italy before the Black Death by applying a method developed by Bocquet-Appel (Bocquet-Appel 2002; Bocquet-Appel and Naji 2006; Barbiera and Dalla-Zuanna 2007, 2009). This method has been developed taking into consideration the two main distortions inherent in data on skeletons: (1) the number of children under 5 years of age is generally underrepresented, either because their fragile skeletons did not withstand the test of time or because they were buried apart from the adults, and (2) in well-preserved samples, the age at death can only be determined with any precision until age 20 (by the growth stages of teeth and the closures of epiphyses) while for adults aged 20–40 there is no precise way of determining age at death and the age of individuals over 40 years old cannot be identified at all with current anthropological methods (Bocquet-Appel and Masset 1982; Wittwer-Backofen and Buba 2002; Hoppa and Vaupel 2002). Bearing in mind these limitations, the method aims to calculate the following ratio for each site considered:

d = ${}_{15}D_5/D_{5+}$ — the ratio between the number of deaths at ages 5–19, the period during which age can be precisely estimated, and the number of deaths at age 5+, excluding children aged 0–5, who could be underrepresented.

In their seminal article on this topic, Masset and Bocquet (1977) show the strong parabolic correlation – under the hypothesis of a stationary population – between a mortality indicator similar to **d** (${}_{10}D_5/D_{20+}$) and two crucial parameters of the life-table (e_0 and q_0), using a set of forty life-tables of pre-industrial populations. Bocquet-Appel (2002), using an enlarged set of 45 pre-industrial life-tables, applies a similar regression technique, showing that under the stationary hypothesis the higher the **d** index the higher the probability of dying during the first year of life, and the lower life expectancy at birth.

Barbiera and Dalla-Zuanna (2009), using the standard West life-table of Coale and Demeny (C&D) with $e_{0,F}<40$ in the stationary hypothesis, show that the linear correlation between e_0 and **d** is –0.98 (**d** = 20, e_0 = 17.0; **d** = 15, e_0 = 26.7; **d** = 10, e_0 = 36.4). The C&D standard tables may not be a very suitable fit for pre-industrial mortality patterns (although their ability to interpret Ancient Régime mortality has been described as “impressive” by some scholars – Scheidel 2001; Santini and Del Panta 1982). In any case, these statistical relationships help understand the practical meaning of **d**.

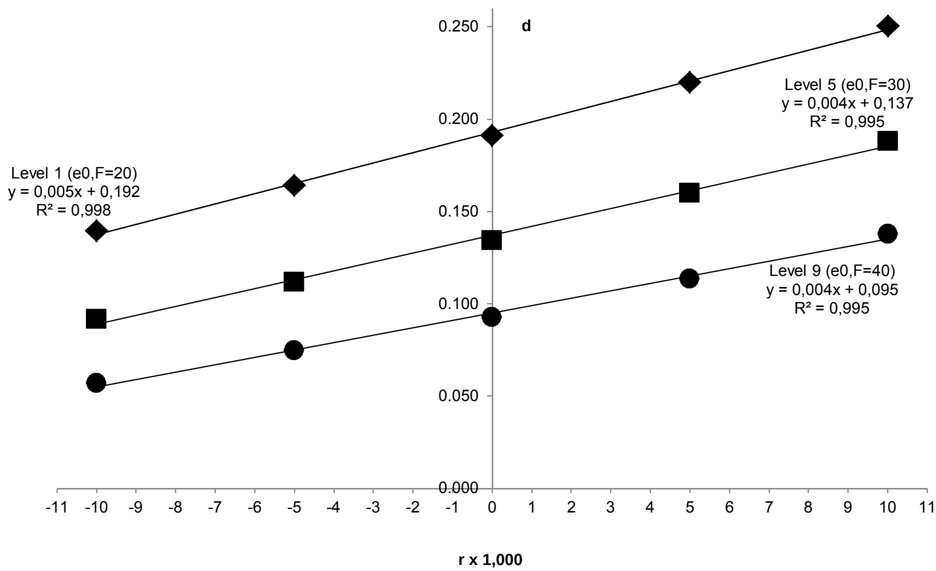
This does not mean, however, that such data fits all historical moments. Moreover, the most problematic aspect is without a doubt the link between adult mortality and infant mortality. If these standard life-tables are first used on data on adults and then to estimate the survival of children, the latter becomes the most important parameter in calculating the principal measures of survival (from average life expectancy to generic mortality rates). This procedure – used, for example, by scholars who have attempted to estimate mortality during Classical Antiquity (Scheidel 2001) – is risky in that infant mortality is used to establish a direct link between general mortality and adult mortality even if adult mortality, in reality, was actually much less important than infant mortality in determining the overall mortality regime.

2. The d index in different mortality contexts

To understand the meaning of **d**, let us first consider unrealistic situations where the relationship between different measures is easy to master, and then approach the ‘real’ world. The first example concerns stationary populations, which are closed to migrations and have a growth rate equal to 0 and crude death and birth rates that are equal and stable over time. In such cases, **d** acquires a precise demographic meaning. If the population is stationary, effective deaths (D) are equal to those of the life table (d) and consequently ${}_{15}D_5 = {}_{15}d_5$ and $D_{5+} = l_5$. Thus the index **d** = ${}_{15}D_5/D_{5+} = {}_{15}d_5/l_5 = {}_{15}q_5$.

But what happens if we leave the world of the stationary populations? Let’s start by examining the case of stable populations (without migrations, with a natural growth rate r different from zero and with crude death and birth rates stable over time). Figure 1 shows the relationship between **d** and r for three levels of mortality in stable populations analyzed by C&D (West Family). At constant mortality levels, the value of **d** changes according to the variation in r; in fact, if the birth rate is higher (or lower) than the death rate the proportion of infants increases (or decreases) and the proportion of child deaths varies accordingly (Ségui and Buchet 2013; Bocquet-Appel 2002; Masset and Bocquet 1977; Bocquet-Appel and Masset 1996). For example, in cases in which mortality is very high (such as level 1 C&D, $e_{0,F} = 20$), where the population increases annually by 1%, **d** = 0.250; conversely, if the population decreases by 1% then **d** = 0.139.

Figure 1: Relationship between d = ($D_{5\text{-}19}/D_{5+}$) and r, stable populations of Coale & Demeny, West Family



These results raise doubts about the possibility of using **d** directly as an indication of mortality level. Suppose that we only know the value of **d** = 0.137 for a single cemetery, without knowing the natural growth rate of the population. This value of **d** would be compatible with $e_{0,F} = 20$ and r = –11‰, with $e_{0,F} = 30$ and r = 0, and also with $e_{0,F} = 40$ and r = +11‰.

However, if the annual population growth rate is low, then the influence of r over **d** is quite limited; for example, again in the case of high mortality (level 1 C&D, $e_{0,F} = 20$), if r varies within the interval ±3‰ then 0,177<**d**<0,207. More generally, as pointed out by Figure 1, if **r** varies in the range of ±3‰, as in the case of stable populations, the **d** index offers a direct measure of the level of mortality. In addition, Figure 1 shows that the relationship between r and **d** is sufficiently linear and regular for mortality levels typical of pre-industrial societies (e_0<40). Therefore, on the basis of the empirical relationships visible in Figure 1, it is possible to correct **d**:

d* = **d** – 0,0045r where **r** is expressed in ‰ and the coefficient of 0.0045 is the average of the slope coefficients of the lines in Figure 1.

The **d*** index can be used to estimate the mortality level when the rate of natural growth r is known. For example, in a population where d = 0.250 and r = +10‰, then d* = 0.205, which corresponds to $e_{0,F} = 18.5$ (and not $e_{0,F}$<15, as would result when using **d** in a direct way).

Otherwise, in periods characterized by recurrent and intense mortality crises – such as in Italy in the three centuries between 1350 and 1650 and, in all likelihood, between the 6th and 7th centuries – the assumption of a stable population does not hold (Bocquet-Appel and Bacro 2008; Ségui at al. 2006; Signoli et al. 2002; Castex and Cartron 2007) because during the crises the number of deaths could increase five to tenfold compared to normal years, and also because the crises influenced other aspects of demography (Del Panta 1980). In particular, during periods of crisis the number of births might significantly decrease and many people might migrate to increase their chances of survival. Moreover, following a crisis marriages and births generally increased while mortality decreased, especially if the crisis had eliminated the weakest individuals.

To understand the meaning of **d** in such circumstances, we performed a simulation. Starting with the female stationary population connected to mortality A of C&D level 1 Family West ($e_{0,F} = 20.0$ and crude birth and mortality rate = 0.05), we hypothesized that over a century there is a year of super-mortality B which occurs every 15 years, along the lines of that observed in the parish of St. Botolph in London during the plague of 1604 (Hollingsworth and Hollingsworth 1971; Del Panta 1980). The year of the plague was followed by five years characterized by mortality C, 20% lower than the normal level, and then by nine years of normal mortality A. In each fifteen-year cycle the sequence of mortality levels is as follows: AAAABCCCCCAAAAA (Table 1): in the first five-year period mortality is (4A+B)/5; in the second five-year period it is 5C/5, and in the third it is 5A/5.

In addition, in the simulation the birth rate is reduced by 40% in the year following the crisis, is increased in the following four-year period (+60% compared to a normal year), and then gradually approaches pre-crisis levels (+20% compared to the levels registered during the final five years). These trends are close to those in the parish of Nonantola (Modena) during the plague of 1630 (Alfani and Cohn 2007a). Therefore, in the three five-year cycles the birth rate is respectively 0.05 (to C&D level 1), 0.07, and 0.06.

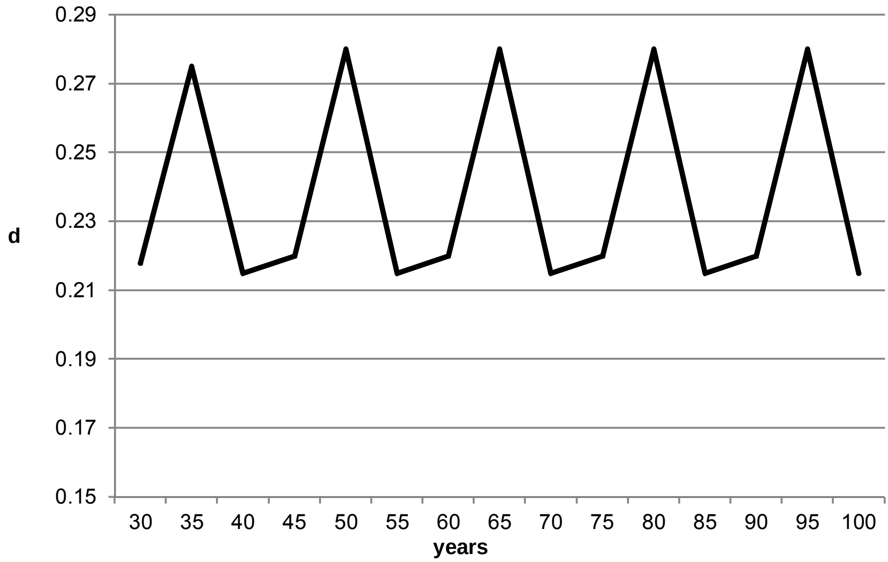
Under these hypotheses, the population fluctuates around the value observed at the beginning of the period (r=+0.35‰ over the century). Thirty years after the beginning of the crisis, **d** oscillates as shown in Figure 2, with an average level of 0.24 (life expectancy at birth slightly above 15 years) and a peak in the years of outbreak. Thus, the distribution of deaths among young adults and older people is close to that observed when the same life expectancy remains constant in time in a stationary population regime.

Table 1: Probability of dying in three five-year cycles of normality, crisis, and recovery

		(A) C&D level 1	(B) (*) Crisis years	(C) Recovery years
0	4	0.428	0.800	0.342
5	9	0.215	0.539	0.172
10	14	0.061	0.300	0.049
15	19	0.065	0.318	0.052
20	24	0.082	0.339	0.066
25	29	0.097	0.263	0.077
30	34	0.109	0.277	0.087
35	39	0.120	0.324	0.096
40	44	0.129	0.273	0.103
45	49	0.137	0.292	0.109
50	54	0.158	0.317	0.126
55	59	0.197	0.256	0.158
60	64	0.260	0.341	0.208
65	69	0.346	0.378	0.277
70	74	0.444	0.649	0.355
75	79	0.580	0.790	0.464
80	84	0.731	0.747	0.585
85	+	0.811	0.811	0.649

Note: (*) In the crisis year the additional mortality detected in St. Botolph during the plague of 1604 was added to the normal mortality (column A).

Figure 2: Trend of d index in the simulation of mortality and demographic crisis



Therefore, in periods afflicted by the coming and going of major epidemics, the value of **d** may have been relatively high, corresponding to a kind of average mortality between years of very frequent epidemic outbreaks and years of normal mortality or recovery. If recovery was determined by an increase in the birth rate, then **d** could also be augmented by the high number of births.

Summarizing the calculations, observations, and simulations described above, it can be argued that the indicator **d** = ${}_{15}D_5/D_{5+}$ is useful in estimating mortality when we only have data on deaths derived from skeletal samples at our disposal, notwithstanding the limits of synthesizing an entire mortality regime by a single parameter. In the case of stationary populations or populations with a natural growth rate r between ±3‰, the indicator is well correlated to some basic parameters of mortality: as **d** grows, mortality increases. If r is larger or smaller, however, it is appropriate to correct the value of **d** to take into account variations in the age structure of the population, and thus of deaths, due to the increasing or decreasing birthrate, according to the formula **d*** = **d**–0.0045r**‰**, under the hypothesis that the C&D standard tables fit the mortality patterns well before the onset of the health revolution.

In general, since **d** is influenced by the growth rate, it is inappropriate to use it to estimate mortality for a single cemetery or for a population of unknown trends over time. On the contrary – as in the example shown below – the index is most useful when observed in a large number of cemeteries (or in any case referring to data on deaths related to several populations) so that the impact of anomalies – frequent in past populations – is diluted, and when population trends are known. Less problematic is the use of **d** to estimate the mortality of populations characterized by sudden dips and subsequent recoveries. In fact, in the long run, in these cases **d** is associated with measures of mortality in a manner not very different to those detected in stationary or stable population, although it may be also influenced by a higher proportion of young people. However, if **d** can be a reliable estimator of mortality after the fifth birthday, caution is needed when estimating overall mortality, which could be greatly affected by the relatively abnormal mortality of children. Finally, under some reasonable hypotheses, the index **d** can also be used to detect different mortality patterns among males and females in societies of the past (Barbiera, Castiglioni, and Dalla-Zuanna 2016b).

3. The trends of d and the Italian population across the centuries

Starting from a previous study of the trends of **d** and its relationship to variations in mortality from Roman times to the end of the 12th century (Barbiera and Dalla-Zuanna 2007, 2009), we extended the data collection and the estimation of **d** to a later period running from the 13th to the 15th century. We considered only cemeteries with more than 40 individuals, excluding those where more than 20% of adult skeletons were of unknown sex or age. In addition, we included only sites having a final **d** value between 0.15 and 0.30. Thus, out of hundreds of cemeteries found in the literature, we selected data from 43 sites comprising 4,244 individuals over five years of age (Barbiera, Castiglioni, and Dalla-Zuanna 2016c).

One important issue is that of chronology. Since most of the cemeteries were in use over long chronological spans and the graves and the bones they contained were very rarely dated with precision, it is not easy to use such data to illustrate changes over time. Hence, we decided to adopt the method proposed by Steckel (2010), which consists of grouping individuals buried within a given time span and assuming that the burials are evenly distributed across the dates in which the sites were in use. We then organized the results by century, thus estimating a mean number of skeletons aged 5–19 years and over 20 years of age for each century considered. For instance, 4 individuals aged 5–19 and 36 individuals over 20 years of age were identified in the cemetery of Torcello, S. Fosca (see Table 2, n 39), which dates from the 10th to the 12th century. We pooled these individuals over the three centuries the cemetery was used, obtaining a mean of 4/3 = 1.33 individuals aged 5–19 and 36/3 = 12 individuals aged over 20 for each century. We finally added together the individuals thus estimated for each century and estimated the value of **d** for each 100-year time span. In this way, the obtained values are indicative of more general trends.[3]

Table 2: List of considered sites

	Site name	Region	Chronology	Settlement type	Total number of individuals	Sex		Age groups		
						M (20+)	F (20+)	5–19	20+	5+
1	Castellecchio di Reno (Bo)	N	2–4	rural settlement	62	31	20	8	54	62
2	Castro dei Volsci (Fr)	C	6	rural settlement	201	101	56	28	157	185
3	Centallo (Cn)	N-W	6–7	church, rural settlement	162	66	31	27	114	141
4	Cividale, S. Mauro (Ud)	N-E	13–15	urban settlement	72	33	14	17	49	66
5	Civitanova (Mc)	C	4	Colonia Claudia, urban settlement	181	62	57	19	119	138
6	Collecchio (Pr)	N	7	rural settlement	154	36	25	27	77	104
7	Collegno (To)	N-W	6–8	rural settlement	81	38	16	18	54	72
8	Egnazia (Br)	S	1–4	urban settlement	136	13	28	18	88	106
9	Formigine (Mo)	N	13–15	church, rural settlement	147	35	29	37	67	104
10	Gallicano (Roma)	C	4	roman villa	105	36	32	18	68	86
11	Gerace, S. Maria del Mastro (Rc)	S	15–18	church, urban settlement	145	35	30	25	65	90
12	Iskra, Kranj*	N-E	6–11	church, urban settlement	241	59	104	36	163	199
13	Milano, piazza Duomo	N	13–14	church, urban settlement	104	60	27	15	87	102
14	Mont-Blanc, Aosta 1-2	N-W	2–5	rural settlement	133	45	46	17	91	108
15	Mont-Blanc, Aosta 3-4	N-W	6–8	rural settlement	131	40	34	12	74	86
16	Monte d’Argento, Minturno (Lt)	C	11–15	church, urban settlement	127	70	39	14	105	119
17	Monte di Croce, Pontassieve (Fi)	C	11	church, castle	71	22	5	12	29	41
18	Ortaria, Povegliano (Vr)	N	7	rural settlement	98	49	36	9	85	94
19	Pauciuri, Malvito (Cs)	S	9–12	roman bath, urban settlement	56	15	20	4	42	46
20	Poggibonsi (Si)	C	7–13	rural settlement	41	22	16	9	38	47
21	Prata di Pordenone, S. Giovanni (Pn)	N-E	13–15	church, rural settlement	62	34	9	7	47	54
22	Quadrella, Isernia	S	1–4	rural settlement	99	26	28	8	54	62
23	Quingentole (Mn)	N	7	rural settlement	70	26	18	15	58	73
24	Rimini	C	2–4	Flaminia road, urban settlement	120	32	30	8	85	93

[3] In a previous work we used the method suggested by Koepke and Baten (2005), which consists of allocating the sample to the average of the earliest and latest date of each site. The trends of **d** that emerged were similar to that obtained here; see Barbiera and Dalla Zuanna (2009). For a discussion of these methods see: Galofré-Vilà, Hinde, and Guntupalli (2017).

Table 2: (Continued)

	Site name	Region	Chronology	Settlement type	Total number of individuals	Sex		Age groups		
						M (20+)	F (20+)	5–19	20+	5+
25	Roma, Casal Ferranti	C	2	urban settlement	56	17	21	4	38	42
26	Roma, Osteria del Curato	C	2	urban settlement	49	15	10	6	25	31
27	Roma, Palazzo della cancelleria	C	14–15	church urban settlement	283	97	63	71	162	233
28	Romans d’Isonzo	N-E	6–7	rural settlement	180	51	39	30	103	133
29	S Benigno Canavese (To)	N-W	15–16	abbey, rural settlement	88	45	38	26	85	111
30	S Pietro di Cavallermaggiore (Cn)	N-W	10–13	church, rural settlement	197	81	60	22	147	169
31	S. Agata, Piana degli Albanes (Pa)	S	4–5	rural settlement	350	98	95	61	195	256
32	S. Sebastiano in Saluzzo (Cn)	N-O	15	church, rural settlement	114	34	18	18	55	73
33	S. Vincenzino di Cecina (Li)	C	5–8	roman villa, rural settlement	130	35	22	27	57	84
34	S.Lorenzo di Aversa	S	10–12	Abbey, urban settlement	49	28	8	5	40	45
35	San Caprasio Ad Aulla (Ms)	N-O	9–15sec	fortified village	79	32	23	10	63	73
36	Selvicciola (Vt)	C	7	abandoned roman villa, rural settlement	110	49	20	16	73	89
37	Siena, S. Maria della Scala	C	13–15	urban settlement	100	49	26	10	84	94
38	Torcello, cemetery (Ve)	N	10–12	urban settlement	72	27	20	10	47	57
39	Torcello, S. Fosca (Ve)	N	10–12	urban settlement	42	18	18	4	36	40
40	Trento, S. Virgilio (Ve)	N	3–4	church, urban settlement	175	73	64	14	137	151
41	Trino Vercellese (Vc)	N-W	10–13	rural settlement	160	56	40	22	112	134
42	Urbino, S. Donato	C	1–3	urban settlement	109	34	35	19	75	94
43	Vicenne, Campochiaro (Cb)	S	7–8	rural settlement	76	28	24	5	52	57
	Totals				5218	1853	1394	788	3456	4244

Note: * Iskra, Kranj is now Slovenia but was part of The Duchy of Friuli at the time it was in use.

The individuals are generally evenly distributed across each chronological period considered and across the different Italian regions (Tables 2 and 3, Figure 3**)**. However, it should be noted that for the Roman period we have a higher proportion of sites located in Southern-Central Italy, while for the medieval period more sites are available in the north. Furthermore, for some periods, such as the 1st, the 5th, and the 9th centuries, only a few cemeteries satisfied our criteria, and for the 1st and the 9th centuries the number of available individuals is low. Thus the results from data referring to these chronological spans might not be indicative of more general Italian trends. Moreover, between the 5th and the 8th centuries the percentage of skeletons from urban settlements is low. This is related to the transition in funerary rituals that began in the early Middle Ages, when burials started to be moved from extended Roman cemeteries located outside city walls to church graveyards within settlements. However, in the first centuries of the early Middle Ages, graves were still few and were scattered within settlements. It is difficult for archeologists to identify them as they are often located under modern towns, and they were not taken into consideration in our study since they generally included less than 40 individuals. From the 9th century there was an increase in burials in church buildings, so larger numbers of skeletons have been found and documented by archeologists (Barbiera 2015).

Figure 3: Map of investigated sites, dated between the 1st and the 15th centuries

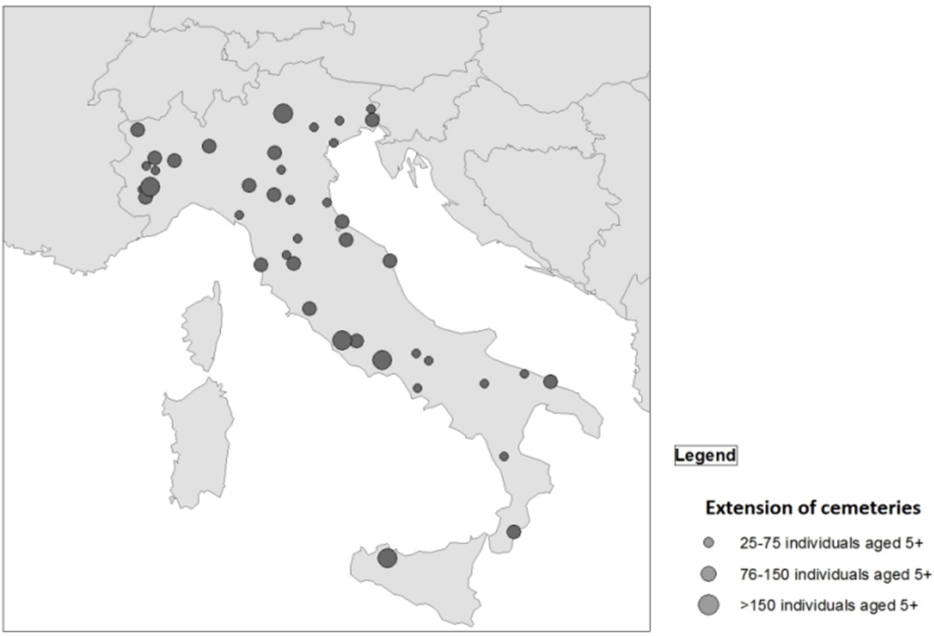


Table 3: Changing composition of the sample over time

Century	Number of cemeteries	Number of skeletons aged 5+	Percentage of skeletons aged 5+			
			Urban	Rural	From Northern Italy	From Central-Southern Italy
1	3	73	78.86	21.14	0.00	100.00
2	8	225	71.93	28.07	21.19	78.81
3	7	228	72.23	27.77	54.14	45.86
4	9	548	49.44	50.56	22.47	77.53
5	3	176	0.00	100.00	15.34	84.66
6	7	429	7.73	92.27	51.96	48.04
7	12	639	5.19	94.81	77.28	22.72
8	6	142	23.35	76.65	60.43	39.57
9	4	62	72.27	27.73	70.53	29.47
10	9	185	49.76	50.24	82.04	17.96
11	11	250	62.80	37.20	60.75	39.25
12	9	176	47.08	52.92	67.52	32.48
13	10	274	46.82	53.18	77.40	22.60
14	8	308	79.50	20.50	44.23	55.77
15	10	415	53.86	46.14	51.44	48.56

Keeping these points in mind, from our sample it emerges that the value of **d** is relatively low between the 1st and 4th centuries, increases in the following period, when the Justinianic Plague spread, and declines to a value similiar to that of Imperial Roman times between the 9th and the 13th centuries. By contrast, the **d** index is much higher in those centuries after 1349 marked by the plague (Table 4). Hence, there is an increase in **d** in periods characterized by mortality crisis.

Undoubtably, these data should be taken with caution because of all the problems inherent in using the **d** indicator as the only flag of mortality. For example, there may be conditions with very high infant mortality but low juvenile mortality, and vice versa. In that case the **d** indicator might underestimate (or overstate) the intensity of mortality: in the past the death of children under 5 years of age sometimes reached 50% of the total. Moreover, osteological data presents several problems. Even though for the purpose of this study we selected a sample of cemeteries that satisfy the above-mentioned criteria and which were extensively and accurately excavated (see Table 2 for details), nonetheless some problems should be borne in mind.

First of all, selection factors and migratory movements can alter the composition of the buried population so that the skeletons discovered may not be representative of the population as a whole. For example, some social, gender, and age groups might have been excluded from the cemeteries. The main problem is the frequent and systematic underestimation of child deaths, which in ancient demographic regimes constituted a large portion of total mortality. For example, in the necropolises analyzed here, with very few exceptions, skeletons of individuals under the age of 5 constitute only 10%–20% of the total, while in the C&D standard table the percentages for those with an average age at death of 20 years, 30 years, and 40 years are 50%, 40%, and 25% respectively. This lack of children could be because they were buried separately from the adults, as demonstrated by several cemeteries found in different Italian regions and dated to different chronological periods where only children were buried (see Barbiera and Dalla-Zuanna 2007 for a discussion), or because the fragility of their bones resulted in their loss from the archeological record (Saunders et al. 2002). Employing the **d** ratio, as explained above, minimizes this shortcoming in the data.

On the other hand, it is difficult to identify selection by migration from the archeological record (Barbiera 2005). Seasonal migration may have meant that some individuals died in places that were not their habitual place of residence. Although traditionally considered a period of low population mobility, repopulation, depopulation, and colonization of virgin territories have also been documented for the Early Middle Ages (La Rocca 1992; Francovich 2002; Lazzari and Santos Salazar 2005). The Later Medieval Period (from the 10^{th}–13^{th} century) is even more problematic, in that urbanization and the construction of new settlements likely had an impact on population mobility (Pinto 1996). Such phenomena, where intense and enduring, may have produced very specific distribution by age of population and thus also of deaths. To overcome this problem we considered cemeteries from various regions and from different settlements types, such as towns and villages (see Table 3). A final problem when dealing with a large territory such as the Italian peninsula is that different micro regions might have been characterized by different demographic patterns. Our research cannot detect diversity at such a detailed level because to date the number of sites at our disposal is quite limited. Given that this study includes almost all published data, perhaps this matter will be clarified when more skeletal data becomes available. At the present state of research we can reveal some general changes that characterize the different chronological periods, thus opening the path for future study.

Nonetheless, one positive point is that the **d** trend can be read together with the population trend (estimates of Lo Cascio and Malanima 2005): when **d** grows the population tends to decrease, and vice versa. An exception is the high value of **d** in the 5^{th} century, which might be distorted by the low number of cemeteries we have for this period. The medieval data we consider is very interesting: the centuries affected by the Justinianic Plague are characterized by an increase in **d,** and the period after the Black Death is characterized by cemeteries with even higher **d** values, which continued in the following centuries (see Table 4). As shown in our simulation, there are two possible reasons for the higher value of **d** in the plague period: high mortality, and a younger population due to fast population recovery after each outbreak. The high **d** values of this period seem to reflect the typical trend of a lengthy mortality crisis triggered by the plague, with alternate stages of high mortality followed by high birth rates.

Table 4: Estimated values of d and population trends according to Lo Cascio and Malanima, 2005 (population in millions, end of the centuries)

Century	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th
Population trend	15	12	9	10	11	8	8	8	9	10	10.5	11	12.5	8	9
Value of **d**	0.175	0.144	0.146	0.169	0.224	0.185	0.191	0.183	0.176	0.155	0.172	0.139	0.174	0.241	0.252

When an epidemic appears the number of deaths rapidly increases to a peak and then begins to fall again. During the mortality crisis the number of marriages decreases drastically due to grieving and the disaggregation of kinship and social relations, the slowdown of economic and trade activities, and emigration to less affected areas. Thus, a sharp decline in conceptions and births follows, which, together with the deaths, decimates the population. The population, however, is extremely resilient and follows the typical Malthusian pattern. In fact, generally a year after the plague a strong recovery in weddings and births begins, which is due to a decline in the age at marriage, a reduction in those never married, and a shortening of the gap between births (Del Panta 1980; Livi Bacci 2000; Alfani and Cohn 2007b; Dalla-Zuanna et al. 2012; Green 2014).

For example, the parish baptism registers of the city of Florence indicate that in the 15th century the number of children baptized decreased by an average of 18% in the years of plague and immediately afterwards. Subsequently, when the outbreak ended, the number of baptisms rose to higher levels than in the pre-plague years. So, for instance, during the outbreak of 1457 the number of children baptized was 1,882, in the preceeding years (1453–1456) it had been on average 2,113, while in the following years, between 1459 and 1461, the average number of baptisms was 2,123 (Herlihy and Klapisch-Zuber 1978). Written sources from the period report a strong increase in marriages and fertility following plague outbreaks: The population pyramid broadens, with a larger presence of children, who, once they reach adulthood, will contribute even more to the growth of the population by marrying at young ages and giving birth to many children. The population will therefore be young and vulnerable once again to new epidemics, since those who were immunized will have since died. In fact, it seems that the epidemic cycles of the years 1363/1364, 1374, 1383, and 1400 affected mainly children who were not immunized by previous outbreaks (Herlihy and Klapisch-Zuber 1978). The epidemic cycles at the end of the 15th century, which cyclically decimated extraordinary numbers of children and the youth every ten years, considerably modified the age structure of the Italian population and compromised its chances of recovery. The high values of **d** found for Italian cemeteries of this period represent these trends of mortality and recovery and selective mortality by age. In fact, because the increase in **d** reflects the rising number of individuals buried between the ages 5–19 compared to the total population, it can reflect both an increase in deaths at these ages (which corresponds by extension to an increase in overall mortality) and an increase in births (and consequently an increase in young deaths, subsequently buried in the cemeteries) (Bocquet-Appel and Naji 2006; McCaa 2005). Our simulations described above do not contradict this interpretation.

4. Conclusions

Using the age-related index **d** = ${}_{15}D_5/D_{5+}$, estimated by cemetery, we were able to gather information on the mortality regimes of both ‘normal’ population periods with moderate growth or decline and population periods affected by recurrent major epidemic cycles. In the latter, our simulation shows that **d** may be high because the mean level of mortality is higher than in periods without strong mortality crises and because the population is younger, as births exceed deaths in the years following the epidemic outbreaks.

It is hoped that this path of research will be extended, using the **d** index to investigate different geographical areas and chronological periods. Regarding our specific example of Italy during the first 1,500 years A.D., archaeological data should be implemented to provide newly excavated and analyzed osteological data, particularly for the early modern period; in this way it will be possible to appreciate regional differences and to systematically compare mortality trends obtained from skeletal samples with the data from cadasters, allowing reconstruction of the age structure of the population (although underestimation of children is sometimes evident in these cases also) in different areas and historical moments (Dalla-Zuanna et al. 2012). This comparison could be broadened to include mortality data collected in the first parochial registers.

5. Acknowledgments

The authors wish to profoundly thank Lorenzo Del Panta, Guido Alfani, the *Demographic Research*’s former associate editor Andrew Hinde, and the anonymous referees for reading the previous versions of this article and for their precious and punctual suggestions.

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