ON THE EPIDEMIOLOGY OF WHOOPING COUGH IN LONDON.

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(With 6 Figures in the Text.)

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I. Introductory.

During the first three decades of last century whooping cough was causing 3 per cent. of all deaths in London, as was measles. The mortality rates in England and Wales attributed to these two diseases have followed a remarkably similar course; thus the mean annual rates per million living under 15 years of age for whooping cough and measles were 1227 and 1259 respectively in the decade 1881–90, and 416 and 437 in the decade 1921–30. The close affinity between the behaviour of the two diseases in other countries as well has been pointed out by Mikulowski (1930), Hirsch, and others.

In the year 1929, 6332 deaths were registered in England and Wales as due to whooping cough, and of these 1141 occurred in London Administrative County, where they formed 1·8 per cent. of deaths from all causes. All these deaths occurred in children under 10 years of age, and they comprised 13 per cent. of the mortality from all causes at those ages. In that year, according to the *Epidemiological Reports of the League of Nations Health Section*, out of 125 cities listed, only Belfast, Manchester, Yokohama and three South American cities gave higher rates than London, and the London rate was six times the average rate in 50 German towns. Allowing for the possibility that peculiarities in death registration may somewhat exaggerate the unfavourable position of London and for the fact that in 1929 the whooping cough mortality in London was unusually high, it still remains evident that from the point of view of immediate mortality alone the whooping cough problem in London is one which merits serious consideration.

The other ravages of this detestable disease, though more difficult to esti-

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mate, must also be important in their effects on the Public Health. Whooping cough is a notifiable disease in several of the Metropolitan Boroughs, and it is possible to estimate its total incidence in London from the records given in Table I (p. 584). Combining the data for the four boroughs, the ratio of notified or reported cases to registered deaths was 36 in 1921–5 and 57 in 1926–30. The higher ratio in the last quinquennium does not necessarily indicate a lower fatality rate but may be due to more complete reporting and ascertainment of cases. It will be shown in this paper that in Battersea about 70 per cent. of the real incidence must now be recorded. Assuming the notified and reported cases to represent this proportion of the actual incidence during the last quinquennium, and the ratio of mortality to incidence to be the same for London as a whole as for the four boroughs combined, the total incidence of whooping cough during the quinquennium may be estimated as $2453 \times 57 \times \frac{100}{70}$, giving an average annual incidence of about 40,000 cases.

Analysis of the Battersea records shows that 25 per cent. of the children attacked are aged 5 and upwards, and allowing an average of two months' absence this would mean an average annual loss of school attendance at those ages in London of 1667 years. Comparing this with measles, the school notifications in 1921–30, including some at age 4, numbered 253,675, and allowing an average absence of three weeks, this would give an average of 1464 years of school attendance lost per annum, or rather less than the loss estimated as due to whooping cough. In neither case is the loss due to exclusion from school of home contacts included.

More important than this is the toll of impaired physique levied upon these 40,000 children annually, which is incalculable. The skiagraphic work of Göttche and Erös (1930) demonstrated that whooping cough is accompanied in a large proportion of cases by a chronic inflammation of the lung tissue itself, and pathological studies show that it may leave behind a stenosis of the smaller bronchioles and permanent changes in the epithelium. In a series of 231 deaths registered as due to whooping cough as primary cause in the County of Durham in 1926, bronchitis was stated as the secondary cause in 25, pneumonia in 112, phthisis in 3, cardiac complications in 3, convulsions in 57, meningitis in 4, and cerebral haemorrhage in 2, and these figures are suggestive of the damage which must be inflicted upon the respiratory, cardiac and nervous systems in non-fatal cases of the disease also. The amount of cardiac damage which results cannot at present be even guessed at, but I venture to predict that more attention will be paid in the future to whooping cough as the real starting-point of heart troubles and other circulatory disorders which become manifest in later life. Psychological trauma resulting in severe cases from the incessant terrifying paroxysms with their sense of impending suffocation is also a factor to which no attention is paid. No one acquainted with modern psychology who has watched a child's behaviour when the approach of one of these attacks is felt can doubt that the fear inspired by them must in many cases be permanently harmful to healthy development on the emotional plane.

Taking these facts into consideration it is difficult to understand the comparative neglect of whooping cough by our profession. Willis remarked in 1674 that whooping cough was left to the management of old women and empirics, and we have advanced a little, but not very greatly, from that position. In the field of public health it is only necessary to search the published literature to become conscious of this neglect. Creighton studied the mortality records of London in his classical work, and thirty years ago Laing and Hay (1901–2) analysed the behaviour of whooping cough in Aberdeen by means of notification records. A mathematical study of the periodicity of epidemics in some English towns was also made by Young (1919–20). Considerable additions have been made to our knowledge of its bacteriology, and some statistical studies of the incidence of whooping cough according to sex, age and season have recently been carried out in America by Crum (1915), Godfrey (1928 *a*, *b*), Fales (1928), Sydenstricker (1928), Collins (1929) and others, but our ignorance of its immunology is still profound.

The introduction of compulsory notification of whooping cough in several boroughs of London has now led to the accumulation of sufficient records to make possible a further study of its epidemiology in the light of modern views about epidemics. For access to such of the original records as were available I am greatly indebted to Drs E. G. Annis, F. G. Caley, C. W. Hutt and G. Quin Lennane, the Medical Officers of Health of Greenwich, Wandsworth, Holborn and Battersea, and to the Public Health and School Medical Departments of the London County Council, who have given every possible assistance. I am also indebted to Dr Franks, County Medical Officer of Health of Durham, for access to mortality records.

II. Fatality of whooping cough in London.

The successive annual totals of deaths attributed to whooping cough in the Administrative County of London from 1921 to 1930 were as shown in Table I. Mortality was highest in 1922, 1925 and 1929, but it cannot be assumed from this that the disease was necessarily most prevalent in those years. In Battersea the numbers of cases notified and reported in each year show little relation to the fluctuations in deaths registered in the corresponding years. Again, although there were $2\frac{1}{2}$ times as many deaths in 1923 or 1924 as in 1926, the total notified and reported cases during these three years were approximately the same. The higher ratios in the earliest years of notification doubtless arise partly from less complete reporting of cases than in the later years.

The much higher ratios of deaths to cases reported in 1927 and 1929 than in 1926 and 1928 respectively are partly due to the fact that epidemics occurred in the autumn-winter of 1926–7 and 1928–9, and the mortality from whooping cough being usually a delayed mortality, many cases notified in the later months of 1926 or 1928 would reach a fatal termination in the early months of the succeeding years. It is therefore advisable in studying the ratio of whooping cough mortality to incidence to combine pairs of years where there is a winter epidemic, as in Table I, or to use as time scale the year from July 1st to June 30th, as in Table III.

When one borough is compared with another the fatality ratios are influenced by the completeness of notification and reporting of the disease which no doubt varies at pre-school ages, being partly dependent upon the activities of the Health visiting staff and other factors. The figures representing incidence in Table I and elsewhere in this paper include cases reported by schools or parents, or ascertained by visiting, as well as those notified by doctors. For the decade 1921–30 the mean fatality ratios per cent., based upon

Table I.

	London deaths			Battersea			Greenwich		
Year	Male	Female	Total	Cases	Deaths	Ratio %	Cases	Deaths	Ratio %
1921	249	297	546	576	30	5·18	321	10	2·88
1922	494	634	1128	428	22		408	11	
1923	174	258	432	1024	16	1·56	329	15	4·56
1924	240	277	517	816	17	1·73	498	15	2·86
1925	412	457	869	1322	20		655	18	
1926	106	125	231	1210	13	1·43	126	4	3·79
1927	264	284	548	749	15		401	16	
1928	185	220	405	1228	14	2·24	506	8	2·30
1929	525	616	1141	1317	43		624	18	
1930	61	67	128	747	7	0·94	100	1	1·00
Total	2710	3235	5945	9417	197	2·09	3968	116	2·92

	Holborn			Wandsworth			Four boroughs		
Year	Cases	Deaths	Ratio %	Cases	Deaths	Ratio %	Cases	Deaths	Ratio %
1921	129	4	4·18	1201	28	3·28	2227	72	3·715
1922	110	6		1056	46		2002	85	
1923	93	5	5·38	1229	30	2·44	2675	66	2·168
1924	95	6	7·21	1108	28	2·06	2517	66	2·255
1925	113	9		2089	38		4179	85	
1926	96	1	3·37	1235	9	1·21	2667	27	1·589
1927	82	5		1829	28		3061	64	
1928	104	4	4·28	1665	9	1·69	3503	35	2·028
1929	153	7		2590	63		4684	131	
1930	33	1	3·30	809	7	0·86	1689	16	0·947
Total	1008	48	4·76	14811	286	1·93	29204	647	—

the incidence thus ascertained, were as follows: Battersea $2{\cdot}09 \pm 0{\cdot}12$, Greenwich $2{\cdot}92 \pm 0{\cdot}18$, Holborn $4{\cdot}76 \pm 0{\cdot}45$, Wandsworth $1{\cdot}93 \pm 0{\cdot}08$.

The large adjoining boroughs of Battersea and Wandsworth agree in giving ratios of about 2 per cent.

By analysis into ages it was found that of 6183 recorded cases of whooping cough in Battersea during 1925–30, 6050 or 97·85 per cent. were children under 10. In Wandsworth (1926–8) the proportion was 4149 out of 4263 or 97·33 per cent., in Greenwich (1919–29) it was 3809 out of 3888 or 97·97 per cent., and in Holborn (1921–8) it was 991 out of 1005 or 98·67 per cent. Multiplying the total incidence from Table I by these proportions to obtain the estimated cases under 10 years of age, the mean annual attack rates and ratios of mortality to

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recorded incidence at these ages were as shown in Table II. The "mean populations" in the last three boroughs are the means of the 1921 and 1931 census figures.

The lower incidence rate combined with higher ratio of mortality to incidence in Greenwich suggests that there may have been a less complete recording of the real incidence in Greenwich than in Battersea and Wandsworth. Thus if the incidence rate in Greenwich be raised to about 32 as in the latter boroughs the "fatality" ratio is reduced to 2 per cent. In Holborn, however, it would still be over 3 per cent. and there can be little doubt that the

Table II.

	Census 1921		1921–30				
					Mean annual rates per 1000 under 10		
Borough	Persons per acre	Rooms per person	Mean population under 10	No. of cases recorded under 10	Incidence	Mortality	Ratio of mortality to recorded incidence
Battersea	78	0·96	27266	9215	33·80	0·722	0·0214
Greenwich	26	0·99	17511	3887	21·75	0·662	0·0298
Holborn	185	0·75	4283	995	23·23	1·121	0·0482
Wandsworth	36	1·19	47886	14416	30·10	0·597	0·0198

worse conditions of overcrowding in Holborn are associated with a definitely higher fatality rate.

The *true* fatality rate in Battersea during 1925–9, taking the recorded incidence to represent 70 per cent. of the real incidence at all ages, as shown in Section V, would be according to Table I, $105 \times 70/5826$ or 1·26 per cent., and this is probably applicable to Wandsworth, and perhaps to Greenwich also. At several small groups of ages up to 5, and at 5–10, after correcting the recorded numbers of cases in accordance with the estimated completeness of notification at those ages as found in Section V, the corrected fatality rates per 100 cases would be as follows, showing the rapid decline with age:

Ages	0–1	1–2	2–5	5–10	All ages
Fatality	4·02	3·35	0·70	0·19	1·26

The true mean annual incidence on the population of children under 10 in Battersea during 1925–9 is estimated to have been $(1{\cdot}417 \times 5702 \times 1000)/(26350 \times 5)$ or 61·3 per 1000 living[1].

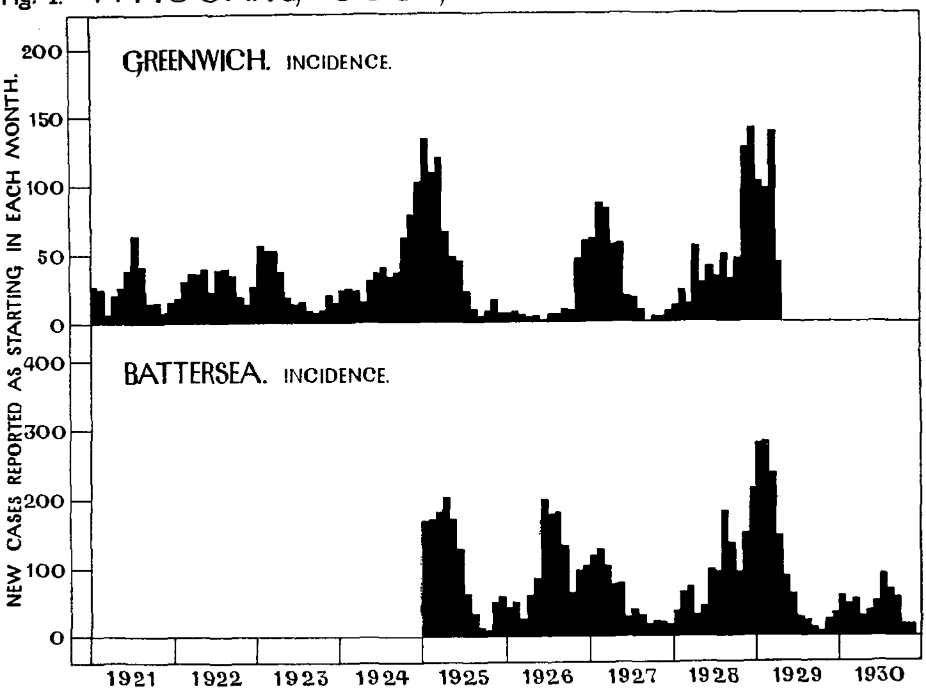
III. Periodicity of whooping cough in London.

In 1919 Matthew Young (1919–20) investigated the periodicity of whooping cough epidemics in London and ten other towns by Brownlee's method of periodogram analysis, using the weekly deaths from 1870–1910. He concluded that there was evidence of a regular periodicity, the most important period in London being 104 weeks, with less pronounced periods of 52 weeks and 160 weeks. Periods of just 2 years were also found in Liverpool, Newcastle and Salford, but in Birmingham the predominant period was 99 weeks, in Bristol 95, in Glasgow 116 and in Edinburgh 119 weeks.

[1] There were 5702 cases recorded under 10 in the 5 years; 1·417 is the correction factor (see Section V, p. 601), and 26,350 the mean population (see Table V, p. 592).

In Fig. 1 is shown the trend during 1921–30 of the numbers of new cases reported as having commenced during each month in Battersea and Greenwich. It is evident that epidemics occur in the London Boroughs at intervals not quite so regular as in the case of measles. The duration of these epidemics is about 9 months if they commence in the autumn, but if an epidemic starts in the late spring it is usually of short duration, declining again during the summer months and often being followed by or merging into a second epidemic which commences about the end of the year. In Greenwich summer epidemics occurred in 1921, 1922, 1924 and 1928, and winter epidemics in 1922–3, 1924–5, 1926–7, 1928–9, that is in alternate winters. In Battersea during the period

Fig. I. WHOOPING COUGH IN LONDON. 1921—30.



1925–30, summer epidemics occurred in 1926, 1928 and 1930, and winter epidemics in 1924–5, 1926–7, 1928–9 as in Greenwich[1].

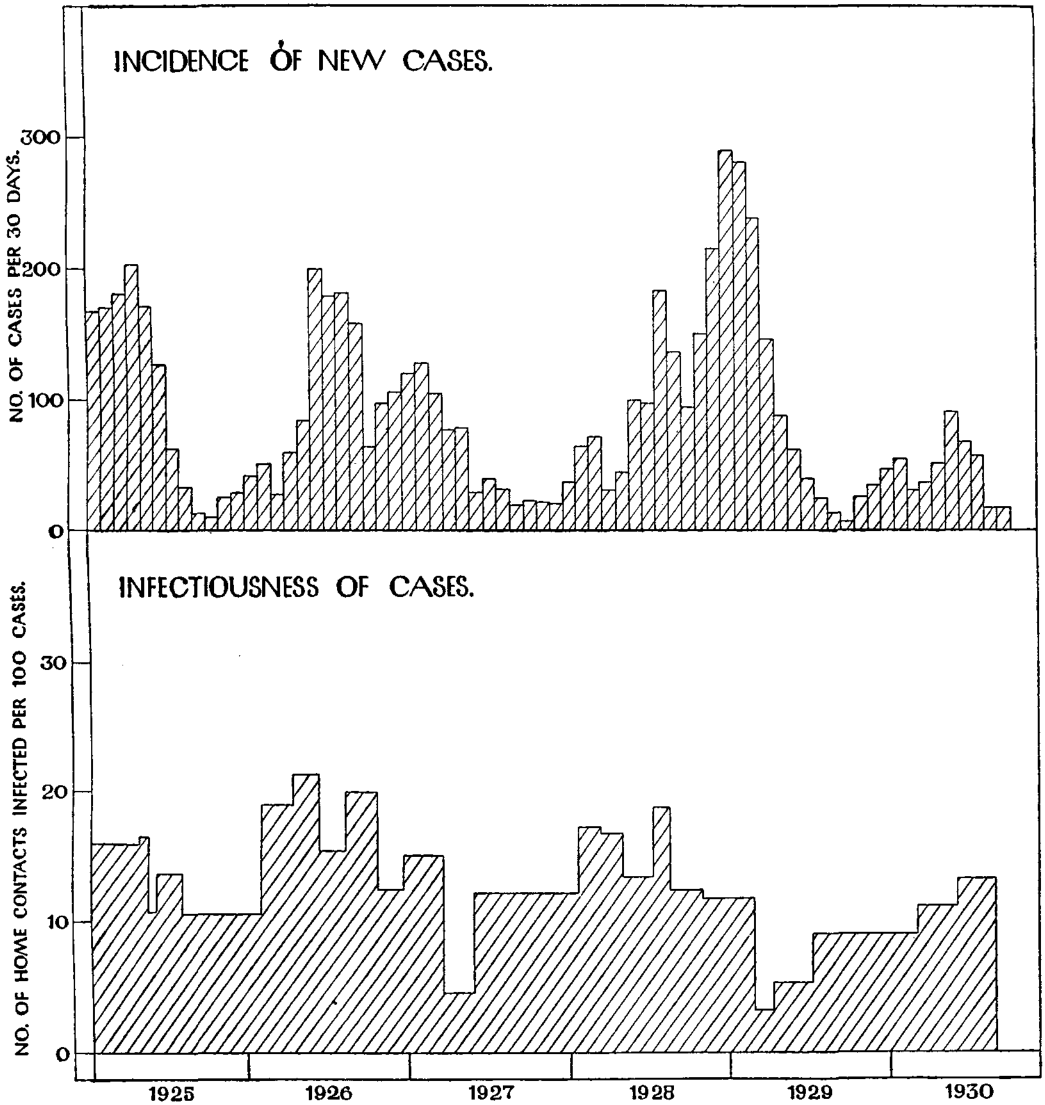
The periodicity of the Battersea epidemics, also shown in Fig. 2, was during these years a biennial one, but it is somewhat obscured by the fact that sometimes the summer peak and at other times the winter peak was the greater. The analysis of data for Wandsworth for 1926–8, represented in a previous paper (1930), showed a summer epidemic in 1928 and winter epidemics in 1926–7 and 1928–9, as in the neighbouring area of Battersea.

The alternation of epidemic years with interepidemic years is not clearly

[1] In Holborn the summer epidemics occurred in 1921, 1922, 1924 and 1927, and the longer winter epidemics in 1922–3, 1924–5, 1925–6, 1928–9.

seen when the incidence is tabulated by calendar years, but is better perceived by enumerating the cases commencing from one mid-year to the next. This has been done in Table III for Battersea and Greenwich, and it can be seen that the ratio of mean annual incidence in the epidemic years to that in the intervening years was 4 in Greenwich and 3·2 in Battersea.

Fig. 2. WHOOPING COUGH IN BATTERSEA. 1925—1930.



In Fig. 3 the borough of Battersea has been divided into six districts, of which four consist of a single electoral ward and the other two of combinations of adjoining wards. The small map at the top of the diagram shows the relative

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positions of the districts. To the north and north-west the borough is bounded by the River Thames, and it is also divided into two parts by the Southern Railway, to the north of which lie Wards 2, 3, 5 and 6 and part of Ward 1. There is free communication between these wards, and also between Wards 4, 7, 8 and 9 which lie south of the railway, but the railway itself is only crossed by a small number of bridges and, owing to the resulting arrangement of the school attendance areas, may therefore form a partial barrier to the spread of epidemic waves. The first district in Fig. 3 is divided into two portions by the railway, joined by only one street. The next three districts are to the north and the last two to the south of the railway.

The actual recorded incidence of cases having their onset in successive 30-day periods is shown by the broken lines, the numbers being given in Table IV. The populations of the districts being unequal, the relative heights of the epidemic peaks in different districts in Fig. 3 signify nothing. In 1925 a winter epidemic was at its height in Wards 5 and 6 in January and it spread eastwards, reaching its culmination in March in Wards 2 and 1. It did not

Table III.

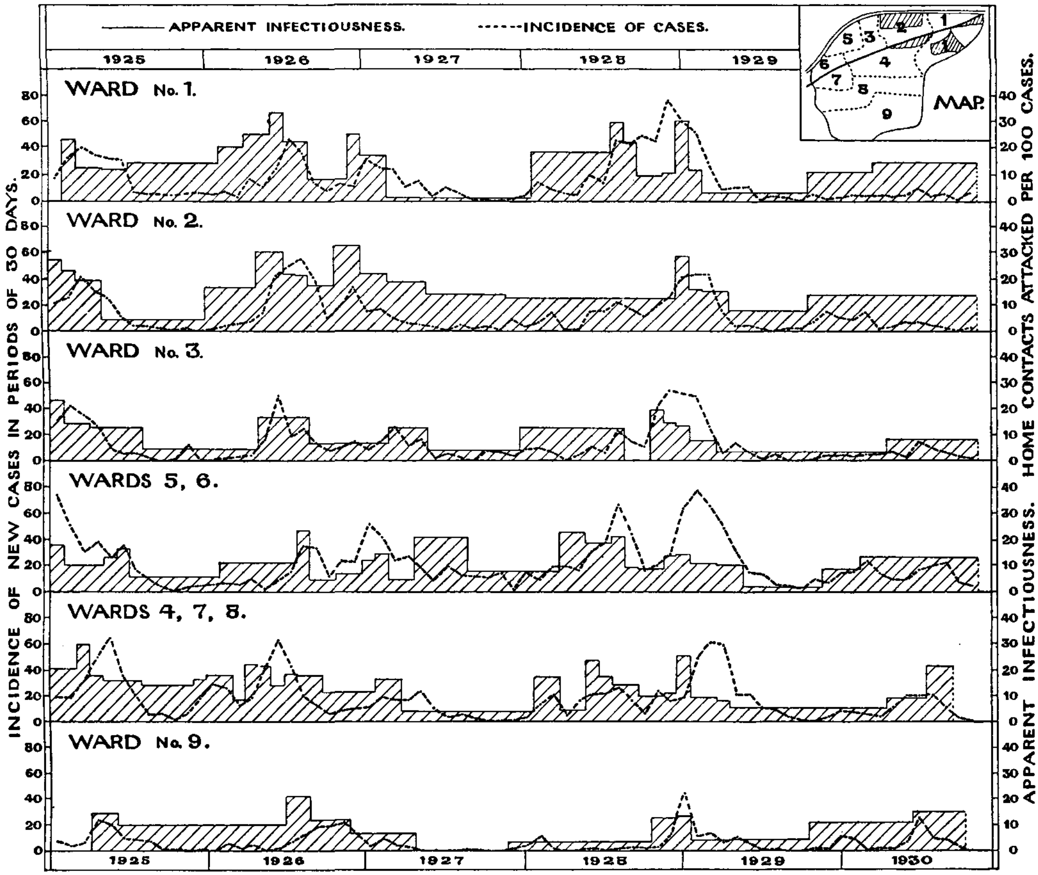
Periods from July 1 to June 30	No. of cases of whooping cough commencing in each period			
	Greenwich		Battersea	
	Epidemic	Interepidemic	Epidemic	Interepidemic
1923–4	—	237	—	—
1924–5	875	—	1570*	—
1925–6	—	102	—	633
1926–7	506	—	1290	—
1927–8	—	227	—	496
1928–9	900*	—	1972	—
1929–30	—	—	—	405
Mean annual	760	189	1611	511

* Approximate estimates.

commence in the districts south of the railway until later, reaching a maximum in April and May and rapidly subsiding before summer. In the winter of 1925–6 there was no epidemic, except a small one in Wards 4, 7 and 8, merging into a large summer epidemic which began in April. A month later the epidemic began simultaneously in Wards 1, 2 and 3, and spread in July to Wards 5, 6 and 9. By October this had subsided in all districts except Ward 9, but a winter epidemic immediately followed in the wards north of the railway. During the summer of 1927 and the following autumn and winter the whole borough was almost free from whooping cough. In the spring of 1928 incidence began to rise in all districts except Ward 9, producing a considerable summer epidemic in Wards 5 and 6 which quickly subsided, and small summer epidemics in the other wards merging into a large winter epidemic throughout the borough. The direction of spread of this wave seems to have been from east to west in the area north of the railway and from south to north in the southern part of the borough. The following summer and winter were almost free from whooping cough, though small outbreaks occurred in some of the wards.

It may be concluded from this and the preceding section that (1) years of high whooping cough mortality in London are not necessarily years of highest incidence; (2) epidemics do not always occur in the same years or parts of the year in areas of London which are separated by several miles; (3) summer epidemics tend to be immediately followed by or to merge into winter epi-

Fig. 3. WHOOPING COUGH IN SIX DISTRICTS OF BATTERSEA. 1925–1930.



demics, with an interval of about 6 months between the peaks, but it is unusual for a winter epidemic to be followed by another before the summer of the next year or the next winter but one; (4) the spread of epidemics of whooping cough is influenced to some extent by barriers to free communication, and some districts thus occasionally escape altogether, or an interval of several months may separate the epidemic peaks in districts a mile or so apart (see Table IV).

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Table IV. *Whooping cough in Battersea wards*, 1925–30.

Period of 30 days from	Total incidence 1	2	3	5, 6	4, 7, 8	9	Total	"Secondary" cases 1	2	3	5, 6	4, 7, 8	9	Total
7. i. 25	17	22	31	73	19	7	169	—	6	7	13	4	—	30
6. ii. 25	31	26	42	51	18	3	171	7	6	5	5	4	—	27
8. iii. 25	39	42	35	31	27	7	181	4	8	6	2	8	—	28
7. iv. 25	34	31	27	38	50	23	203	5	6	3	5	9	3	31
7. v. 25	31	25	9	23	64	20	172	3	2	—	3	9	3	20
6. vi. 25	30	11	5	36	36	9	127	4	—	2	6	6	—	18
6. vii. 25	7	4	5	17	21	8	62	1	—	1	—	5	1	8
5. viii. 25	5	3	2	10	6	7	33	1	—	—	2	1	—	4
4. ix. 25	—	2	—	4	6	1	13	—	—	—	—	1	—	1
4. x. 25	4	—	1	1	2	1	9	1	—	—	—	—	—	1
3. xi. 25	1	2	12	3	7	—	25	—	—	1	—	1	—	2
3. xii. 25	6	—	—	4	18	1	29	1	—	—	—	3	—	4
2. i. 26	5	2	1	5	29	—	42	—	—	—	—	4	—	4
1. ii. 26	7	4	2	6	26	5	50	2	—	—	1	6	—	9
3. iii. 26	3	5	—	5	12	2	27	—	2	—	2	1	3	8
2. iv. 26	17	7	4	9	18	4	59	4	1	—	—	4	—	9
2. v. 26	11	14	16	2	41	—	84	3	8	2	—	9	—	22
1. vi. 26	24	43	50	8	73	2	200	8	9	7	2	10	—	36
1. vii. 26	46	50	18	15	43	7	179	10	11	2	1	8	3	35
31. vii. 26	35	55	25	35	20	12	182	8	12	7	10	3	1	41
30. viii. 26	14	41	13	34	13	18	133	1	9	—	2	3	2	17
29. ix. 26	8	10	8	12	6	19	63	1	—	—	—	3	2	6
29. x. 26	13	19	11	24	8	22	97	1	5	3	2	—	3	14
28. xi. 26	12	33	15	23	10	12	105	3	12	1	1	—	—	17
28. xii. 26	30	15	9	51	11	3	119	5	2	1	6	1	—	15
27. i. 27	25	17	16	41	19	9	127	4	5	—	6	3	2	20
26. ii. 27	23	10	26	24	17	4	104	1	2	3	2	3	—	11
28. iii. 27	11	6	12	27	17	3	76	—	—	2	—	1	—	3
27. iv. 27	15	5	16	18	23	—	77	—	2	2	—	2	—	6
27. v. 27	4	3	2	9	10	—	28	—	—	—	4	—	—	4
26. vi. 27	10	1	5	19	4	—	39	—	1	—	8	—	—	9
26. vii. 27	6	4	2	12	6	1	31	—	1	—	1	—	—	2
25. viii. 27	1	2	—	11	3	1	18	—	—	—	2	—	—	2
24. ix. 27	1	3	7	10	1	—	22	—	—	1	1	—	—	2
24. x. 27	—	1	6	13	1	—	21	—	—	—	—	—	—	—
23. xi. 27	2	8	4	2	1	2	19	—	3	—	—	—	—	3
23. xii. 27	4	3	9	14	3	4	37	—	—	2	2	—	—	4
22. i. 28	14	7	10	9	13	11	64	5	3	3	—	2	—	13
21. ii. 28	9	14	6	19	21	2	71	—	2	1	1	4	—	8
22. iii. 28	6	1	—	19	5	—	31	3	—	—	7	—	—	10
21. iv. 28	5	1	4	16	17	1	44	1	—	—	1	1	—	3
21. v. 28	19	15	11	31	21	2	99	1	3	—	8	5	—	17
20. vi. 28	14	15	7	38	22	1	97	2	—	—	5	4	—	11
20. vii. 28	44	22	23	66	26	2	183	13	2	3	14	2	—	34
19. viii. 28	42	17	15	43	16	3	136	9	4	—	4	4	1	22
18. ix. 28	48	11	11	16	6	2	94	4	—	—	—	1	—	5
18. x. 28	44	18	41	20	24	3	150	5	—	8	3	2	1	19
17. xi. 28	76	26	54	29	17	13	215	8	3	8	4	2	1	26
17. xii. 28	60	42	52	63	19	45	281	18	12	7	9	5	6	57
16. i. 29	52	43	50	77	50	11	283	6	7	4	4	3	1	25
15. ii. 29	28	43	27	65	62	13	238	1	2	2	11	8	—	24
17. iii. 29	9	15	6	49	60	7	146	1	7	—	7	5	—	20
16. iv. 29	10	3	14	30	21	10	88	—	—	2	1	—	—	3
16. v. 29	10	4	6	14	21	6	61	—	—	—	—	1	1	2
15. vi. 29	1	2	2	12	11	1	29	—	—	—	—	—	—	—
15. vii. 29	4	—	5	5	9	1	24	—	—	—	—	3	—	3
14. viii. 29	3	2	—	4	4	—	13	—	1	—	—	—	—	1
13. ix. 29	1	2	—	3	1	—	7	—	—	—	1	1	—	2
13. x. 29	5	7	1	9	1	2	25	—	5	—	—	—	—	5
12. xi. 29	2	15	4	7	4	2	34	1	1	—	1	—	—	3
12. xii. 29	12	10	4	13	8	11	58	2	—	—	2	—	2	6
11. i. 30	4	8	3	15	7	9	46	—	—	—	—	—	—	—
10. ii. 30	4	14	5	23	6	1	53	—	3	—	4	—	—	7
12. iii. 30	4	2	5	13	4	2	30	—	—	—	4	—	1	5
11. iv. 30	3	3	7	9	12	2	36	—	—	1	—	1	—	2
11. v. 30	4	6	3	9	21	7	50	—	1	—	3	2	1	7
10. vi. 30	9	6	15	16	20	25	91	2	—	2	3	2	2	11
10. vii. 30	3	4	10	19	21	10	67	1	—	—	—	4	1	6
9. viii. 30	5	2	7	22	11	9	56	—	—	1	2	3	4	10
8. ix. 30	1	—	3	7	3	3	17	—	—	—	—	—	—	—
8. x. 30	6	2	2	6	1	—	17	2	1	—	—	—	—	3
Totals	1093	911	859	1516	1254	434	6067	163	170	100	188	177	45	844

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IV. Population at risk in relation to the epidemic cycle.

The epidemic cycle in whooping cough is usually assumed to be accounted for by the fact that (1) there is some cycle of activity of the bacillus influenced by seasonal conditions, or (2) epidemics begin when sufficient children have accumulated in the population who have not previously had the disease and are terminated when this surplus of susceptibles has been depleted, or (3) there is a combination of both effects. The first of these assumptions has been examined by Young (1919–20), but with inconclusive results as far as the validity of the theory is concerned, the period not being identical in different towns. The second has not been subjected to any searching examination.

If a cycle of activity of the infecting organism is the main controlling factor it seems unlikely that this cycle could be in a different phase by several months in two areas of London streets whose populations were continually mixing with each other, though the conception of a periodic change in the organism itself is so hypothetical that this cannot be ruled out as impossible. An examination of Fig. 3 shows several examples of this; from February to May 1925 the epidemic wave was in ascending phase in Wards 4, 7 and 8, and in descending phase in Wards 3, 5 and 6; from June to October 1926 it was in ascending phase in Wards 4, 7 and 8 and in descending phase in the adjoining Ward 9; from December 1928 to March 1929 it was again in ascending phase in Wards 4, 7 and 8, and in descending phase in Ward 1. The intervals between the epidemic peaks also differed by several months in adjoining areas; thus from 1926 to 1928 the intervals between the maxima of the winter epidemics were, in the six areas, 23, 26, 21, 25, 22 and 26 months respectively, and between the summer peaks in the second, third, fourth and fifth areas they were 24, 26, 24 and 26 months respectively.

The changes which must have taken place in the proportions of children at defined ages who had never had whooping cough can be calculated as follows, with the results shown in Table V. The method used involves approximations; an exact actuarial solution would be difficult and laborious and of doubtful advantage owing to the uncertain factors involved. Starting from the births centred at January 1st of each year 1921 to 1931 and the census population of 1921, and deducting successively the deaths from all causes at ages 0–1, 1–2, etc., and assuming no migratory change for the moment, the survivors s'_x at each exact age x were estimated at the beginning of each calendar year, on the supposition that the births centred at January 1st were concentrated at that date. The mid-year populations at each age interval were then estimated from these values by deducting half the deaths in that year and age interval.

The resulting mid-year populations for 1931 were then compared with the census population of 1931, and it was found that the estimated figures, on the basis of no balance of migration either way, were in excess of the actual census figures, indicating an emigratory balance of movement of young children from the borough during the decade. The total loss by migration increased up to the age-group 4–5 and then remained fairly steady, from which it was inferred that an outward movement, no doubt to the suburbs, of families with children under

Table V. *Whooping cough incidence with age in Battersea.*

	Age x	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930		1925–9 A	1925–9 B
Estimated population aged x to $x+1$ at middle of each year	0–	3531	3361	3346	2967	3085	3059	2995	2732	2509	2543		2876	2931
	1–	3832	3333	3144	3126	2772	2855	2795	2758	2490	2340		2728	2742
	2–	2259	3575	3209	2992	2948	2637	2675	2634	2556	2316		2691	2641
	3–	2146	2124	3341	3126	2861	2806	2503	2523	2481	2378		2639	2613
	4–	2671	1987	2000	3126	3046	2737	2666	2374	2370	2331		2639	2563
	5–	2956	2578	1907	1935	3016	3004	2673	2592	2306	2291		2720	2577
	6–	3099	2940	2566	1898	1928	3010	2996	2666	2584	2300		2640	2714
	7–	3268	3087	2931	2561	1892	1921	3003	2991	2659	2579		2496	2633
	8–	3236	3258	3080	2925	2554	1888	1914	2997	2985	2654		2469	2491
	9–	3225	3227	3252	3074	2920	2549	1883	1910	2992	2981		2452	2465
	0–10												26350	2449†
Ratio at end of year of the survivors of whooping cough attacks during the year to all survivors at age x exactly, that is $(W_{x-1}-d_{x-1})/s_x$	1		·01742	·01499	·03886	·02771	·04473	·04348	·02690	·04467	·04581	·02025	·04105*	
	2		·02150	·01585	·04301	·03451	·05167	·04766	·02948	·05187	·05494	·02442	·04712*	
	3		·02452	·01828	·04550	·03604	·05776	·05257	·03336	·05702	·06335	·02705	·05281*	
	4		·02738	·02018	·05500	·03994	·06660	·06192	·03875	·06780	·07344	·03307	·06170*	
	5		·03270	·02606	·06457	·05367	·07515	·07487	·04796	·08178	·09421	·03961	·07479*	
	6		·03408	·02654	·06803	·05367	·09043	·07375	·05082	·08821	·09831	·04314	·08030*	
	7			·01289	·03153	·02629	·04145	·04081	·02268	·04234	·04907	·02129	·03927*	
	8				·01295	·01015	·01742	·01610	·01065	·01571	·01991	·00852	·01596*	
	9					·00410	·00665	·00687	·00417	·00693	·00737	·00339	·00640*	
	10						·00308	·00313	·00212	·00616	·00434	·00168	·00377*	
Cumulative fractions of population aged x to $x+1$ at middle of year who have been recorded as having whooping cough at some time since birth	0–	·00871	·00750	·01943	·01385	·02236	·02174	·01345	·02233	·02290	·01012			
	1–		·02534	·03649	·05611	·05354	·06856	·05822	·05283	·07214	·05802			
	2–			·05602	·07602	·10225	·10566	·10907	·10147	·11044	·11313			
	3–				·09874	·12734	·16209	·15132	·15965	·16670	·15865			
	4–					·15628	·19807	·21703	·21159	·24065	·22322			
	5–						·23073	·26092	·28511	·30163	·30933			
	6–							·27895	·30750	·35375	·36143			
	7–								·29814	·33862	·38255			
	8–									·30969	·34942			
	9–										·31421			
	0–2				·0355	·0371	·0443	·0359	·0376	·0477	·0413			
	2–5					·1289	·1551	·1573	·1583	·1709	·1750			
	5–7							·2505	·2961	·3271	·3354			
	0–7							·1400	·1606	·1800	·1758			
	0–10										·2327			

Notes. A = Mean population at middle of years 1925 to 1929 at ages x to $x+1$.
B = Mean survivors to end of years 1925 to 1929 at age x exactly.
† = At age 10 exactly.
* = Mean of ratios at end of years 1925 to 1929 at age x.

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5 was taking place throughout the decade. The estimated populations at the beginning and middle of each year were therefore corrected by distributing the excess uniformly over the period from birth (or 1921) to age 5 or mid-1931, whichever came first, and deducting the appropriate fraction of the excess[1]. The same process of correction was applied to the survivorship figures s'_x at the beginning of each year, and the corrected numbers of survivors will be denoted by s_x.

The numbers of children notified and reported as having whooping cough in each year 1921 to 1930 in Battersea, shown in Table I, were divided up into age groups on the basis of the ascertained attack rates at each age in 1925–9. The deaths from whooping cough were obtained from registration figures. Let w_x be the number of children having whooping cough recorded, and d_x the number dying from it in a given year at ages x to $x+1$, and let P_x be the probability of escaping death from *causes other* than whooping cough between ages x and $x+1$, deduced from the mortality during the year corrected for the emigration factor. To simplify the calculation it is assumed that throughout the year of attack a child surviving an attack is subject to the same risk of dying from other causes than whooping cough as any other child, and in subsequent years such children are subject to the same rate of reduction by death and emigration as the whole population of children of the same age. As regards emigration there seems no reason to suppose any important selection as regards previous whooping cough history, though if there had been an excess of inward migration from the country this could not have been assumed. As regards risk of death the above assumptions may slightly exaggerate the risk to whooping cough survivors in the year of attack and may underestimate it in the year following, but the net result may be regarded as near enough to the truth. The total survivors s_1 left in the borough at age 1 exactly on January 1st, 1922, include $P_0(w_0 - d_0)$ survivors of whooping cough attacks during 1921; the total survivors s_2 at age 2 exactly on January 1st, 1923, include $P_1(w_1 - d_1)$ survivors of whooping cough attacks during the year 1922 and

$$\frac{s_2}{s_1} P_0 (w_0 - d_0)$$

survivors of whooping cough attacks during 1921. In this way the children can be followed through till they reach age 10, that is to say such proportion of them as remain in the borough. It follows that the fraction of all survivors s_1 aged 1 exactly who had had whooping cough recorded since birth, at the beginning of 1922, would be $P_0(w_0 - d_0)/s_1$ and the fraction of all survivors s_2 aged 2 exactly at the beginning of 1923 would be

$$\frac{1}{s_2}\left\{P_1(w_1 - d_1) + \frac{s_2}{s_1} P_0 (w_0 - d_0)\right\} = \frac{P_0(w_0 - d_0)}{s_1} + \frac{P_1(w_1 - d_1)}{s_2}$$

and so on.

[1] Thus the population at ages 2–3 at mid-1924 was first estimated to be 3275; at mid-1931 these children would be aged $9\frac{1}{2}$ and the census discrepancy at ages 9–10 was 564; hence the correction to be deducted from 3275 at $2\frac{1}{2}$ years from birth would be half of 564, or 282 since the migratory loss was assumed to be distributed evenly over the first 5 years of life.

At the middle of 1922 the fraction of the population aged 1–2 who had had whooping cough since birth is, to a close enough approximation, given by the mean of the fractions at age 1 at the beginning of the year and at age 2 at the end of the year, namely

$$\frac{P_0(w_0-d_0)}{s_1}+\tfrac{1}{2}\frac{P_1(w_1-d_1)}{s_2},$$

which is the arithmetical mean of the above expressions.

The values of the successive fractions of all survivors aged exactly x who had been attacked *in the preceding year*, that is of $P_{x-1}(w_{x-1}-d_{x-1})/s_x$, were first tabulated for the beginning of each year, and are shown in the middle portion of Table V, the values below the zig-zag line not being necessary for the present calculation. In the lower part of the table the cumulative fractions representing the proportions of the populations aged x to $x+1$ at the middle of each year who had been attacked *since birth* are shown, these being calculated by simply summing in a diagonal direction the fractions in the table above as far as age x at the beginning of the year in question, and adding in half the fraction for age $x+1$ at the end of the year in question, in accordance with the above formula. As an example, the cumulative fraction of the population aged 3–4 at mid-1925 having had whooping cough since birth is

$$0{\cdot}01499+0{\cdot}04301+0{\cdot}03604+\tfrac{1}{2}(0{\cdot}06660)=0{\cdot}12734.$$

Table VI.

	Percentage of children having had an attack recorded since birth				Percentage susceptible after correcting for incomplete notification (see Table X)							
					40 % born immune				None born immune			
Ages...	0–2	2–5	5–7	0–7	0–2	2–5	5–7	0–7	0–2	2–5	5–7	0–7
June, 1925 End of winter epidemic	3·7	12·9	—	—	53·9	39·4	—	—	93·9	79·4	—	—
June, 1926 Start of summer epidemic	4·4	15·5	—	—	52·3	35·2	—	—	92·3	75·2	—	—
June, 1927 End of winter epidemic	3·6	15·7	25·0	14·0	54·1	34·9	21·5	37·6	94·1	74·9	61·5	77·6
June, 1928 Start of summer epidemic	3·8	15·8	29·6	16·1	53·7	34·7	14·4	34·2	93·7	74·7	54·4	74·2
June, 1929 End of winter epidemic	4·8	17·1	32·7	18·0	52·1	32·6	9·6	31·2	92·1	72·6	49·6	71·2
June, 1930 No epidemic	3·3	17·5	33·5	17·6	54·6	32·0	8·4	31·8	94·6	72·0	48·4	71·8

Combining several ages and expressing the proportions of children known to have had whooping cough as percentages, the changes in these proportions in relation to the occurrence of epidemics are shown in Table VI.

The first portion of the table shows the percentages of children who must have had an attack recorded since birth. If the recording were complete and every child were exposed to the risk of infection and susceptible until immunised by an attack, the difference between these figures and 100 would represent the percentages of the population at the stated ages who were at risk to attack at the middle of each year. These points of time conveniently mark the end of the winter epidemics in 1925, 1927 and 1929, and the beginning of "epidemic years," containing a summer followed by a winter epidemic, in 1926 and 1928. In 1930 no epidemic followed.

Comparing the proportions susceptible at the end of the 1924–5 epidemic with those a year later when a fresh epidemic started, it is seen that at all ages under 5 there were actually smaller percentages of susceptibles in the population when an epidemic was starting than when it was ending, and at the same time of the year. The same is true at ages under 7 when the state of affairs at the end of the 1926–7 epidemic is compared with that a year later when an epidemic was again starting. The large epidemic in 1928–9 only reduced the percentages unattacked according to the records at ages under 7 from 84 to 82. The anomalous fact that the percentages "susceptible" according to this definition did not increase during the interepidemic intervals is accounted for by the effect of the falling birth rate. If the assumption that notification is complete is taken as correct for the moment, this analysis definitely disproves the theory that epidemics of whooping cough (1) are brought to an end by the exhaustion or reduction of children who have not previously had whooping cough, and (2) start again when the supply of such children has been replenished by fresh births and the season of year is favourable.

It is shown in Table VII (p. 598) that by the time the tenth year of life is completed 42·3 per cent. of children born in Battersea have had a reported attack, and the distribution of reported cases according to age[1] suggests that only one case occurs after the tenth year to every 50 during the first ten years, so that 43 per cent. of all children born are destined to have an attack of whooping cough reported at some time during life. Second attacks sometimes occur, but not with sufficient frequency to require any correction to the statistics. It will also be shown in Section V that the recorded cases in Battersea probably represent 70 per cent. of the true incidence in the age-group 0–10, and that therefore about three-fifths of all children born may be presumed to suffer an attack at some time during life, and the remaining two-fifths to escape attack. We have no certain evidence that this fraction who escape are really at risk to attack, for some of them may be born with a permanent immunity to it and others may never come in contact with infection, though in an urban population the probability of the latter event must surely be small.

On the supposition that the extreme limit of two-fifths of children born are never at risk for these reasons, the proportions of the population of children who were susceptible at the given times must have been as shown in the second part of Table VI. An examination of these percentages leads to the same conclusion as before. On the other extreme supposition that all of this fraction of two-fifths of children born who escape are nevertheless at risk to attack, the percentages susceptible would be as given in the last portion of Table VI. The conclusion is still the same, that changes in the proportions of children of given ages who have not had whooping cough cannot be important in determining

[1] Out of 15,283 recorded cases in the four boroughs, 225 were aged 10–14, and 114 aged 15 and over. The age and sex distribution is discussed in another paper.

the periodicity or cessation of epidemics in London. During the period studied the annual numbers of births were continually falling. Had this not been so there would have been a slight increase in the proportions of children not previously attacked occurring during the interepidemic periods, and it would not have been possible to prove so conclusively that this factor is not of sufficient importance to determine the periodicity.

The behaviour of the epidemics in neighbouring districts has been shown to be unfavourable to the view that a "cycle of activity" of the organism is the main cause, and the changing susceptibility of contacts after exposure, as compared with other children, demonstrated in Section VII, also cannot be explained on this theory. It is therefore necessary to seek for some other hypothesis.

Before proceding to this, the data in the lower part of Table V can be used to ascertain the rate at which children are attacked by whooping cough with advancing age. In Table VII are shown the mean percentages of survivors to each age x who had been recorded as having whooping cough during the *preceding* year of age, these being obtained by taking the means of the corresponding ratios at the end of each year 1925 to 1929 as given in the last column of the middle portion of Table V and multiplying by 100. In the next column of Table VII are shown the cumulative percentages attacked *before age* x, obtained by summing the preceding column from the top. This represents the rate at which children in Battersea would have been attacked by whooping cough if subjected to attack rates at each age equal to the mean of those in the quinquennium 1925–9 according to the records. For comparison, in the next column are given the cumulative rates of attack found by Collins (1929) from individual enquiry at successive ages in a composite population from Hagerstown and other towns in the U.S.A.[1] It will be seen that the Battersea figures at each age are approximately two-thirds of the American figures (see also Section V, p. 598). The curves are shown in Fig. 4.

By the tenth birthday 42·3 per cent. of children in Battersea have been recorded as having whooping cough. In the whole population under 10 the percentage who would have been recorded as having had whooping cough, assuming a steady incidence, can be obtained by summing the products[2] of the cumulative percentages at each age with the mean numbers of survivors in 1925 to 1929 at the corresponding ages according to column B in Table V and dividing by the total survivors[2] at ages 0 to 10, which gives 25·051 per cent. as the average proportion having had whooping cough at any given time, according to the records.

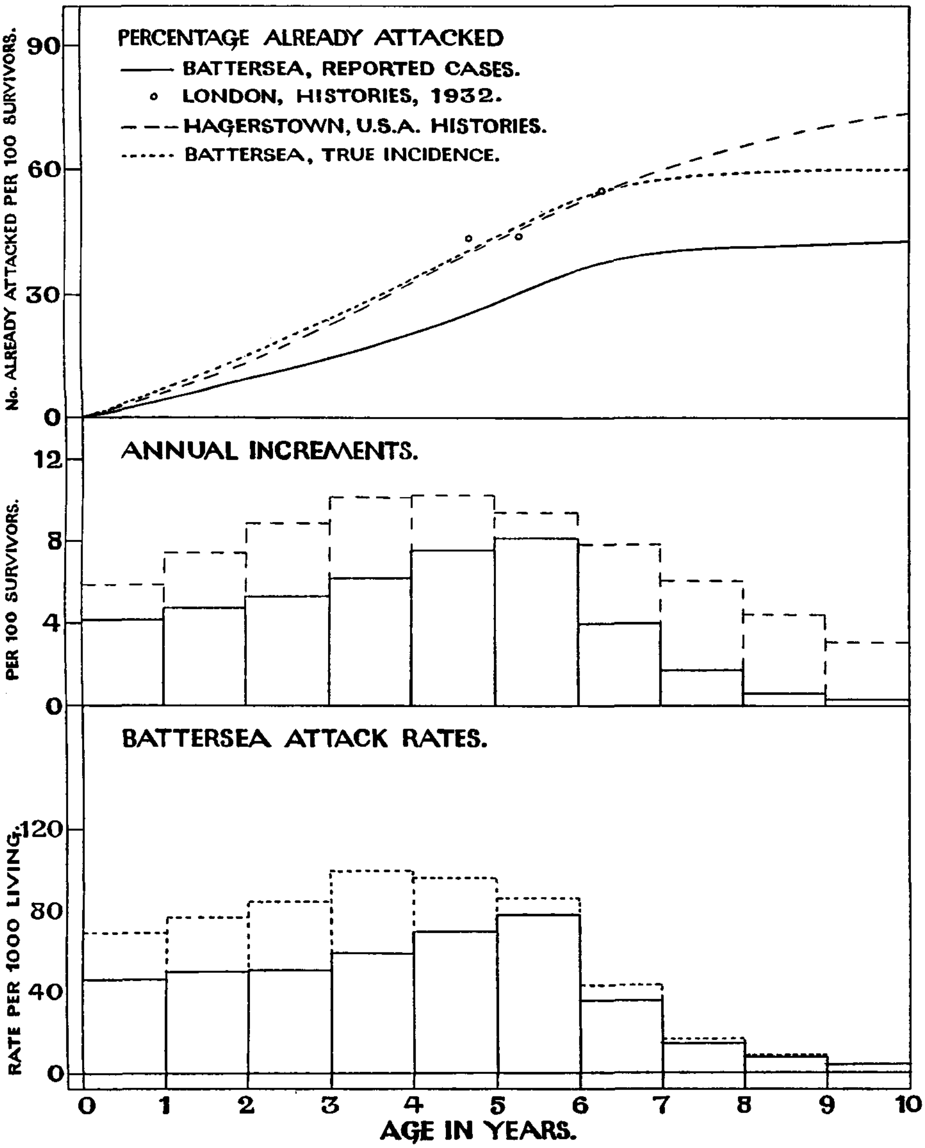
The effect of the falling birth rate is to lower slightly the proportions attacked, for it is seen by reference to the lower portion of Table V that in the year following the 1928–9 epidemic 23·3 per cent. of children under 10 had been recorded as attacked since birth instead of 25 per cent. on the basis of the

[1] Smoothed by fitting a catalytic curve $y=77\ (1-e^{-0\cdot 04385-0\cdot 01334x-0\cdot 02703x^2})$ where x = age in years.

[2] Half the products at 0 and at 10, and half the survivors at 0 and at 10, are added to the sum of the figures at ages 1 to 9 in computing these totals.

same attack rates with a stationary birth rate. It may also be noted that in 1930 only 31·4 per cent. of the 9-year-olds had been attacked, whereas 38·3 per cent. of the 7-year-olds must have been attacked, this being due no doubt to

Fig. 4. INCIDENCE OF WHOOPING COUGH WITH AGE.



the effect of the sudden wave of high birth rate in 1920–1. The upper part of Table V shows that there were great changes going on in the age distribution during the decade produced by the birth rate fluctuations since 1916. The effect on the populations, incidence of whooping cough by ages, and attack rates, in two years 1925 and 1929, is indicated by the comparison in Table VIII.

Table VII.

Exact age x in years	Mean percentage of survivors who have had whooping cough, according to records, during *preceding* year of age $x-1$ to x	Cumulative percentages who have had an attack, according to records, at some time *since birth*	Cumulative percentages in Hagerstown, U.S.A. according to individual histories (Collins)
0	0	0	0
1	4·1050	4·1050	5·85*
2	4·7124	8·8170	13·24
3	5·2812	14·0986	22·04
4	6·1702	20·2688	32·11
5	7·4794	27·7482	42·27
6	8·0304	35·7786	51·55
7	3·9270	39·7056	59·32
8	1·5958	41·3014	65·37
9	0·6398	41·9412	69·75
10	0·3766	42·3178	72·72

* This figure not reliable.

Table VIII.

		Ages 0–	1–	2–	3–	4–	5–	6–	7–	8–	9–
Per mille distribution of population under 10 years old	1925 1929 1920–2†	217 193 211		215 194 200		224 180 198		141 202 196		203 231 195	
Per mille distribution of whooping cough cases under 10	1925 1929	209 220		274 262		414 335		88 151		15 32	
Attack rates per 1000 living at each age	1925 1929 Mean 1925–9	42·1 39·1 41·93	46·2 52·6 46·48	49·9 54·4 51·14	66·4 54·0 59·26	83·1 61·2 70·03	85·2 88·5 77·50	41·0 43·1 39·32	15·9 18·8 15·78	5·1 6·7 6·16	1·7 4·3 3·10

† Life table population for London.

V. Completeness of notification and reporting.

In order to study with greater certainty what changes occur in the state of immunity of the child population during epidemics and in the intervals between them it is necessary to estimate how completely the record of incidence obtained by the Public Health Departments represents the real incidence of clinically recognisable whooping cough. Enquiries from boys entering Rugby School (1932) showed that out of 437 boys, about 75 per cent. were said to have had whooping cough before about the twelfth year. This figure agrees closely with the proportions of children who were stated to have had whooping cough by that age in various localities in New York State, where enquiry was made by house-to-house visitation. These cumulative rates obtained by Collins are shown in the last column of Table VII, and similar rates were found in Cattaraugus County, also in New York State, by Sydenstricker (1928). An enquiry amongst freshmen of the University of Wisconsin gave a rather lower rate of about 63 per cent. as having had whooping cough, according to Fales (1928).

Comparing these estimates, obtained from family histories, with the computed rate of 42 per cent. who have the disease by the end of elementary school life in Battersea, according to the Public Health records, it is evident that either a larger proportion of children in a crowded area of London escapes a clinically recognisable attack or else only about two-thirds of the actual incidence is reported.

At ages between 5 and 10 almost all the children in Battersea attend public elementary schools; in 1931 the estimated percentages on the registers based upon the census population were respectively 97·7, 98·5, 99·1, 96·2 and 97·5 at ages 5, 6, 7, 8, 9. Large numbers of children also attend these schools at age 4, and some at 3. Since the cause of every absence from school is reported to the head teacher or investigated by the school attendance officers and, if due to recognised whooping cough, is reported to the Borough Health Department, it follows that between ages 5 and 10 the combined systems of notification by doctors, parents and schools, and ascertainment by attendance officers, health visitors and nurses, must result in an almost complete record of recognised cases, and it is safe to assume that at ages 5 to 10 at least 90 per cent. of the real incidence of recognised whooping cough is recorded.

In families where it occurs in children under school age, and where there are no children attending elementary schools, it is possible that the reporting of cases may be much less complete. If this is the case we should expect to find an exaggerated rise, or a rise where there should really be a fall, in the curve representing rates of incidence in passing from the 3-year-old to the 5-year-old group. The graph of mean annual recorded incidence per 1000 living at each age in Battersea during 1925–9 is shown in the lower part of Fig. 4, the rates being given in Table VIII. There is a gradual rise to age 5 and a sharp fall from 5 to 6, and although there is no obvious discontinuity between 3 and 5, the form of the curve is unusual and suggests the flattening of a curve which would naturally be rounded. The maximum apparently occurs at 5–6, whereas the urban rates obtained in New York State by house-to-house enquiry, mentioned above, show the maximum at 3–5, the rates at these ages being about 8 per cent. higher than at 5–6 and 30 per cent. higher than at 6–7. If the true maximum occurs at 3–5 in London also, and the early parts of the curves are similar, then the recorded rates at 2, 3 and 4 must be a good deal too low. Thus, comparing the annual increments of the two curves drawn in the upper part of Fig. 4, the ratios of the Battersea increments to the corresponding increments in the Hagerstown smoothed curve derived from Table VII are as follows:

Age	0– 1–	2–	3–	4–	5–	6–	7–	8–	9–
Ratio	0·67	0·60	0·61	0·74	0·87	0·51	0·26	0·15	0·13

The ratio falls off from the sixth to the tenth year, and this more rapidly diminishing liability to whooping cough in London after the sixth year cannot be due to peculiarities of notification, but must denote a real difference, due no doubt to the denser population. The depressed ratios at ages up to 4 in

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comparison with that at 5 suggest that reporting at these pre-school ages before school supervision has begun is less complete than at age 5.

During the summer term of 1932 a special enquiry was carried out in the course of the medical inspection of entrants to London County Council schools by the Medical Officers concerned in order to determine what proportion of children were known by their parents to have ever suffered from whooping cough. We are greatly indebted to Dr C. J. Thomas for kindly suggesting and organising this enquiry, and also to the School Medical Officers who questioned the parents and made the necessary returns.

The statistics relate to all children aged 3, 4, 5, 6, or 7, one of whose parents was present at the medical inspection, and the children were classified into three groups, namely those known by the parents to have had whooping cough, those known not to have had it, and those for whom there was a doubt. The totals for London County are given in Table IX[1].

Table IX.

Age last birthday	Total children whose parents were questioned	No. of these uncertain	Total with known history	No. of these having had whooping cough	Whooping cough in age group %	Presumed at age 5 exactly %
3	843	12	831	306	36·823	
4	1759	47	1712	744	43·458	43·764
5	2214	72	2142	944	44·071	
6	614	31	583	315	54·031	
7	49	3	46	26	56·522	

It cannot be assumed that the mean ages of these groups were 3·5, 4·5, etc., but the form of the distribution of ages at admission is such that the mean ages of the 4 and 5 groups may be taken as equidistant from 5 exactly, being probably about 4·7 and 5·3 respectively, and the mean of the percentages for the 4- and 5-year-old groups must represent to a close approximation the percentages who have had whooping cough before age 5 exactly. This figure 43·764 must therefore be compared with 27·748, the percentage actually reported to the Public Health Authority as having had whooping cough by their fifth birthday in Battersea according to the calculation in Table VII[2], and it is evident that during the first 5 years of life only about 63 per cent. of the complete incidence is notified or reported.

During the school ages 5–10, for reasons already given, it is safe to assume that 90 per cent. of the true incidence is reported, and the true incidence curve from 5 to 10 can be constructed by starting from the ascertained figure 43·764 at age 5 exactly and adding on the successive increments for subsequent

[1] Entrants examined from April 26th to June 30th. A more complete analysis of the results of this enquiry will be given in another paper.

[2] In Battersea schools the entrants enquiry showed $38{\cdot}2 \pm 4{\cdot}0$ per cent. at 4 and $45{\cdot}7 \pm 3{\cdot}3$ per cent. at 5, so that the mean of these does not differ significantly from that for London as a whole, which is based on much larger numbers.

years from Table VII, each corrected by the factor $\frac{10}{9}$, giving the following result:

Age x	5	6	7	8	9	10
Percentage recorded attacked up to age x exactly	27·748	35·779	39·706	41·301	41·941	42·318
True percentage attacked	43·764	52·687	57·050	58·823	59·534	59·952

The ratio of the estimated true cumulative incidence to the notified and reported cumulative incidence up to age 10 is thus given by

$$p = 59{\cdot}952/42{\cdot}318 = 1{\cdot}417,$$

and this is the factor by which attack rates based on the whole population under 10 must be multiplied in order to obtain estimates of the real attack rates.

In order to complete the curves shown in Fig. 4 during the first 5 years of life, it must be remembered that in the year of age 4–5 a more complete record of incidence is to be expected than in the four preceding years, since a considerable proportion of the 4-year-olds were at school. At each year of age before 4 it may be assumed that the true incidence bears a constant ratio, p_0, to the recorded incidence; at ages 5 to 10 the ratio is assumed to be 10/9, and at age 4 its value, p_4, is intermediate between p_0 and 10/9. From Table VII it follows that $20{\cdot}269\, p_0 + 7{\cdot}479\, p_4 = 43{\cdot}764$, the percentage found above from the histories at age 5 exactly, and since p_4 lies between p_0 and 10/9, p_0 must lie between 1·577 and 1·749. By trying different values of p_0 it is found that the successive increments give a reasonably smooth curve when $p_0 = 1{\cdot}65$ and $p_4 = 1{\cdot}38$, the values of the increments being then as follows:

Age x to $x+1$	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Increment ($p_0 = 1{\cdot}65$)	6·773	7·776	8·714	10·181	10·320	8·923	4·383	1·773	0·711	0·418

In Table X are shown, as deduced from the above calculation, the most probable ratios of real to reported incidence at each age; the cumulative percentages of children attacked up to each age, obtained by adding up the

Table X.

Age x	Ratio of true to recorded incidence at x to $x+1$	Probable % of children already attacked by age x exactly	Corrected attack rate per 1000 living at age x to $x+1$
0	1·650	0	69·18
1	1·650	6·773	76·69
2	1·650	14·549	84·38
3	1·650	23·263	97·78
4	1·380	33·444	96·64
5	1·111	43·764	86·11
6	1·111	52·687	43·69
7	1·111	57·050	17·53
8	1·111	58·823	6·84
9	1·111	59·534	3·44
10	1·111	59·952	—

above increments; and the corrected attack rates for each age interval in Battersea, obtained by multiplying the attack rates in Table VIII by the appropriate ratios.

Fig. 4 shows the probable true curve of cumulative incidence with advancing age for comparison with the curve deduced from American data, and at the foot of the diagram the probable true attack rates for comparison with the recorded attack rates. It is now seen that the ages of maximal attack rate are 3–5, and that children tend to be attacked at almost the same rate up to age 6 in London as in the American towns investigated. Comparing Table X with Table VII it is seen that by the fourth birthday about 33 per cent. of London children have been attacked and 32 per cent. in the American data; at the sixth birthday the proportions are 53 and 52 respectively, but at subsequent ages more of the London children apparently escape, either by virtue of greater inherent immunity or perhaps, as seen later, by successive temporary latent immunisations.

It is possible from the corrected cumulative percentages in Table X to calculate the percentage of the whole population of children under 10 who had *actually* had whooping cough at a given time, by using the same method as in Section IV[1]. The resulting figure is 37·360 per cent., which may be compared with the fraction who had been *recorded* as having whooping cough at some time, 25·051 per cent. The fraction 0·3736, roughly three-eighths, of the whole population under 10, having previously had whooping cough, is used in Section VIII, where it is denoted by the symbol k.

VI. Changes in infectiousness during epidemics.

In a previous paper on measles (1928) an "index of apparent infectiousness" was defined, which could be conveniently measured during any period of time by finding the ratio to the total cases of an infectious disease which occur in that period of the number of secondary cases which follow in the same houses and after a specified interval of days from onset to onset. For measles the specified interval chosen was 10 to 13 days inclusive between the dates of appearance of the rash in two cases reported in the same house. For whooping cough I have given elsewhere (1930) reasons for choosing intervals of 4 to 28 days inclusive for the calculation of the apparent infectiousness, and it is perhaps better to limit the secondary cases to children under 15, though the effect of this is statistically unimportant.

Thus if N = number of persons commencing with whooping cough during a given period of time δt,

S = number of children under 15 developing whooping cough in the same houses as the N cases and having the onset of attack from 4 to 28 days later,

then $100S/N$ = apparent infectiousness during the period δt.

In order to convert this to an index which is independent of the conditions of overcrowding or average size of family in a particular locality, it may be expressed, if desired, in terms of the mean apparent infectiousness in the same

[1] *I.e.* summing the products of the cumulative percentages, and the mean number of survivors in Column B of Table V, at each age and dividing by the total survivors at 0–10.

locality during interepidemic periods of steady incidence, and called the index of apparent infectiousness. This, however, has not been necessary in the present paper.

In Fig. 2 (p. 587) the changes in apparent infectiousness in Battersea as a whole are shown in relation to the epidemic periodicity, and in Fig. 3 they are shown for each of the six districts of the borough separately. The data, N and S, are set out in Table IV.

A study of Fig. 2 indicates that each epidemic period was preceded by a rise of apparent infectiousness to about 20, and during the epidemics this fell gradually, reaching the low level of 4·5 at the end of the 1926–7 epidemic and 3·2 at the end of the 1928–9 epidemic. From these low levels there was a gradual rise in infectiousness during the year following each epidemic. In a similar analysis of Wandsworth records which only covered 3 years (1930), an increase of infectiousness at the start of epidemics was shown, but the important fact that there was also a gradually increasing infectiousness during the year following the cessation of an epidemic was not perceived owing to the shortness of the period and large extent of the area dealt with. An increase of apparent infectiousness may be caused by either (1) an actual increase in the true infectiousness or "facility of transmission" from case to case, or (2) an increase in the proportion of home contacts who have a certain measure of susceptibility to attack at the time. Evidence has been found in the study of measles epidemics (1928, 1930) for the belief that the sudden increases in apparent infectiousness at the start of epidemics are due to an upsetting of the balance between immunity and infection pressure associated with an increased facility of transmission. The latter may depend upon many factors such as changes in activity of the infecting agent or changed habits of life which are influenced by seasonal changes. Gradual changes, up or down, in apparent infectiousness are more probably due, on the other hand, to changes in the specific immunity, active and latent, of the population at risk, which is probably not influenced by season.

The same may be true for whooping cough. The gradual reduction in apparent infectiousness from about 20 to about 5 during epidemics cannot, however, be accounted for by reduction in the proportion of contacts who have never had whooping cough (see Section IV, p. 595), but can be readily explained if latent immunisation of children accompanies the visible epidemic. The gradual rise of infectiousness, which immediately sets in again at the end of the epidemic and continues during the year following, also cannot be accounted for by the increase in children not having had an attack, but suggests very strongly the rapid loss of the latent immunity gained by the population during the epidemic.

In Fig. 3 the changes in apparent infectiousness are shown in each of the six districts of Battersea separately. At the start of each epidemic it rose to 20 or 30 or over. The maxima attained were greater in Wards 1, 2, 5 and 6 than in Wards 3 and 9, and this is what might be expected from the average numbers of persons per dwelling in those wards at the census of 1921, as shown below:

Ward no.	5, 6	1	2	3	4, 7, 8	9
Persons per dwelling, 1921	6·8	6·6	6·3	5·9	5·7	4·9
Maximal apparent infectiousness in epidemics	28·6	33·3	32·7	22·6	29·7	21·0

In comparing one district with another the ratios are partly dependent on the mean number of children living per house, since the ratios have not been standardised by converting to indices.

A study of Fig. 3 shows that although a summer epidemic alone did not necessarily bring down the apparent infectiousness below about 10, as seen in Ward 1 in 1925 and Wards 4, 7 and 8 in 1925 and 1926, yet when a summer epidemic was followed by a winter epidemic or a winter epidemic occurred alone the level was usually brought to a low value of about 5. This is seen in all districts in 1929, in all except Wards 2, 5, and 6 in 1927, and in Wards 5 and 6 in 1925. When for some reason there was a sudden rise of infectiousness in May 1927 at the end of a winter epidemic in Wards 5 and 6, no epidemic resulted, but a similar rise in May 1926 in Ward 3, where incidence had been low for a year, was followed by a large epidemic. During the year following a winter epidemic the tendency for apparent infectiousness to rise slowly is best seen during 1930 and 1926, but in some of the districts the numbers of cases occurring in the interepidemic periods are too small to show any but random changes in the ratio.

In Table XI a combined analysis has been made of the interepidemic periods in order to demonstrate conclusively that this rise occurs and to measure its rate. Starting from the end of the epidemic in each district, not necessarily occurring in the same month, the total cases of whooping cough having their onset in each month (N), and the number of "secondary" cases following in the same houses after intervals of 4 to 28 days (S) have been tabulated, the latter figures for the separate districts being shown in brackets. This has been done in the three periods, (i) of 9 months from summer of 1925 to spring of 1926, (ii) of 15 months from spring of 1927 to summer of 1928, (iii) of 15 months from spring of 1929 to summer of 1930. The first period is shorter in order to avoid including small outbreaks in the summer of 1926, and for the same reason Districts 4, 7 and 8 have been omitted entirely from the first period and Districts 5 and 6 from the second, since they do not show a sufficient number of months free from epidemic disturbances. Adding together the totals for each 3-months period after the end of an epidemic, the apparent infectiousness is found to have the successive values 5·80, 9·92, 11·49, 12·98, 11·67, that is to say it rises rapidly during the 6 months following an epidemic and then more slowly, to attain a steady value of about 12 after 6 or 8 months have elapsed.

If this is due to the loss of a transient latent immunity in the population who have been exposed to infection but escaped a recognised attack, the average duration of this immunity can be estimated by adding to the time scale in Table XI, measured from the *end* of an epidemic, the mean duration of

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Table XI.

District	Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		No. of months after the month in which epidemic ended														
Ward 1	June 1925–Mar. 1926	30 (4)	7 (1)	5 (1)	—	4 (1)	1	6 (1)	5	7 (2)	3	—	—	—	—	—
,, 2	July 1925–Apr. 1926	4	3	2	—	2	—	2	4	5 (2)	7 (1)	—	—	—	—	—
,, 3	July 1925–Apr. 1926	5 (1)	2	—	1	12 (1)	—	1	2	—	4	—	—	—	—	—
Wards 5, 6	Sept. 1925–June 1926	4	1	3	4	5	6 (1)	5 (2)	9	2	8 (2)	—	—	—	—	—
Ward 9	June 1925–Mar. 1926	9	8 (1)	7	1	1	—	1	—	5	2 (3)	—	—	—	—	—
	Total incidence N	52	21	17	6	24	7	15	20	19	24	—	—	—	—	—
	Secondary cases, S	5	2	1	—	2	1	3	—	4	6	—	—	—	—	—
Ward 1	Apr. 1927–June 1928	11	15	4	10	6	1	1	—	2	4	14 (5)	9	6 (3)	5 (1)	19 (1)
,, 2	June 1927–Aug. 1928	3	1 (1)	4 (1)	2	3	1	8 (3)	3	7 (3)	14 (2)	1	1	15 (3)	15	22 (2)
,, 3	June 1927–Aug. 1928	2	5	2	—	7 (1)	6	4	9 (2)	10 (3)	6 (1)	—	4	11	7	23 (3)
Wards 4, 7, 8	May 1927–July 1928	23 (2)	10	4	6	3	1	1	1	3	13 (2)	21 (4)	5	17 (1)	21 (5)	22 (4)
Ward 9	May 1927–July 1928	—	—	—	1	1	—	—	2	4	11	2	—	1	2	1
	Total incidence N	39	31	14	19	20	9	14	15	26	48	38	19	50	50	87
	Secondary cases, S	2	1	1	—	1	—	3	2	6	5	9	—	7	6	10
Ward 1	Apr. 1929–June 1930	10	10	1	4	3	1	5	2 (1)	12 (2)	4	4	4	3	4	9 (2)
,, 2	May 1929–July 1930	4	2	—	2 (1)	2	7 (5)	15 (1)	10	8	14 (3)	2	3	6 (1)	6	4
,, 3	May 1929–July 1930	6	2	5	—	—	1	4	4	3	5	5	7 (1)	3	15 (2)	10
Wards 5, 6	June 1929–Feb. 1930	12	5	4	3	9	7 (1)	9 (1)	7	13 (2)	15	23 (4)	13 (4)	9	9 (3)	16 (3)
,, 4, 7, 8	May 1929–July 1930	21 (1)	11	9 (3)	4 (1)	1 (1)	1	4	8	7	6	4	12 (1)	21 (2)	20 (1)	21 (4)
Ward 9	Apr. 1929–June 1930	10	6 (1)	1	1	—	—	2	2	11 (2)	9	1	2 (1)	2	7 (1)	25 (2)
	Total incidence, N	63	36	20	14	15	17	39	33	54	53	39	41	44	61	85
	Secondary cases, S	1	1	3	2	1	6	2	1	6	3	4	7	3	7	11
All above combined	Total incidence, N	154	88	51	39	59	33	68	68	99	125	77	60	94	111	172
	Total secondary, S	8	4	5	2	4	7	8	3	16	14	13	7	10	13	21
	Apparent infectiousness 100 S/N		5·80			9·92			11·49			12·98			11·67	

Note. The figures in brackets represent the secondary cases to the N cases, which are unbracketed.

such immunity from the moment of its establishment to the end of the epidemic. This addition must be approximately equal to half the mean duration of the epidemics, or about $4\frac{1}{2}$ months. Hence the beginning of month no. 2 in Table XI may be taken as equivalent to 6 months since exposure to infection on the average, and the apparent infectiousness can be calculated in periods of 3 months starting from this point, with the result in Table XII.

Table XII.

Mean interval since exposure to infection in epidemic (months)	Apparent infectiousness			
	N	S	$100S/N$	
6–9	178	11	6·14	8·87
9–12	160	19	11·87	
12–15	292	33	11·30	12·03
15–20	514	64	12·45	

This suggests that the loss of acquired latent immunity—if such is the explanation—is more rapid than in measles, and that little or none remains after a year. More complete confirmatory evidence that such a temporary latent immunisation occurs, and accounts for many of the epidemic phenomena of whooping cough, will be found in the next section.

VII. Evidence for transient latent immunisation of contacts.

The after histories of home contacts to whooping cough were studied by three independent methods, using data from the boroughs of Holborn, Greenwich and Battersea respectively.

(*a*) *Holborn data.* In a previous paper (1930) the subsequent behaviour of 721 children under 10 years of age, who were home contacts to whooping cough in Holborn during 1921–8 and who had not previously been attacked, was analysed and the conclusion was "that, after the immediate risk of infection had subsided, the contacts were subject during the first and second year to almost exactly the expected rates," and that there was therefore no evidence of any acquired protection through exposure. In Table II of that paper the actual figures up to 2 years after exposure to infection were set out as in Table XIII

Table XIII.

Time after exposure	Expected no. of attacks	Actual no. of attacks	Ratio of actual to expected
4–28 days	1·88	153	81·4
1–2 months	1·94	34	17·5
2–3 ,,	1·94	2	0·93
3–6 ,,	5·82	7	
6–12 ,,	8·86	6	
1–$1\frac{1}{2}$ years	7·75	7	0·96
$1\frac{1}{2}$–2 ,,	5·80	6	

below. It may be noted, however, that during the period 2 to 6 months the ratio was 1·16, and during the period 6 to 12 months it was only 0·68. The actual numbers of cases were too small to base any conclusions upon the low ratio at 6 to 12 months, but in view of confirmatory findings from data which have since been examined it is justifiable now to point out, what could not then be perceived, that these figures are quite compatible with a latent immunisation of a very transient kind, not lasting more than a year. Owing to the long duration of, and occurrence of relapses in, some cases of whooping cough, it is not safe to assume that the danger of contracting the disease is past until 6 months have elapsed from the onset of the primary case, and therefore the higher ratio 1·16 for the period 2 to 6 months may easily be explained by late infection in a few cases.

This preliminary investigation demonstrated that there could not be any latent immunisation of contacts of a lasting character, and this is supported by the further evidence to follow. My tentative conclusion that it seemed to rule out latent immunisation altogether proves from further investigation to have been too sweeping. If the danger of direct infection cannot be excluded until 6 months have elapsed, and latent immunity does not last more than 1 year, the only period during which evidence for it can be sought by statistical methods amongst home contacts is the short period from 6 to 12 months after the primary case. The combined evidence from Holborn, Greenwich and Battersea, worked out by quite different methods of approach, seems sufficient to demonstrate satisfactorily that during this period there is in fact a lowered susceptibility to attack below that of other children in the same borough and at the same time.

(*b*) *Greenwich data*. The records were analysed as follows. The sex, age, address and date of onset of each of the 4102 cases of whooping cough notified or reported between June 23rd, 1919, and April 25th, 1929, were entered on cards, all cases occurring in one house being entered on a single card. The annual incidence of these cases in 1919, 1920, 1929 and in each half-year from 1921 to 1928 is shown in Table XIV and the monthly incidence is represented in Fig. 1.

The figures in Table XIV represent the numbers of cases, corrected for duplication, whose *onset* was within the period stated, and they do not therefore agree precisely with the totals reported within each year as given in Table I.

Table XIV.

1919	1920	1921		1922		1923		1924	
June 23–Dec.	Jan.–Dec.	Jan.–June	July–Dec.	Jan.–June	July–Dec.	Jan.–June	July–Dec.	Jan.–June	July–Dec.
101	352	145	161	185	175	224	79	158	354

1925		1926		1927		1928		1929	
Jan.–June	July–Dec.	Jan.–June	July–Dec.	Jan.–June	July–Dec.	Jan.–June	July–Dec.	Jan.–April	Total
521	70	32	140	366	49	178	431	381	4102

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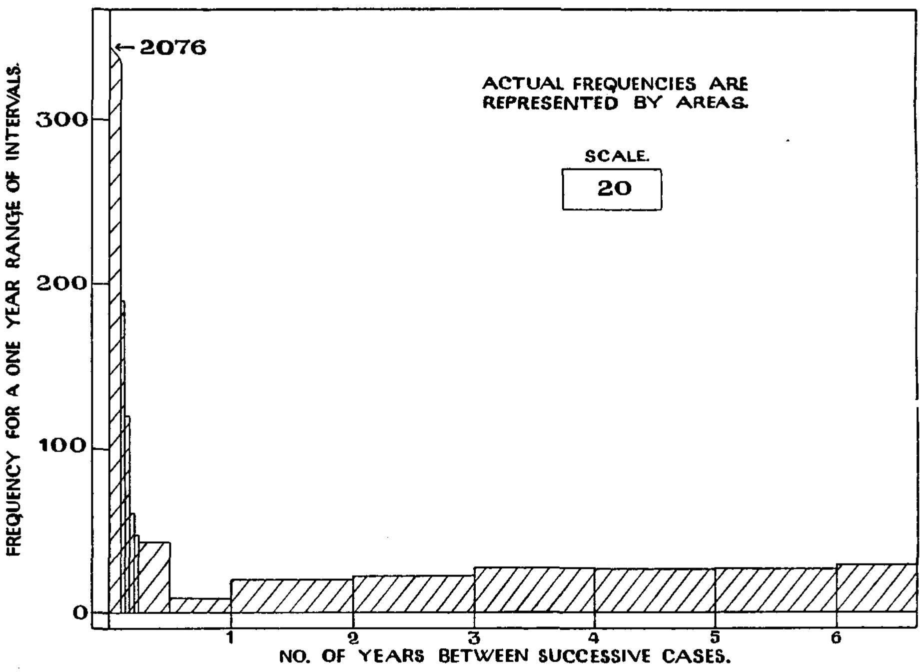
The method here employed is to start from the fact that all these 4102 cases, whether first, second or later cases in houses, were liable to infect others, or to be followed by another case arising *de novo*, in the same house or some other house in the same street after some interval ranging from one day to 9 years. In some houses there would be no other persons liable to whooping cough, but this does not affect the statistical argument. Out of every 1000 cases following which the history of the house in respect of whooping-cough cases was known from the records over the necessary interval of time after onset, the numbers N_t which were followed by another case after interval t from onset to onset are

Fig. 5. CORRECTED FREQUENCY OF INTERVALS BETWEEN SUCCESSIVE CASES OF WHOOPING COUGH IN SAME HOUSE IN GREENWICH. 1919—1929.



shown in the second column of Table XV for different groups of intervals. In the third column these frequencies are made comparable for convenience by dividing them by the fraction of a year covered by the range of intervals forming the group; thus it is to be expected on a random basis that the frequency of intervals ranging from $t = 6$ months to $t = 12$ months would be only half that of intervals ranging from $t = 1$ year to $t = 2$ years, and the former frequency is therefore divided by one-half.

Where more than two cases occurred in a house in the 10 years the only intervals taken notice of were those between the first and second, second and third and so on. Second cases occurring in a house after long intervals of

6 months or more must be assumed to have arisen afresh by some source of infection outside the house. Inmates of houses where a case had occurred and ceased to be infectious would, unless their immunity underwent some change after being exposed to and escaping infection, be in the bulk *equally* liable to attack after *any* interval, except in so far as this might be influenced by a periodicity of epidemics or by removal of families from the house.

For a disease which may give rise to direct infection for a period not exceeding 6 months we should therefore expect a constant frequency of intervals longer than this in the last column of Table XV, if these two factors can be shown to be unimportant. As regards removals the effect, if any, would be a gradual uniform change spread over some years; a pronounced frequency change within a short period could not be attributed to this. The possible effect of periodicity of epidemics on the frequencies will be examined presently by dealing in the same way with cases following in houses not adjacent but in the

Table XV.

Interval, t, between onsets of successive cases in the same house	Frequency per 1000 cases, N_t	Frequencies raised to an equivalent scale (*i.e.* corrected for range of t)
0– 3 days (inclusive)	92·88	—
4–28 " "	97·05	1416·9
29–34 " "	8·45	514·0
5– 6 weeks	4·25	221·0
6– 7 "	3·03	157·6
7– 9 "	4·58	119·1
9–11 "	2·32	60·3
11–13 "	1·83	47·6
3– 6 months	10·56	42·2
6– 9 "	2·95	11·8
9–12 "	1·84	7·4
1– 2 years	20·66	20·7
2– 3 "	21·63	21·6
3– 4 "	26·82	26·8
4– 5 "	26·47	26·5
5– 6 "	26·74	26·7
6– 7 "	28·72	28·7

same street, as a control series. The curve of frequencies from the third column in Table XV is shown in Fig. 5.

It is admitted that this method of distributing intervals is one which may be criticised on various grounds, and if any other satisfactory explanation of the form of the curve in Fig. 5 can be advanced, after taking into consideration the control test in Table XVII, this will be welcomed. In the meantime it may be regarded as confirming the results of the more exact methods used for Holborn and Battersea.

Remembering that the intervals are between dates of onset of successive cases in the same house, it is evident that the risk that another child will show first symptoms of whooping cough on any given day between, say, the fourth and twenty-eighth day after a case has commenced in the house is about 70 times as great as it would be on a given day 1 or 2 years later. The risk falls very quickly to about tenfold in the sixth week and does not reach the steady level of ordinary risk until 6 months have passed. From 6 to 12 months after onset of the first case the risk of another child developing whooping cough is temporarily much less than the ordinary risk, being less than one-half of the risk of attack after a period of 1 or 2 years. After a year has elapsed this advantage is almost lost, the risk after 1 to 2 years being only 10 to 20 per cent. less than in subsequent years.

That this cannot be explained merely by the occurrence of periodic epidemic waves in a given district is proved by comparing the frequencies of intervals between cases not in the same house but in houses in the same street having numbers differing by integers from 2 to 20. If these frequencies are corrected in the same way as in Table XV, the results are as shown in Table XVI.

From this there is only evidence of a very slight depression in the risk that

Table XVI.

Interval, t, between successive cases	Frequency per 1000 cases, the second case occurring in *another* house in same street	Frequencies raised to an equivalent scale (equal range of t)
3– 6 months	24·78	99·1
6– 9 ,,	20·64	82·6
9–12 ,,	21·13	84·5
1– 2 years	89·43	89·4
2– 3 ,,	86·54	86·5

Table XVII.

Interval, t, between successive cases	Second case in a house in same street, not adjacent		Second case in the same house	
	Frequency per 1000 cases	Frequencies in terms of that for 1 to 5 years taken as 16	Frequency per 1000 cases	Frequencies in terms of that for 1 to 5 years taken as 16
0– 3 months	36·58	2·40	224·89	36·87
3– 6 ,,	15·55	1·02	10·56	1·77
6– 9 ,,	12·09	0·80	2·95	0·49
9–12 ,,	12·87	0·84	1·84	0·31
1– 2 years	54·25	3·56	20·66	3·46
2– 5 ,,	189·29	12·44	74·92	12·54

some child living in the same street will develop whooping cough during a period 6 to 12 months after a given case has occurred, compared with the risk 1 or 2 years later. Taking pairs of houses in the same street whose numbering differed by some integer from 11 to 20, that is to say, houses not very close together, the frequencies of intervals between the onset of whooping cough cases were as shown in Table XVII, where they are compared with corresponding values for successive cases in the same house.

Each series has been reduced to an equivalent scale by making the total frequency of intervals of 1 to 5 years equal to 16. On such a scale, if the intervals were merely distributed on a random basis, the expectation in any 3-months period would be unity. The comparison on this control basis shows that whereas second cases follow at intervals of 6 to 12 months in the same house with less than half the frequency expected, in the *other* houses of the same street they follow with about eight-tenths of the expected frequency, a result which would be expected if home contacts became temporarily immunised to a greater extent than street contacts. Any effect of epidemic periodicity on the distribution of intervals should affect both series to the same extent, and this control test was designed to get rid of such effects.

With the reservation about this method already made, these results appear to confirm the findings from the Holborn study in suggesting that there occurs a temporary latent immunisation of home contacts which reduces the risk of developing whooping cough to less than one-half during the period 6 to 12 months after exposure to infection, but is almost lost again after a year has elapsed.

(*c*) *Battersea data*. The fate of contacts was here studied more directly. Through the courtesy of the Public Health Department of the London County Council the names of all children of certain ages excluded from schools in Battersea as home contacts to cases of whooping cough, scarlet fever, diphtheria, measles and chicken pox between August 1926 and December 1929 were extracted from the returns made by Head Teachers, and entered upon cards. The ages selected were 5 and 6 during the school year 1926–7; 5, 6 and 7 during the school year 1927–8; and 5, 6, 7 and 8 during 1928–9 and the summer and autumn of 1929. The record slips of all whooping-cough cases notified or reported to the Battersea Health Department during 1926–30 were arranged in alphabetical order of names, and the dates at which any of the 2291 contacts were found to have been attacked by whooping cough after exclusion as contacts were entered upon their cards. The contacts were then arranged according to (*a*) disease for which they were excluded as contacts, (*b*) age last birthday at the time of exclusion, (*c*) year and quarter of year during which they were excluded. Any of those contacts who were attacked by whooping cough before the end of the next quarter were then discarded and the numbers left at risk to contract the disease from the beginning of the next quarter but one to the end of 1930 were as shown in Table XVIII. It could then be assumed that the whooping cough contacts were subject to the same risk during any given quarter of being infected by whooping cough as the other contacts of the same ages, who could therefore be used as controls. The ages were adjusted by moving up all those aged 5 last birthday into the 6-year-old group after half a year had elapsed, since their average age at the time of exposure would be $5\frac{1}{2}$, and into the 7-year-old group after $1\frac{1}{2}$ years and so on. Thus the 5-year-olds at the time of exposure were regarded as 6 years old in the second, third, fourth and fifth quarters after the quarter in which they were exposed, that is after intervals of 6, 9, 12 or 15 months, 7 years old in the sixth, seventh, eighth and ninth quarters after exclusion, and so on.

The attack rates in Battersea per 1000 of the population living at the ages in question, as estimated from Table V, were then calculated at ages 5, 6, 7, 8 and 9 in each quarter year during 1927–30 from the known total incidence in each quarter, and by multiplying the numbers at risk by these rates the expected cases of whooping cough amongst the contacts until they reached the age of 10 were obtained at different intervals from the time of exposure, and compared with the actual numbers attacked before the age of 10. The results of this analysis are shown in Table XIX.

Thus if $R_{a,n}$ represents the attack rate per unit at age a to $a+1$ during the nth quarter, starting from the third quarter of 1926 as $n = 0$, the total expected attacks amongst the whooping cough contacts during the fifth quarter after the time of exclusion from school, that is at a mean interval of $1\frac{1}{4}$ years, would be

$$(6R_{6,5} + 8R_{6,6} + 21R_{6,7} + \ldots) + (5R_{7,5} + 14R_{7,6} + 25R_{7,7} + \ldots) \\ + (R_{8,9} + R_{8,10} + 3R_{8,12} + \ldots) + (3R_{9,13} + 14R_{9,14} + 18R_{9,15} + \ldots),$$

each series being continued to the end of the line of frequencies at risk in Table XVIII.

Of the 1771 control children, who were excluded from school as contacts to other diseases than whooping cough, 22 were attacked by whooping cough before the end of the next quarter, leaving 1749 at risk from the beginning of the second quarter onwards. Of these, 25 were attacked, according to the records, during the next 3 years as compared with an expectation of 45·37, a ratio of 0·55. This ratio averages 0·57 during the period from the second to the fourth quarters, 0·53 from the fifth to seventh quarters, and 0·51 from the eighth to the fourteenth quarters. A falling off in the ratio was to be expected owing to deaths and removals from the borough. Changes in address and differences in the Christian names of children as reported by schools and as given in the notification records must partly account for the ratio not being nearer unity after short intervals, but these sources of error affect the whooping cough contacts to precisely the same extent, and are therefore eliminated when the one set of ratios is expressed in terms of the other.

Of the 520 whooping cough contacts 50 were attacked[1], according to the records, by the end of the next quarter, leaving 470 at risk, and of these none was attacked during the second and third quarters after exclusion, though four attacks were to be expected. During the fourth quarter one attack was expected and one noted, and subsequently the ratio to expectation was 0·99 during the fifth to seventh quarters and 1·37 during the eighth to fourteenth quarters. Expressing the ratios in terms of those for the controls the results at the foot of Table XIX suggest that susceptibility is reduced up to one year but afterwards becomes greater than that of the controls. This is precisely what would be expected if (*a*) there is a certain amount of hereditary susceptibility to whooping cough rendering members of some families more liable to attack than those of others, and (*b*) some children when in contact with infection acquire a latent immunity lasting 6 to 12 months. Although the figures by themselves are insufficient as evidence of this, owing to the paucity

[1] The smallness of this number is accounted for by the fact that many contacts developing whooping cough within a few days would never be recorded as contacts, but only as cases. This is of no importance in the present calculation.

Table XVIII.

Excluded as contacts to		Age last birthday	1926 3rd	1926 4th	1927 1st	1927 2nd	1927 3rd	1927 4th	1928 1st	1928 2nd	1928 3rd	1928 4th	1929 1st	1929 2nd	1929 3rd	1929 4th	1930 1st	1930 2nd	Totals	
Whooping cough	No. of contacts excluded from school in each quarter	5	9	9	23	10	3	5	1	9	15	27	57	19	3	5	—	—	195	
		6	8	15	25	8	2	2	—	12	31	37	46	11	2	1	—	—	200	
		7	—	—	—	—	1	1	—	3	12	28	29	5	2	2	—	—	83	520
		8	—	—	—	—	—	—	—	—	3	14	18	2	1	4	—	—	42	
	Nos. left at risk in the next quarter but one, with ages adjusted	6	—	—	6	8	21	9	3	4	1	7	13	23	50	19	2	5	171	
		7	—	—	5	14	25	7	2	2	—	12	28	34	40	11	2	1	183	470
		8	—	—	—	—	—	—	1	1	—	3	10	26	27	5	2	2	77	
		9	—	—	—	—	—	—	—	—	—	—	3	14	18	2	1	1	39	
Scarlet fever, Diphtheria, Measles or Chicken pox	No. of contacts excluded from school in each quarter	5	24	42	37	50	27	56	9	119	41	58	43	49	22	58	—	—	635	
		6	13	55	41	38	35	62	8	129	28	54	33	40	30	36	—	—	602	1771
		7	—	—	—	—	20	59	2	65	32	39	35	39	34	39	—	—	354	
		8	—	—	—	—	—	—	—	—	17	43	41	31	21	27	—	—	180	
	Nos. left at risk in the next quarter but one, with ages adjusted	6	—	—	22	42	34	50	27	55	9	116	40	56	43	48	22	57	621	
		7	—	—	13	55	41	38	35	60	8	128	28	54	31	40	30	36	597	1749
		8	—	—	—	—	—	—	20	59	2	65	32	38	34	38	24	39	351	
		9	—	—	—	—	—	—	—	—	—	—	17	43	41	31	21	27	180	

Table XIX.

Excluded as contacts to		Interval after exclusion from school (central values): 6 mo.	9 mo.	1 yr.	1¼ yr.	1½ yr.	1¾ yr.	2 yr.	2¼ yr.	2½ yr.	2¾ yr.	3 yr.	3¼ yr.	3½ yr.
Whooping cough	Expected no. of attacks	2·22	1·55	1·34	1·49	0·78	0·75	0·74	0·42	0·11	0·05	0·06	0·06	0·02
	Actual no. of attacks	—	—	1	2	1	—	—	—	—	1	—	—	1
	Ratio of actual to expected	0		0·75		0·99					1·37			
Other exanthemata	Expected no. of attacks	8·46	10·72	7·08	7·54	2·81	2·83	2·30	2·26	0·52	0·32	0·24	0·23	0·06
	Actual no. of attacks	4	6	5	3	2	2	2	—	1	—	—	—	—
	Ratio of actual to expected	0·52		0·71		0·53					0·51			
Susceptibility of whooping cough contacts in terms of that of controls of same ages exposed to same risks		—		1·06		1·87					2·69			
		0·26			1·47									

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of the numbers of expected attacks among the group of whooping cough contacts, they support the previous evidence from Holborn and Greenwich, and from Table XI, without ambiguity[1].

VIII. Immunity changes in the population in relation to epidemics.

By means of the evidence in Tables III, V, VII, IX, XI, XIII, XV, XVII and XIX it is now possible to estimate the extent to which latent immunisation occurs in the population, and to envisage the immunity changes which occur during and between epidemics.

Suppose there is a y-fold increase of children under 10 years of age who are really susceptible to whooping cough during the year following the cessation of an epidemic, as shown by the gradual rise in apparent infectiousness. Let p be the ratio of actual to reported incidence amongst children under 10 as a whole, shown in Section V to have a value of about 1·417 in Battersea, and let h be the proportion of children born who either have permanent inherent immunity or are so situated as to escape contact with infection and therefore to be outside the effective population. Let l_0 represent the proportion of the population under 10 who have temporary latent immunity sufficient to protect them at the end of an epidemic, and l_1 the proportion one year later, the year being free from any epidemic. It is found from Table V that with a constant number of births occurring each year equal to the mean annual births during 1925–9, the annual addition of children by births would have been approximately 10·9 per cent. of the total population under 10, and the loss from the population under 10 by ageing of the 9-year-olds to 10 years old would be approximately 9·3 per cent. of the population under 10. Of the added births a fraction $1 - h$ would be at risk to whooping cough. Of those passing out of the population under consideration by reaching age 10 during the year a fraction $h + 0{\cdot}423p$ would be permanently immune (see Table VII), and a fraction $(l_0 + l_1)/2$ temporarily immune, so the proportion of those at risk would be $1 - h - 0{\cdot}423p - (l_0 + l_1)/2$. In a year from midsummer to midsummer following a winter epidemic, the total reported cases under 10 in Battersea averaged 500 or 1·9 per cent. of the population under 10 (see Table III); hence in such years the gain in immunity by incidence of sporadic cases would amount to a fraction $0{\cdot}019p$ of the population under 10.

The mean proportion of children under 10 estimated to have had whooping cough in Battersea at some time since birth has been denoted in Section V by k, and at the middle of an interepidemic period the proportion who would be

[1] The method has been described at greater length than may seem justified by the results because, provided sufficient cases are thus followed up, it provides a useful means of studying immunity changes following exposure to any disease of childhood, with a statistically adequate control. The data here used, greatly amplified, are being employed in similar studies of the other exanthemata.

permanently not at risk to attack is $k + h$. The decrease during the inter-epidemic year in the proportion not at risk would amount to

$$0{\cdot}109\,(1-h) - 0{\cdot}093\,(1-h-0{\cdot}423p) - 0{\cdot}019p + (l_0 - l_1),$$

the first term representing the addition by births to the fraction susceptible, the second term the loss of permanent immunes by ageing of the 9-year-olds to 10 years old, the third term the loss by occurrence of whooping cough, and the fourth term the loss of latent immunity during the year.

At the end of an epidemic and the beginning of an interepidemic year, the proportion *permanently* not at risk would be

$$k + h + \tfrac{1}{2}\,[0{\cdot}109\,(1-h) - 0{\cdot}093\,(1-h-0{\cdot}423p) - 0{\cdot}019p] = k + 0{\cdot}992h + 0{\cdot}0102p + 0{\cdot}008.$$

The total increase in the proportion susceptible during the year, shown above,

$$= 0{\cdot}109\,(1-h) - 0{\cdot}093\,(1-h-0{\cdot}423p) - 0{\cdot}019p + l_0 - l_1$$
$$= 0{\cdot}016\,(1-h) + 0{\cdot}0203p + l_0 - l_1,$$

and the total proportion susceptible at the *beginning* of the year

$$= 1 - l_0 - [k + 0{\cdot}992h + 0{\cdot}0102p + 0{\cdot}008]$$
$$= 0{\cdot}992\,(1-h) - k - 0{\cdot}0102p - l_0.$$

Hence, since the proportion susceptible is y times as great at the end as at the beginning of the post-epidemic year,

$$y - 1 = \frac{0{\cdot}016\,(1-h) + 0{\cdot}0203p + l_0 - l_1}{0{\cdot}992\,(1-h) - k - 0{\cdot}0102p - l_0}\,.$$

Thus far the only assumptions have been that p is constant and that the gradual rise in apparent infectiousness during the post-epidemic periods is due to immunity changes and not to changes in the infecting agent. It only remains to substitute the possible values of y, p, k, h and l_1, and determine l_0. From Table XI it is evident that the apparent infectiousness in the child population of all houses attacked rose from about 6 at the end of an epidemic to about 12 a year later, so that $y = 2$ approximately, and substituting this the formula simplifies to

$$l_0 = 0{\cdot}488\,(1-h) - 0{\cdot}0152p + \frac{l_1}{2} - \frac{k}{2},$$

and, giving p its estimated value 1·417 and k its estimated value 0·374, as determined in Section V,

$$l_0 = 0{\cdot}280 - 0{\cdot}488\,h + \frac{l_1}{2}\,.$$

The evidence against the persistence of any appreciable amount of latent immunity after a year is such that l_1 must be small, not exceeding one-tenth, which would mean that 10 per cent. of all children retain a latent immunity more than a year after an epidemic. The value of h, the proportion of children who escape contact with infection through life or who have a permanent inherent immunity sufficient to escape attack, cannot exceed 0·4, since 60 per cent. have been shown to have whooping cough at some time. It is difficult to believe that many children living in Battersea could escape all contact with infection from whooping cough, and it can be proved indirectly that this proportion is small. Thus in the living population of children under 10 at a given moment $37\frac{1}{2}$ per cent. have had an attack and another 23 per cent. will have one before the end of life, which means that of the children in the population under 10 who have not yet had whooping cough about $(62{\cdot}5 - 23)/0{\cdot}625$, or 63 per cent., will escape permanently. But it has been shown in a previous paper (1930) that 70 per cent. of Holborn home contacts who had not had whooping cough before exposure nevertheless escaped it altogether, an even larger proportion than in the unattacked population as a whole, and it must therefore be concluded that the great bulk of those who escape do so by virtue of immunity of some kind rather than by avoidance of infection.

It may be that the proportion h consists chiefly of children with permanent inherent immunity sufficient to combat infection, but it is difficult to distinguish this in its effects from the power to acquire latent immunity of a transient character repeatedly during successive epidemics, which might account for a large part of the 40 per cent. who escape attack. Substituting the limiting values of h and l_1, if $l_1 = 0$, $h = 0$, then $l_0 = 0{\cdot}280$; if $l_1 = 0$, $h = 0{\cdot}4$, then $l_0 = 0{\cdot}085$; if $l_1 = 0{\cdot}1$, $h = 0$, then $l_0 = 0{\cdot}330$; if $l_1 = 0{\cdot}1$, $h = 0{\cdot}4$, then $l_0 = 0{\cdot}135$; so that l_0 must lie between $0{\cdot}085$ and $0{\cdot}330$. This means that some proportion between $8\frac{1}{2}$ and 33 per cent. of all children under 10 will have acquired a temporary latent immunity at the end of a large winter epidemic, this being mostly lost during the succeeding twelve months. In the Battersea population of 26,000 children this represents between 2200 and 8600 children. About 1600 children are recorded as having whooping cough during an average "epidemic year," and since $p = 1{\cdot}417$, about 2300 children must have recognised attacks. Hence between one and four children must have subclinical attacks conferring to each one a temporary immunity from having a clinically recognisable attack.

The broad conclusion is that to every 100 children who have recognisable whooping cough during an epidemic, at least 100 escape by acquiring a transient latent immunity; another 300 escape either by the same process or by virtue of an inherent passive immunity, and the remainder escape by having had whooping cough, or in a small fraction by avoidance of infection.

The changes which occur in the state of immunity of the 26,000 children under 10 years of age during the twelve months following an epidemic year from midsummer to midsummer with a total incidence of 2300 cases are shown diagrammatically in Fig. 6, the alternative limiting assumptions being (*a*) $h = 0$, $l_1 = 0{\cdot}05$, and hence $l_0 = 0{\cdot}305$; (*b*) $h = 0{\cdot}4$, $l_1 = 0{\cdot}05$, and hence $l_0 = 0{\cdot}110$. It is seen that in either case the children at risk are doubled during the year, and this would be true for any intermediate values of l_0 and h, so that the effect on the epidemic cycle would in any event be the same if the insusceptible fraction is regarded as neutral. The actual change which occurs must be represented by some curve, not necessarily a straight line, lying be-

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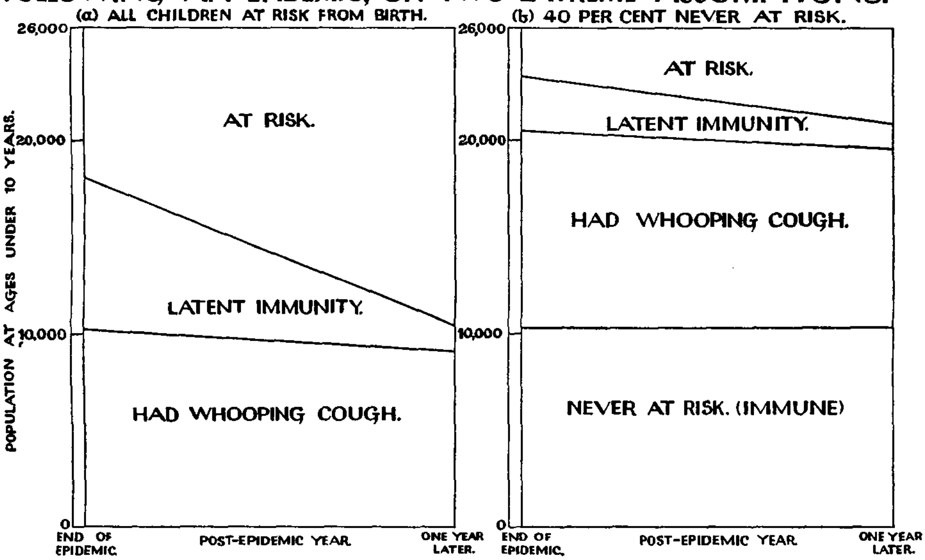
tween these limits, and is quite sufficient to explain most of the epidemic phenomena.

Fig. 6. IMMUNITY CHANGES IN THE CHILD POPULATION FOLLOWING AN EPIDEMIC, ON TWO EXTREME ASSUMPTIONS.



IX. Summary of conclusions.

1. Whooping cough is now in London the most important epidemic disease of childhood in causing physical suffering, loss of school attendance, impairment of physique and mortality.

2. The mean annual incidence of whooping cough in children under 10 in Battersea during the quinquennium 1925–9 is estimated to have been about 60 per 1000 living, and the fatality rate 1·26 per 100 cases. The fatality rates in the first two years of life were estimated to be 4·0 and 3·3 respectively, at ages 2 to 5, 0·7 and at ages 5 to 10, 0·2 per 100 cases.

3. Epidemics of whooping cough in Battersea and Greenwich tend to have a biennial periodicity; a summer epidemic is often immediately followed by or merges into a winter epidemic subsiding by midsummer, and then follows a year of low incidence, so that the total incidence of cases in successive years from midsummer to midsummer shows an alternation of epidemic and inter-epidemic years.

4. Epidemics do not always run concurrently in areas of London separated by several miles; the spread is checked to some extent by barriers to free communication and small districts thus occasionally escape an epidemic, or an interval of several months may separate the epidemic peaks in districts a mile or so apart.

5. The view that the epidemic cycle in whooping cough can be explained by a periodic reduction of the proportion of children not previously attacked below some critical limit, is shown to be untenable. Both the termination of epidemics and their periodicity can be explained by the occurrence of a latent immunisation of contacts as in measles, such immunity only lasting about 1 year instead of 2 or 3.

6. The occurrence of such a transient latent immunisation is indicated by (*a*) measurement of the rise and fall of apparent infectiousness of cases to other children in the same house during 6 years in Battersea, (*b*) measurement of the frequency of second cases in houses after different intervals of time during a decade in Greenwich, and (*c*) analysis of the attack rates amongst home contacts in Holborn and Battersea during several years following exposure to infection as compared with those among control groups of children. These phenomena would be difficult to explain as resulting from a "cycle of activity" of the organism.

7. In London as a whole a special enquiry into the previous histories of school entrants proves that 44 per cent. of children have an attack of whooping cough before their fifth birthday. According to Battersea records 27·7 per cent. are notified or reported to the Public Health authority as having whooping cough by this age, and 42·3 per cent. by the tenth birthday. It is concluded that in that borough about 60 per cent. of the true incidence is notified at ages under 4, about 72 per cent. at age 4, and 90 per cent. at ages 5 to 10 when school supervision is fairly complete. At all ages under 10 the recorded incidence in Battersea represents about 70 per cent. of the true incidence.

8. It follows that about 60 per cent. of London children have whooping cough by the tenth year, and about 61 per cent. at some time during life, this proportion being rather lower than estimates made from histories given by parents in a group of American towns. The bulk of the remaining 40 per cent. must escape attack by virtue of some kind of immunity rather than by avoidance of contact with infection through life, and a part of these no doubt escape by the repeated acquisition of transient latent immunity during epidemics, and the remainder by virtue of an inherent immunity to the disease.

9. During the year following an epidemic the proportion of children under 10 who are susceptible is approximately doubled and again halved during the next epidemic. This must be mainly due to temporary latent immunisation during an epidemic of x children to each one attacked, the value of x lying between the limits 1 and 4, this depending upon the unknown proportion who are inherently immune. If the bulk of the two-fifths of all children who escape attack have inherent immunity, as is suggested but not proved by the data, then the ratio of latent to recognisable infections lies between 1 and 2.

10. Superposed upon the gradual rise and fall of infectiousness believed to be due to these immunity changes, there occurs a sudden rise at the commencement of an epidemic which must be attributed to an enhanced real infectiousness. This probably arises from a sudden increase in activity of the

organism itself under seasonal influences setting in at the moment when the herd immunity becomes insufficient to withstand the infection pressure, so that the balance is upset and the epidemic begins.

11. These findings are similar to those for measles, the chief differences being, (i) epidemics are usually spread over a year instead of 6 months; (ii) latent immunity apparently lasts about a year instead of 2 or 3; (iii) about 60 per cent. of children are attacked at some time during life instead of about 90 per cent.; (iv) there is probably inherent immunity in a certain proportion, but not in measles; (v) the ratio of latent to manifest infections is lower.

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