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Airborne infection in a fully air-conditioned hospital

IV. Airborne dispersal of *Staphylococcus aureus* and its nasal acquisition by patients

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SUMMARY

Studies in a newly built hospital furnished with complete air conditioning where most of the patients are nursed in 6-bed rooms showed that the transfer of air from one patient room to another was very small, especially when there was substantial flow of air in a consistent direction between the patient rooms and the corridor, and that the direct transfer of airborne particles was even less. There was, however, no evidence of any reduction in the rates of nasal acquisition of *Staphylococcus aureus* compared with those to be found in naturally ventilated hospitals.

The numbers of *Staph. aureus* found in the air of a given room that appeared to have originated from patient carriers in other rooms were many times greater than could be accounted for by direct airborne transfer. Although there was evidence that many carriers were not detected, detailed study showed that this excess transfer to the air of other rooms was genuine. It seems probable on the basis of investigations in this hospital and elsewhere that this excess transfer occurs indirectly, through dispersal from the clothing of the nursing and medical staff into the air of another room of strains with which their outer clothes have become contaminated while dealing with patients.

Reduction in direct airborne transfer of micro-organisms from one room to another, whether by ventilation or other means, can only be of clinical advantage if transfer by other routes is, or can be made, less than that by the direct airborne route.

INTRODUCTION

The significance of airborne bacteria in relation to the transmission of infection in hospitals and the possible role of ventilation as a means of control have been

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matters of concern and controversy for more than a century. Sir John Simon in his report to the Privy Council in 1863 expressed clearly the objectives of hospital ventilation in this respect when he declared that not only ought those 'contagions which are spread by inoculation or by dirty towels, bedding, fingers, etc. be absolutely incommunicable within a hospital' but also those 'which will not spread except when pus or matters like pus are floating in the air'.

That we have made so little progress in distinguishing with confidence the relative importance of the several possible routes of infection and in evaluating the value of preventive measures such as ventilation is a reflection of the extreme complexity of the hospital situation and the difficulty of extracting from it significant statistics.

During the last 20 years, most often in collaboration with the Department of Bacteriology of St Bartholomew's Hospital, members of the Staphylococcus Reference laboratory and of the Cross Infection Reference laboratory of the Central Public Health laboratory have engaged in a series of studies of the spread of coagulase positive staphylococci in hospital wards (Shooter *et al.* 1958; Williams *et al.* 1959; Shooter, Girling, Matthias & Williams, 1960; Williams *et al.* 1962; Noble, 1962; Shooter *et al.* 1963; Parker, John, Emond & Mahecek, 1965; Lidwell *et al.* 1966; Lidwell *et al.* 1970; Lidwell *et al.* 1971). Hospital infections are not a homogeneous group and the selection of *Staph. aureus* as a subject of study was prompted both by the intrinsic importance of infections by this organism and by the availability of techniques, such as phage-typing, which allow the identification with a good degree of probability of strains derived from a common source. These 'pus' organisms are resistant to drying, are to be found among the bacteria carried by airborne particles and are frequent colonizers of the nasal mucosa of man. There are therefore reasonable *a priori* grounds for the proposition that transfer from one patient to the nasopharynx of another takes place by means of these airborne particles. It is less apparent that wound infection is likely to arise in this way but the realization that nasal carriage commonly leads to widespread contamination of the skin of the body suggests an easy mechanism by which infection could follow on nasal colonization. Nasal carriers of *Staph. aureus* have been found more likely to develop post-operative wound sepsis than non-carriers, and with the strain carried in the nose (Williams *et al.* 1959).

It was early noticed that the dispersal of *Staph. aureus* by carriers of this organism in hospital wards was very variable (Shooter *et al.* 1958) and it became apparent that little dispersal occurred directly from the nose and mouth but was chiefly mediated via the desquamating skin (Davies & Noble, 1962). As a consequence the most extensive dispersal is usually from patients with either skin lesions or positive skin colonization (e.g. Solberg, 1965). The hospital environment differs in many ways from normal living conditions and the differences in selection pressures applied to a micro-organism with the character variability found in *Staph. aureus* lead to the development of a population characteristic of this environment. In particular the use of antibiotics gives a selective advantage to strains that are resistant to these agents so that the hospital population usually includes a high proportion of 'resistant' strains. The creation and maintenance of

this differing population among the hospital patients and staff depends, however, on the transfer of strains to newcomers from persons who have been resident for some time in the hospital environment. A quantitative relation appears to exist between the exposure to airborne staphylococci of a single strain and the chance that it will be acquired in the nose, but it is by no means certain that the actual dose which leads to colonization is in fact transmitted by the airborne route (Lidwell & Brock, 1970). If it is, then reduction in airborne *Staph. aureus* in the hospital environment should lead to a reduction in the frequency of nasal colonization. Support for this can be derived from the low rate of acquisition of new strains by patients nursed in the cubicles of an infectious disease hospital where each cubicle opened off a covered way open to the outside air, a circumstance which might be supposed to prevent most of the direct movement of air between the patient rooms (Parker *et al.* 1965). Attempts to apply the same principle, but employing controlled mechanical ventilation, for the protection of surgical patients during their pre-operative stay in a ward were not very successful (Lidwell *et al.* 1970) and the general application of mechanical ventilation to a large race-track type ward was also without effect on rates of nasal acquisition and sepsis following surgery (Whyte, Howie & Eakin, 1969). Neither of these experiments, however, was entirely satisfactory. In the first the widespread dissemination of one strain with a high potential for dispersal rendered interpretation of much of the data uncertain since there was most often more than one carrier who might have been the source of an acquisition; in the second the balanced ventilation system used allowed substantial exchange of air between rooms and corridors so that the reduction in exposure to airborne strains carried directly from one patient to another was only moderate. Because the evidence suggests that the reduction in the risk of nasal colonization is much less than proportional to the reduction in the airborne dose (Lidwell *et al.* 1966, 1970, 1971) the effect that might have been expected was only small.

After moving from open type wards into a race-track type building with a positive ventilation supply to the patient rooms Smylie, Davidson, Macdonald & Smith (1971) reported less airborne contamination and a substantial reduction in post-operative wound sepsis. No direct evidence of the extent to which airborne transfer was reduced by the ventilation was obtained and many other changes had also taken place, e.g. the provision of new operating rooms and a high proportion of single patient rooms. The move was also preceded by an 'epidemic' of a particular staphylococcal strain which disappeared shortly after.

The construction of a fully air-conditioned hospital at Greenwich in South East London, with ventilation designed to minimize air transfer between patient rooms, provided the opportunity for further investigation. It has been shown in the preceding papers (Foord & Lidwell, 1975*a*, 1975*b*) that the ventilation system in this hospital is indeed highly effective in preventing the direct transfer of airborne particles from one patient room to another. The spread of *Staphylococcus aureus* within the ward areas, as reflected in the rates of nasal colonization of patients with new strains, is the subject of this paper.

The patients studied were those admitted to three medical wards on the 2nd

(the top) floor of the building. The patient rooms were situated in the outer areas of two adjacent sides of the building (Foord & Lidwell, 1975*a*) and all opened off one side of a single 'dog-leg' corridor. Ward A, for female patients, included five 6-bed patient rooms. Ward B, a high dependence nursing unit for male and female patients, contained initially three but eventually four 6-bed patient rooms next to Ward A, and 3 single-bed rooms. Ward C, for male patients, had 3 single-bed rooms adjacent to those in Ward B and initially four, eventually six, 6-bed rooms around the angle of the corridor.

It will be useful to compare the findings with those reported from a study of patients in the medical wards of another recently built hospital. This, the Queen Elizabeth II Hospital, Welwyn Garden City, 30 km. north of London, was constructed with the patient areas divided into six 4-bed rooms separated from the corridor only by dividing walls 3 feet high. There was thus free circulation of air between all parts of the ward (except, to some extent, with the 5 single bed rooms) as in open wards. Acquisition of new nasal strains of *Staph. aureus* was found to take place almost as easily from patient carriers in other bedrooms as from carriers in neighbouring beds (Lidwell *et al.* 1971).

ORGANIZATION AND METHODS

The bacteriological and epidemiological methods were essentially similar to those described in earlier publications (e.g. Lidwell *et al.* 1966, 1971).

A research nurse collected the data relating to each patient. Nasal swabs were obtained from each patient on admission and on each Monday following so long as he or she remained in the wards included in the study. Nasal swabs were also obtained weekly from the medical nursing and auxiliary staff working in the wards. As far as possible these were also taken on the Monday but for various reasons this could not always be done. The swabs were taken by the research nurse appointed for the investigation, except for admissions on Saturday or Sunday, or for staff on night duty or otherwise difficult to reach. In these cases the swabs were taken by a member of the nursing staff, or in the case of swabs from medical staff, by the staff members themselves. If the research nurse was absent on leave or sick the swabs were obtained by one of the hospital laboratory staff. Primary isolation of *Staph. aureus* and confirmation by coagulase testing was done in the hospital laboratory. Confirmed strains were then sent to the Central Public Health Laboratory for phage typing. Antibiotic sensitivity testing, against penicillin and tetracycline, was also done there so as to ensure that methods and criteria were uniform with those used for staphylococci isolated from the air. Most of the strains resistant to tetracycline were also resistant to penicillin and, when tested, to several other antibiotics.

On the same day, Monday, as that on which the weekly nasal swabs were taken, petri dishes, 14 cm. diameter, filled with a phenolphthalein-phosphate serum agar were exposed in the ward. Usually they were exposed for about 7 hr., from 9.30 until 16.30, but on some occasions plates were similarly exposed during the night, from 23.30 until 6.30. During the 1st period of the study, from 2.2.70 until 4.12.70,

plates were exposed in two patient rooms in each of the three wards and in two of the single bed rooms. The rooms were selected each week according to a balanced randomized design. One plate was also exposed in the corridor near to the nursing station in each ward. From 7.12.70 onwards until the investigation ended plates were exposed weekly in all the 6-bed patient rooms and in two randomly selected single bed rooms, as well as at the three corridor sites. By comparison with the nasal swabbing for the same day possible sources for the air strains could be found.

The period of study covered 187 weeks. For assessment in relation to the ventilation conditions (Foord & Lidwell, 1975*a*) the results were analysed in four periods:

I	Weeks	1–44	2.2.1970–30.11.70
II	Weeks	62–105	5.4.1971–4.2.72
III	Weeks	106–151	7.2.1972–18.12.72
IV	Weeks	152–187	27.12.1972–28.8.73

The dates given are those of the Monday swabbing days. During Periods I, II and III the ventilation system was such that the patient bedrooms were mostly positively pressurized with respect to the passage and there was, therefore, a net outflow of air from these rooms. This was greatest during Period I and from the rooms in Ward A. During Period IV this had been changed and the rooms and passage were approximately in balance (Foord & Lidwell, 1975*a*). Weeks 45–61 have been omitted from the analysis since, on account of technical difficulties, there were doubts about the reliability of the bacteriological results. In addition there was some disturbance of the normal nursing routines during the period owing to the opening of Phase II of the hospital. An additional 6-bed patient room, No. 12, was then taken into use in Ward B and two, Nos. 26 and 27, added to Ward C, increasing the number of patient beds included in the study, Wards A, B and C from 78 to 96. Throughout the study the bed-occupancy was around 80 % in the 6-bed rooms with a slightly lower figure of about 70 % in the single-bed rooms.

RESULTS

Characteristics of the patient population

Information was obtained for 2277 male patients and 2019 female patients; these figures include patients already in the wards when the study started and those remaining when it finished.

Most of the patients remained in the wards for only a short time. The distribution of the length of stay is shown in Figure 1. Only about 50 % were still in the wards when the 2nd weekly nasal swab was due to be taken, i.e. the median duration of stay was about 10 days. About 10 % remained for longer than 5 weeks but these accounted for 36 % of the more than 12,000 patient-weeks of observation included in the study.

There was a preponderance of elderly patients, about 61 % were over 60 years of age. The commonest diagnoses related to the heart or circulatory system. The next most frequent were respiratory diseases, more often diagnosed for males than

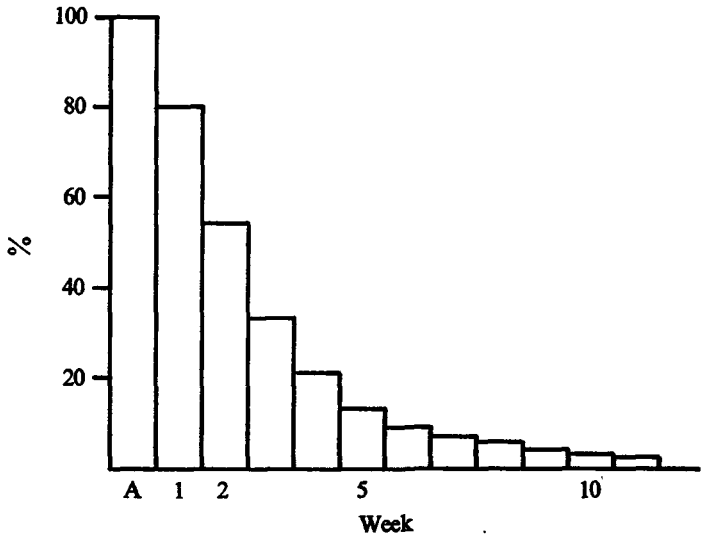

Fig. 1. Duration of patient stay. The columns show the percentage of patients still in the ward at the time of taking the 1st and subsequent weekly nasal swabs, up to the 11th. A = admission.

Table 1. *Age distribution of patients* (%)

Age (yrs)	Males	Females
–19	1·9	3·2
20–39	9·7	15·2
40–59	26·2	21·4
60–79	50·3	45·7
80–	11·9	14·4

There were 2277 male and 2019 female patients

Table 2. *Patient diagnosis on admission* (%)

Diseases of	Males	Females
Heart and circulatory system	38·4	35·9
Respiratory system	21·3	15·0
Gastro-intestinal	9·1	11·2
Neoplasm	8·7	6·3
Diabetes	7·0	13·8
Skin conditions	2·5	3·2
Other	19·1	23·8

Some patients were admitted with more than one diagnosis.

for females. Diabetes was the third commonest diagnosis among the females but was only half as frequent among the males. The distribution of age and diagnosis among the male and female patients is given in Tables 1 and 2.

Over one third (36·7 %) of the patients had been in hospital in the 6 months before admission to the wards. In any one week the proportion of patients receiving some form of penicillin was about 15 % and about 10 % were receiving some other antibiotic. The use of penicillin remained fairly constant throughout the study but

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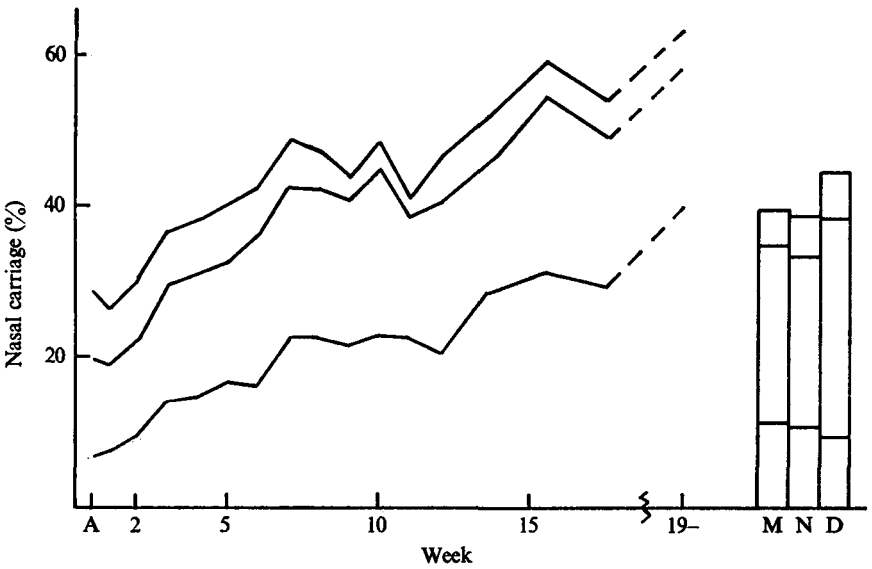

Fig. 2. Changes in nasal carriage of *Staphylococcus aureus* during stay in hospital. The top line shows the percentage of patients carrying *Staph. aureus* in their noses after the specified length of stay in the wards. The bottom line shows the percentage carrying strains resistant to tetracycline. The middle line shows the percentage carrying strains resistant to penicillin or tetracycline or to both antibiotics. A = admission swab. The three histograms at the right show the average carriage state of the Medical (M), Nursing (N) and Domestic staff (D) respectively.

the use of other antibiotics increased during this time from about 8 % to over 14 % in the last period. A significant part of this increase was related to a particularly high rate in Ward 26, which was occupied by elderly male patients.

Patients were usually ambulant, i.e. left their rooms for toilet and other purposes but rarely visited patient rooms other than their own (Lidwell & Brock, 1970). More than 80 % of the patients in the 6-bed rooms were ambulant at any one time. Patients in single bed rooms were more often confined to them and rather less than 60 % were able to leave the room at a particular time. For the first two periods not much over 60 % of the patients in Ward B were ambulant.

Nasal carriage

Staph. aureus was isolated from nearly 30 % of the nasal swabs taken on admission; no admission swab was obtained from 135 patients (3·1 %). The antibiotic sensitivity of the strains varied according to whether the patient had been in hospital during the preceding 6 months (Table 3). Strains resistant to an antibiotic other than penicillin were twice as frequent among such patients.

The proportion of patients carrying *Staph. aureus* in their noses increased with length of stay in hospital. This was largely a consequence of a steady increase in the proportion carrying tetracycline resistant strains (Figure 2). Carriage of strains resistant to penicillin only also increased over the first 6 weeks of stay but thereafter remained approximately constant. Carriage of strains sensitive to all antibiotics decreased over the same period and then remained steady. This pattern, in

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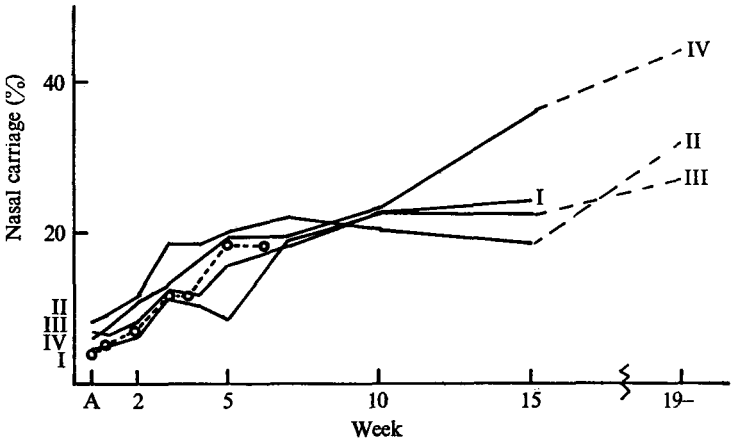

Fig. 3. Nasal carriage of tetracycline resistant strains of *Staphylococcus aureus*. The four curves show the percentage of patients carrying tetracycline resistant strains of *Staph. aureus* in their noses after the specified length of stay in the wards during each of the four periods of the study. A = admission swab. The corresponding figures for the Queen Elizabeth II hospital, Welwyn, are shown by the circles and broken line (Lidwell *et al.* 1971).

particular the increase in carriage of 'hospital' strains usually resistant to several antibiotics in addition to penicillin, has been frequently reported previously from hospitals with large open 'Nightingale' type wards (e.g. Lidwell *et al.* 1966) and is indicative of an environment in which transfer of staphylococcal strains between patients occurs relatively freely but acquisition of sensitive strains is restricted by antibiotic therapy. As is shown in Figure 3 the rate of increase was similar over all four periods of study and did not differ significantly from that found in the Welwyn hospital, although the average rate of increase over the first 6 weeks of hospital stay was somewhat higher at Welwyn.

Nasal carriage among the staff was also similar to that found at Welwyn. The total carriage rate was about 40 %, rather higher for the domestic than for the medical and nursing staff. About 60 % of the strains isolated were resistant to penicillin only and 10 % to tetracycline.

The longer duration of this study in comparison with the previous ones, the larger number of patients observed and the appreciable proportion of long stay patients among them made it possible to follow changes in nasal carriage up to 4 or 5 months in hospital.

The frequency of carriage of tetracycline resistant strains appears to rise throughout this period (Figure 2). This might, however, be an artefact if the longer stay patients, who alone determine the carriage rate after lengthy periods of hospital stay, reached a high carriage rate relatively quickly. These patients obviously differ in various respects from those who are discharged after no more than a few weeks. The experience of the longer stay patients has therefore been examined separately (Figure 4). It can be seen that all groups showed a rising carriage rate throughout their hospital stay although the rate of rise appears to be less in the longest stay group beyond 14–15 weeks of stay. The final carriage rate

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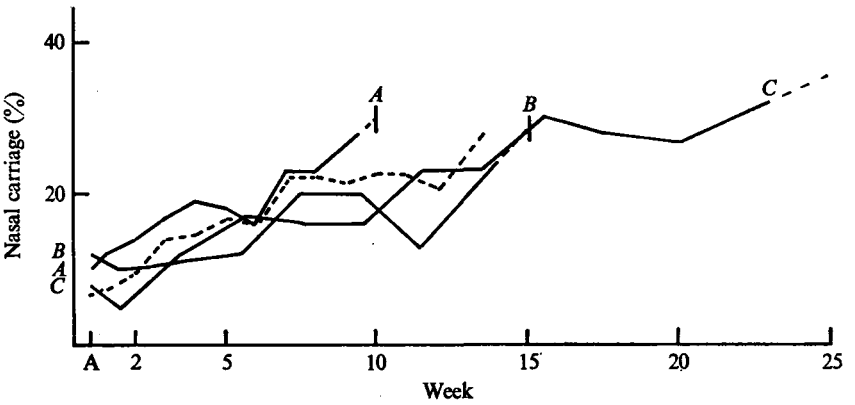

Fig. 4. Nasal carriage of *Staphylococcus aureus* by long stay patients. The three full lines show the percentage of patients carrying tetracycline resistant strains in their noses after the specified lengths of stay in the wards. Each represents a different group of patients according to the duration of their stay in the wards; Curve *A* for patients who stayed from 6–10 weeks, curve *B* for patients who stayed between 11 and 15 weeks and curve *C* for patients who stayed 16 weeks or longer. The broken curve shows the average for all patients, from Figure 2.

Table 3. *Percentage of nasal carriers of* Staph. aureus *among patients on admission, in relation to previous admission to hospital*

Nasal carriage of *Staph. aureus*	In hospital within previous 6 months	
	Yes	No
Carrier of any strain	29·8	28·1
Carried a strain sensitive to all antibiotics tested	7·3	10·3
Carried a strain resistant to penicillins only	13·1	12·9
Carried a strain resistant to tetracycline	9·4	4·9

36·7 % of patients had been in hospital within the previous 6 months.

in this group was over 40 % for the tetracycline-resistant strains and over 65 % for all strains together.

The longer stay patients entered hospital with a somewhat higher carriage rate of tetracycline-resistant strains than the average of all patients. This was not related to more frequent previous hospitalization during the preceding 6 months. The figure was 37·7 % for the longer stay patients compared with 36·7 % for all patients. However, those who had been in hospital during the preceding 6 months were admitted with a carriage rate for tetracycline-resistant strains of about 14 %, substantially greater than the figure of 9·4 % for all patients (Table 3), while the carriage rate of such strains among those who had not been in hospital during this time (4·6 %) was insignificantly different from that for all patients (4·9 %). They did not differ greatly either in the diagnosed conditions for which they were admitted or in the extent or character of the antibiotic treatment which they

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Table 4. *Apparent rates of nasal acquisition of* Staphylococcus aureus

Ward	Total number of patient-weeks	Rate per 1000 patient-weeks: All strains	Rate per 1000 patient-weeks: Strains resistant to tetracycline
A	4018	81·6	31·6
B*	3570	74·5	35·3
C*	4813	99·5	53·2
S	719	73·7	27·8
Period			
I	2815	61·1	25·2
II	3208	96·9	56·4
III	3572	103·0	42·0
IV	2806	83·4	38·5
Wards, A, B & C†	12401	87·3	41·1
Short stay patients	7828	76·0	30·8
Long stay patients	4573	106·5	58·7
Queen Elizabeth II Hospital, Welwyn‡	3327	77·4	29·0

S stands for single bed rooms.

* Including their respective single rooms.

† Including 10 acquisitions (1 with a strain resistant to tetracycline) not assignable to a particular ward as the patients concerned were moved during the preceding week.

‡ Lidwell *et al.* 1971.

received, although there was a somewhat higher use of antibiotics other than penicillin for elderly male patients during the latter part of the study. The one significant difference was age. While 59 % of patients who were discharged from hospital after 5 weeks or less were over 60 this figure was 78 % for those in the wards between 6 and 10 weeks and 88 % for those who remained after 15 weeks. As will be seen later these older longer stay patients showed a much higher rate of acquisition of new strains of *Staph. aureus* in their noses than the other patients.

Nasal acquisition of Staphylococcus aureus

More than 12,000 nasal swabs were obtained from patients after an earlier sample. On 1803 occasions a strain of *Staph. aureus* was isolated which, on our criteria, had not been present in the previous specimen, and 510 of these were resistant to tetracycline. If the interval between an admission swab and a regular weekly swab is reckoned as a full week the apparent rates of nasal acquisition, per 1000 patient-weeks of exposure in the different ward units and during the different periods of this study are as given in Table 4. The rates are somewhat higher than those found in the Welwyn hospital but the difference is entirely due to the higher rates of acquisition experienced by those patients who remained in the wards for longer than 5 weeks. As has already been noted these patients were older than the average of all patients. A higher rate of nasal colonization and acquisition among older patients was also observed at Welwyn.

Patients in the single rooms, who were predominantly short stay patients, acquired new strains at as high a rate as the other patients.

Table 5. *Percentage distribution of apparent sources of* Staph. aureus *acquired by patients in the nose*

	Greenwich District General Hospital										Queen Elizabeth Hospital, Welwyn*	
	All strains, ward				All strains, period				All wards and periods			
Apparent source	A	B	C	S	I	II	III	IV	All strains	T strains only	All strains	T strains only
Other patients†												
In same room	17	14	23	—	12	18	20	25	19 [23]	21	7	6
In other rooms of same ward	46	26	38	40	33	41	39	34	38 [38]	42	37	42
In adjacent wards	8	27	7	10	23	13	7	10	12 [10]	12	—	—
In a remote ward	7	—	2	5	5	2	4	0	3 [2]	2	17	11
Medical and Nursing staff†												
Working in same ward	16	19	24	30	20	17	19	26	20	17	39	42
Working in another ward	6	13	6	15	6	8	10	5	8	5	—	—
No identified unique source‡												
Ambiguously located	26	22	30	6	20	24	16	31	22	29	32	45
No source identifiable§	32	33	37	51	38	32	33	36	35	29	21	13
Untypable strains§	11	11	11	9	4	12	16	8	11	10	8	4

S stands for single-bed rooms.

T strains, strains resistant to tetracycline.

* Lidwell *et al.* 1971.

† As percentage of acquisitions from identified apparently unique possible sources.

‡ As percentage of all acquisitions.

§ By comparison of resistance patterns with those for acquisitions from identified unique sources and from admission swabs it appears likely that 41 % of these were probably spurious (carrier state not detected on admission). These included 23 % of the T strains and as many as 66 % of the fully sensitive strains.

[ ] Corrected for missed carriers, see text.

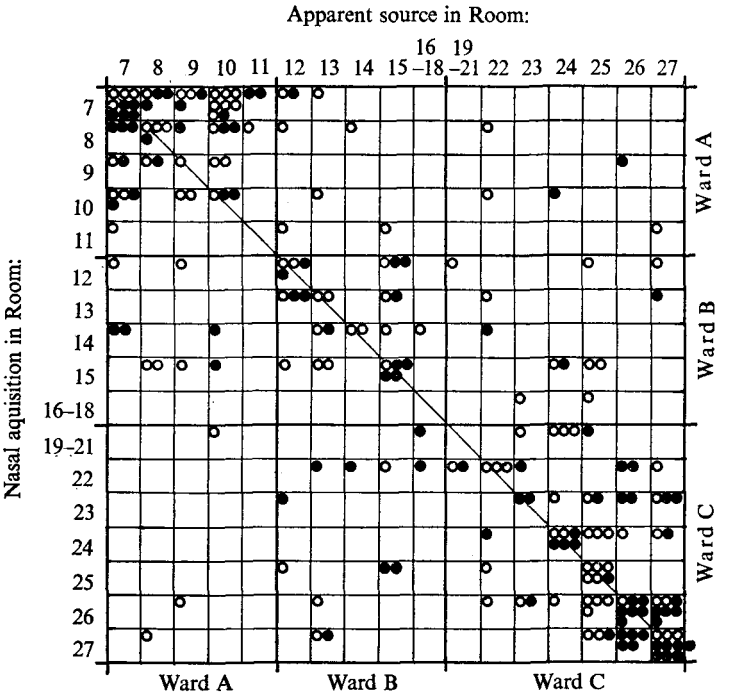

Fig. 5. Nasal acquisition of *Staphylococcus aureus* apparently derived from unique patient sources (carriers) in known positions in the wards. The numbers along the top of the figure marking the 17 columns specify the room which contained the apparent source. The numbers marking the 17 horizontal rows specify similarly the room in which the acquisition occurred. The three single-bed rooms associated with ward B, rooms 16–18, have been grouped together. Rooms 19–21 have been treated similarly. The grouping of the rooms within the wards is given at the bottom and right hand side of the figure. The location and apparent source of each of the 217 acquisitions is indicated in the appropriate cell. The filled circles indicate acquisition of strains resistant to tetracycline.

On comparison of the acquired strains with those strains isolated during the preceding weeks from nasal swabs or lesions a single possible source, i.e. a patient or member of staff carrying an indistinguishable strain, was found for about $\frac{1}{3}$ of these. On about 10% of occasions the strain was untypable, in another third no possible source could be identified. In nearly a quarter there was more than one possible source and these were located in different situations in the wards, e.g. patients in more than one room or the same strain carried both by a patient and a member of the hospital staff, these sources have been classified as ambiguously located.

The percentage distribution of the identified sources is given in Table 5. The largest proportion, nearly 40%, of these nasal acquisitions appeared to derive from patients nursed in other rooms of the same ward. An additional 15% could be ascribed to patient carriers in other wards and about 25% of the acquisitions appeared to be from staff carriers. These proportions did not vary very much between the different periods of the study. Ward B contained fewer 6-bed rooms and was situated between the two other wards; it is not surprising therefore to find

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that a rather smaller proportion than average, 26 %, of nasal acquisitions by patients in this ward could be ascribed to patients in other rooms of the ward and a rather larger proportion, 27 %, to patients in the other two wards. At first sight it would seem that a substantially smaller proportion of the acquisitions from other patients at Welwyn were derived from patients in a bed in the same room as the patient acquiring than was seen at Greenwich, only 7 % compared to 19 %. The difference, however, appears much less when account is taken of the fact that the Welwyn patient had on average only a little over 2·5 companions in the same room whereas the Greenwich patient had 4 (these figures take into account the average bed occupancy). The proportion of acquisition from patient sources in other rooms lies between 50 % and 56 % in both hospitals, both for all strains and for the strains resistant to tetracycline.

The widespread distribution throughout the three wards of the patient sources from which the nasal acquisitions were apparently derived is shown in Figure 5. Although there is substantial clustering along the diagonal of the figure, indicating a higher probability of acquisition from a patient source located near to the recipient, the majority of the sources are to be found in other rooms, often at some considerable distance. It is clear that the exclusion of direct airborne particle transfer from one patient room to another has not eliminated, or even substantially reduced, nasal acquisition from sources in other rooms than that in which the recipient is nursed.

Airborne Staphylococcus aureus

The results of the air sampling are shown in Table 6.

The numbers of particles carrying *Staph. aureus* that settled from the air was very variable from one occasion to another and at different sites on the same day. The average values did not, however, differ significantly in the different wards and during the different periods except perhaps for rather higher numbers found during period III when there was an episode involving widespread colonization with, and dispersal of, a particular strain (Lidwell & Brock, 1970). The numbers settling from the air of the wards, between 196/100 m². min. and 339/100 m². min., were about twice those isolated from the samples taken in the passage, 141/100 m². min.

All these figures are much greater than those from the Welwyn hospital where the average daytime value in the wards was no more than 89 colonies of *Staph. aureus*/100 m². min. We are not able to give any convincing reason for this. The numbers of staphylococcus-carrying particles in the air of the Greenwich hospital would seem to be as great as we found in any of the earlier studies (*v.* Table 11). The only similar figures are from observations made at St Bartholomew's Hospital between 1956 and 1961, although variations in sampling methods make strict comparison impossible. These were obtained in open-plan wards and showed a very pronounced pattern of peaks of widespread airborne dispersal of particular strains occurring in a random manner through the duration of the investigations. Similar bursts of dispersal were also characteristic of the situation found at Greenwich, similar to that occurring during Period III referred to above. Higher counts could

Table 6. Staph. aureus *in the air of the hospital*

Ward (patient rooms)	No. of plates exposed*	No. of particles carrying *Staph. aureus* settling/100 m². min.
	Greenwich Hospital	
A	626	278
B	518	196
C	736	339
S	296	256
Passages	451	141
Period (all patient rooms)		
I	242	222
II	470	265
III	660	317†
IV	508	269
All patient rooms and periods	1880	279
	Welwyn Hospital‡	
Patient rooms	588	89

S stands for single bedrooms, included in wards B and C.

* Each 14 cm. diameter plate was exposed for 7 hr. during the day, i.e. each corresponded to 6·5 m². min. of exposure.

† During this period there was widespread dispersal of one particular strain resulting in many occasions when the source was ambiguous owing to the simultaneous presence in the wards of more than one carrier of the strain.

‡ Lidwell *et al.* 1971. Day samples only. These figures are about 2·3 times greater than those taken during the night.

arise if the samples included a period or periods of high activity without any similar events taking place during the other samples with which the first were being compared. Although the settle plate samples at Greenwich covered a full 7 hr. from approximately 9.30 a.m. until 4.30 p.m. while in most of the other studies relatively short duration volumetric samples were used, the samples from Welwyn were of 8 hr. duration. In addition the ratios of the counts obtained from these samples to those obtained during the night hours, when activity was minimal in both places, were similar. This ratio was 1·9 : 1 at Greenwich and 2·3 : 1 at Welwyn. Another circumstance which could lead to larger numbers of colonies on the settle plates would be the dispersal of *Staph. aureus* in larger particles with a higher sedimentation velocity, but we have no evidence for this. The provision of mechanical ventilation, at the rate of 5–7 air changes per hour, would not in itself be expected to lead to any substantial reduction in the numbers of airborne bacteria. The fresh air ventilation rate in a naturally ventilated ward may be anything from two air changes per hour upwards to which must be added an allowance for exchange through the room doors, usually left open. This would have been very substantial at Welwyn where the patients' rooms were open to the corridor above a level of about 1 m. Loss of particles by sedimentation is likely to be equivalent to additional ventilation at a rate of 6–8 per hour. As a result of all these

factors the airborne counts in the mechanically ventilated rooms might be expected to lie anywhere between essentially the same as in the naturally ventilated ones, down to about $\frac{2}{3}$ of this $((2+6)/(7+6)=0{\cdot}61)$, cp. the effect of mechanical ventilation on the numbers of airborne micro-organisms in the air of offices (Kingston, Lidwell & Williams, 1962).

As nasal swabs were obtained from all patients on the day that the settle plate samples were obtained it was a straightforward matter to compare the strains isolated. No source could be found for 12 % of the strains recovered from the settle plates and a further 7 % were untypable (Table 7). In addition 44 % were indistinguishable from strains carried by more than one carrier located in different situations in the wards. This left 37 % for which only one source could be found. Of these over half could be related to patient sources in the same room, $\frac{1}{3}$ however appeared to derive from patients in other rooms of the same ward and a further small proportion, about $\frac{1}{20}$, from patients in the other wards. These proportions were fairly consistent over the whole period of the study and for each ward, except for the single rooms. In these rooms only a little over 20 % of the strains recovered appeared to come from sources in other rooms.

When these figures are compared with those found at Welwyn it can be seen that a rather higher proportion of the airborne strains at that hospital were derived from sources in other rooms and a considerably higher proportion from the nursing staff. Although this could be taken to indicate that there was rather less airborne transfer between rooms at Greenwich than at Welwyn the difference is only small. More striking is the enormous discrepancy, in the Greenwich results, between what appears to be very considerable transport of airborne strains from the room containing the source into other patient rooms, especially those within the same ward, and the much smaller transport of airborne tracer particles. The distribution of the apparent sources of airborne strains (Table 7) may be used to calculate the concentrations, relative to that in the source room, found in other rooms in the ward.

For example, over the whole investigation 51 % of the strains derived from apparently unique sources could be related to sources in the same room as that in which the samples were taken, 33 % to sources in other rooms of the same ward and approximately 3 % and 2 % to sources in adjacent and remote wards respectively, more precisely 3·2 % and 2·3 %. Taking an average over all the three wards, weighted according to the numbers of patients in each, a 6-bed patient room was associated with 4·1 other such rooms in the same ward, 5·9 rooms in adjacent wards and 4·0 rooms in a remote ward. The airborne concentrations, in parts per thousand relative to that in a source room, found in other rooms of the same ward, in rooms in an adjacent ward or in rooms in a remote ward are then given by simple proportion as: $[33/(51\times4{\cdot}1)]\times10^3$, $[3{\cdot}2/(51\times5{\cdot}9)]\times10^3$ and $[2{\cdot}3/(51\times4{\cdot}0)]\times10^3$ or 158, 10·6 and 11·3, respectively. These figures are those given in the right hand column of Table 8 (rows i). The other values in rows (i) of the table have been calculated in a similar way for the indicated data groupings.

All these values for the numbers of airborne particles carrying *Staph. aureus* which would seem to derive from apparently unique sources of the strains are more than 100 times greater than the relative concentrations observed for airborne

Table 7. *Percentage distribution of apparent sources of airborne* Staph. aureus *found on settle plate samples*

Apparent source	Greenwich District General Hospital: Passages	Patient rooms, ward: A	B	C	S	Patient rooms, period: I	II	III	IV	All patients, rooms and periods	Queen Elizabeth Hospital, Welwyn*: 4 bed bays	single rooms
Patients†												
In same room	82	54	61	46	77	51	52	50	50	51	39	68
In other rooms of same ward		38	24	33	18	38	40	22	41	33	37	16
In adjacent wards	7	2	8	2	3	4	3	4	2	3	—	—
In a remote ward	3	1	—	4	0	1	1	4	1	2	—	—
Medical and Nursing staff†												
Working in same ward	5	3	5	13	1	3	3	18	4	9	24	15
Working in other wards	2	2	2	2	1	4	2	2	1	2	—	—
No unique identified source‡												
Ambiguously located	44	52	50	36	70	45	47	39	48	44	48	78
No source identifiable	11	9	11	14	2	12	7	15	13	12	19	7
Untypable strain	5	7	6	7	1		6	8	5	7		

S stands for single bed rooms.

* Lidwell *et al.* 1971.

† As percentage of colonies from identified apparently unique possible source.

‡ As percentage of all colonies.

Where two 'apparent sources' are bracketed, colonies apparently derived from these were not distinguished.

Table 8. *Apparent airborne transfer of* Staph. aureus *compared with transfer of a particle tracer*

Location of potential recipient	Type of transfer	Quantity transferred, parts per thousand of concentration in the source room: Period and ward: II & III A	II & III B	II & III C	IV A	IV B	IV C	All periods and wards
Other room in same ward	Airborne *Staph. aureus*							
	i From all apparently unique sources	189	171	91	99	121	216	158
	ii From individual dispersing sources	16·6	36·0	23·5	31·5	14·7	32·5	25·8
	Particle tracer							
	iii Arithmetically averaged data	0·30	1·32	0·74	1·50	3·33	2·38	1·66
Other room in adjacent ward	Airborne *Staph. aureus*		A+B+C			A+B+C		
	i From all apparently unique sources		12			8		11
	ii From individual dispersing sources		3·2			3·2		3·2
	Particle tracer							3·2
	iii Arithmetically averaged data		<0·04			0·51		0·27
Other room in remote ward	Airborne *Staph. aureus*		A+C			A+C		
	i From all apparently unique sources		14			6		11
	ii From individual dispersing sources		(0·3			0·0)		0·16*
	Particle tracer							
	iii Arithmetically averaged data		< 0·01			< 0·01		< 0·01

No data derived from individual sources nor for transfer of the particle tracer were obtained during period I. During periods II and III the patients' rooms, especially those in ward A, were mostly at a positive pressure with respect to the passage. During period IV rooms and passage were approximately balanced to each other.

The particle tracer figures have been calculated for arithmetically averaged data for tracer gas transfer combined with the estimated particle loss factors (Foord & Lidwell 1975*a*, 1975*b*).

* Based on very small numbers, only 5 colonies of *Staph. aureus* in all the samples together.

transport of tracer particles between the rooms of the wards (rows iii in Table 8). It is also noticeable that during Periods II and III when, as a result of the ventilation conditions at that time, the extent of particle transfer between patient rooms in Ward A was extremely low, about $0{\cdot}3 \times 10^{-3}$, the apparent transfer of airborne *Staph. aureus* between the same rooms was higher, at over 180×10^{-3}, than its average value for the whole period of the study. It seems certain, therefore, that the majority of the airborne *Staph. aureus* that were found in rooms other than that in which the only identifiable source of the strain was found must have reached these places otherwise than by being carried directly through the air after dispersal in the source room.

The dispersal of identified strains from unique sources

No system of sampling can ever have 100% efficiency. There is evidence to suggest (Shooter *et al.* 1963) that *Staph. aureus* is not isolated from a nasal swab on perhaps 10% of the occasions when it is in fact present. In addition two strains may be present in perhaps 10% of carriers (Solberg, 1965), but unless the colonies are morphologically distinct only one strain will usually be isolated. Other body sites than the nose may also carry the organism, even in the absence of lesions, and this strain may differ from that in the nose or may colonize that site without nasal carriage. Bøe, Solberg, Vogelsang & Wormnes (1964) found perineal carriage in the absence of nasal carriage in 3% of medical patients. Polakoff, Richards, Parker & Lidwell (1967) found the same situation in 2% of surgical patients examined.

The total effect of the possibilities discussed above, and of others, is impossible to assess quantitatively but it is obvious that a considerable proportion of the possible sources for the dispersal of *Staph. aureus* are likely to have been missed. As a consequence a supposedly unique source may not in fact be so and there might be other carriers of the strain simultaneously present in the ward. Some, or even most, of the discrepancy referred to above between the apparent transfer of airborne strains from 'unique' sources into other rooms and the transport of an airborne particle tracer might be due to such unrecognized carriers.

If the supposed source is in fact the actual source from which the strains recovered in other rooms are derived, then, whatever the means by which they are transported from the source, the numbers arriving at any other place should be proportional to the numbers being dispersed, and the airborne concentration in the room containing the source should be a good index of this.

All the occasions on which colonies were recovered from the air-sampling plates which apparently arose from a single patient source present in the wards at the same time were therefore listed individually. Several such instances might be found on the same day. When these were examined it was at once apparent that there were a substantial number when the highest air count was not found in the room containing the source but in some other place. Among a total of 559 occasions there were 175 such, and on 152 of these the strain was not recovered at all from the sample taken in the supposed source room. The distribution of the sources and the sites from which the source strain was recovered in the largest numbers is given in Table 9.

Table 9. *Position where the highest air-count of* Staph. aureus *derived from an apparently unique carrier of the strain was found*

(Number of occasions observed)

	Carrier in a 6-bed room in ward			
Highest count found in	A	B	C	Any ward
Same room as the carrier	128	88	168	384
Another room in the same ward	27	13	51	91
A room in an adjacent ward(s)	3	17	10	30
A room in a remote ward	7	—	2	9
The passage in the same ward	11	7	12	30
The passage in an adjacent ward(s)	1	6	3	10
The passage in a remote ward	0	—	5	5
Total	177	131	251	559

It seems reasonable to suppose, at least in the great majority of instances, that when the highest count occurred in another room than that containing the source this was due to the presence in that room of an unrecognized carrier of the strain. Only a minority of carriers dispersed their strains to a sufficient extent for colonies to be recovered from the air samples; there were 1725 instances when an apparently unique source was present in one or other of the 6-bed rooms in the wards on a particular swabbing day but only 384 (559–175) of these (22·2 %) dispersed their strain according to the above criterion. The simultaneous presence of dispersers of a given strain is, therefore, likely to be infrequent and the unrecognized carrier referred to above is then probably the only disperser.

Among the dispersing strains derived from apparently unique sources 41 % were resistant to tetracycline compared with 34% among the whole group of unique possible sources. Where, however, the greatest dispersal was in the same room as the recognized source the percentage of resistant strains was only 37, little more than that for all strains. This rose to 48 % where the greatest dispersal was in a different room from that in which the apparent source was situated, i.e. the missed dispersing strains were more often tetracycline resistant than the average of apparently unique strains, which is in accordance with previous observations of the greater propensity of many such strains to be dispersed into the air of hospital wards (Lidwell *et al.* 1966, 1970).

When the highest count was recorded at one of the passage sampling points this might be taken to indicate that there was an unrecognized dispersing carrier among the staff of that ward. The numbers of colonies found in most of these samples were, however, small and a proportion of the occasions when the highest count was observed in a passage sample may have arisen as a result of sampling error.

When the air counts in the source room are plotted against those in other rooms in the wards for those 384 instances when the highest air count was found in the room containing the apparently unique source there is a good linear relation between the two, both for the air counts in other rooms in the same ward as the source room and for the air counts in rooms in adjacent wards (Figure 6). The

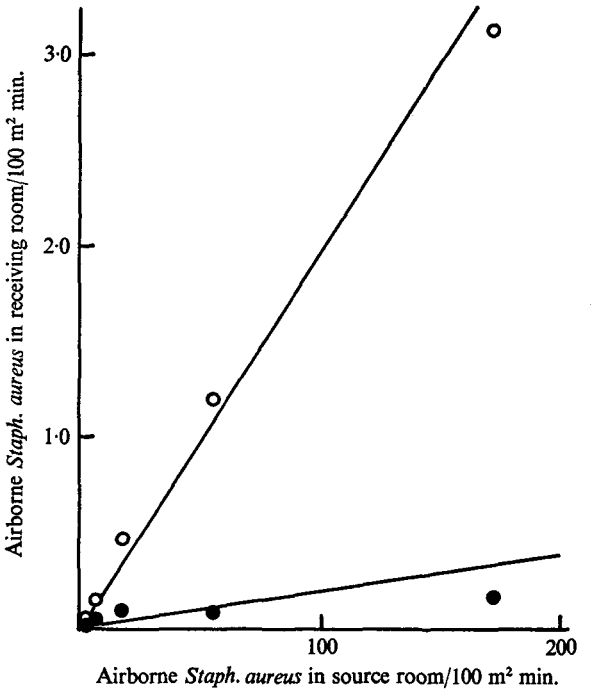

Fig. 6. The numbers of airborne *Staphylococcus aureus* found in rooms other than that in which a dispersing source was located. Only those occasions when the highest count was found in the room containing the apparent source have been included. The data have been divided into groups according to the numbers found in the samples taken in the source room, i.e. 1–3, 4–9, 10–29, 30–99, 100–300 and the points plotted at the geometric mean of the range. The upper curve ○, gives the numbers found in samples taken in other rooms of the same ward as that containing the source. The lower curve, ●, gives the numbers found in rooms in an adjacent ward.

counts in the rooms closer to the source room are also a much greater fraction of those in the source room than are those in more distant rooms. This is entirely in accord with expectation if the apparent sources are indeed those from which the colonies isolated in the rooms other than the source room are derived. The numbers of airborne *Staph. aureus*, derived from these instances, found in rooms other than that containing the source have been expressed as a fraction (parts per thousand) of those found in the source room for different periods of the study, for the three wards and for rooms in differing spatial relation to the source room (Table 8, rows ii). The removal of the 25 % of instances when the dispersing source was probably an unrecognized carrier has appreciably reduced the fraction reaching rooms other than the source room compared with that deduced from the crude figures for all strains derived from apparently unique sources (Table 8, rows i). For the whole investigation, the reduction is from 158 to 25·8 for sources in other rooms of the same ward, from 11 to 3·2 for sources in adjacent wards and from 11 to, perhaps, as low as 0·16 for sources in remote wards, i.e. by from 3 to over 50 times, although the accuracy of this last figure is not very high. The dispersal of airborne *Staph. aureus* deduced in this way is still however about 15 times that estimated for direct

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airborne carriage of the particle tracer. A difference of this order is found for all the wards and in both the two periods into which the data have been divided.

It is of some interest to compare the extent of dispersal from the unrecognized sources with that from the 384 apparently genuine and unique sources. From these 384 sources 5639 colonies were recovered in the source rooms, equal to 14·7 colonies per source sample. For the unrecognized sources the corresponding figures are 1699/130 = 13·1, assuming that the effective dispersing source was in the room showing the highest sample count. In other words these unrecognized sources disperse to about the same extent as those found by nasal swabbing. Since it would seem likely that unrecognized nasal carriers would be preponderantly carriers of only small numbers in the nose it is, perhaps, probable that most of the unrecognized dispersers were carriers of the organism at other sites. Most of the infected lesions will have been recognized and swabbed so that perineal carriers seem the most likely to have been concerned.

If the airborne *Staph. aureus* found in rooms other than those containing the source are not transported by air movements, and the evidence discussed above suggests that less than 10% could have been carried in this way, how do they reach these situations. This problem has already been discussed in a preliminary report on the Greenwich hospital studies (Lidwell & Brock, 1970). From the evidence presented there it does not seem at all likely that inter-room visiting by patients could account for even a small part of the transfer recorded and it is more probable that this takes place by means of the contamination of the clothing of nurses and other staff when dealing with patients, the organisms are then dispersed into the air of the other rooms by activities within them.

Exposure to airborne Staph. aureus *and nasal acquisition*

In previous investigations (Lidwell *et al.* 1966, 1970, 1971) it was possible to relate the risk of nasal acquisition of *Staph. aureus* by patients in particular spatial relation to carriers of the strains acquired, e.g. in the same or different rooms of the ward, to their exposure to airborne staphylococci of strains apparently dispersed by carriers situated in the same spatial relation. In each case the risk of acquisition from carriers in different situations varied as no more than a fractional power of the variation in air exposure. The ascertainment of this relation was based on the assumption that the apparent sources of both the nasal acquisition and the organisms found in the air samples were a reasonably good approximation to the actual sources. In the previous section it has been shown that, at Greenwich, some 25–30% of the sources which dispersed sufficient numbers of staphylococci into the air of the wards for these to be isolated from the air-samples had not been recognized by the bacteriological methods employed. The extent of the difference between the real distribution of the sources of nasal acquisition and of air strains and the apparent distribution consequent upon the failure to detect these carriers will depend on the distribution in space of these missed carriers themselves. It is at once apparent from Table 9 that they are by no means randomly distributed in relation to the location of the recognized, but non-dispersing, carrier of the same strain. The two are most often within the same ward and the frequency falls off

with greater separation. This suggests there is a relation between them, either that one is the source of the other or that both have a common origin.

Assuming that the distribution of unrecognized dispersing carriers shown in table 9 is representative of all carriers (ignoring those occasions when the highest counts occurred in the passage) it is possible to deduce the actual distribution of carriers, including those that escaped recognition. Taking the average patient carrier rate of 34 % and bed occupancy of 5 the average number of recognized carriers in a 6-bed room will be $5 \times 0{\cdot}34 = 1{\cdot}70$. These will be associated with undetected carriers of the same strains in other rooms, i.e. $\frac{1{\cdot}70 \times 91}{384 \times 4} = 0{\cdot}101$ in each of the 4 other rooms of the same ward, with $\frac{1{\cdot}70 \times 30}{384 \times 6} = 0{\cdot}022$ in each of the 6 rooms of an adjacent ward and with $\frac{1{\cdot}70 \times 9}{384 \times 4} = 0{\cdot}010$ in each of the 4 rooms of a remote ward. The figures are calculated for a formalized representation of the wards in which each 6-bed patient room is part of a ward of 5 such rooms with 6 such rooms in an adjacent ward and 4 such rooms in a remote ward. This gives rise to the distribution of possible sources given in Table 10. For example, if we consider the situation where the recognized source is in the same room as the potential recipient then there will also be 0·101 possible sources of these strains in each of the 4 other rooms in the same ward resulting in $4 \times 0{\cdot}101 = 0{\cdot}40$ sources in other rooms of the same ward. For recognized sources in rooms in adjacent wards there will be $1{\cdot}70 \times 6 = 10{\cdot}20$ recognized sources in the 6 rooms and those in each room will be associated with 0·101 undetected possible sources in each of the other 5 rooms, i.e. a total of $0{\cdot}101 \times 6 \times 5 = 3{\cdot}02$ undetected sources for the same strain making a total number of sources in the adjacent wards of $10{\cdot}20 + 3{\cdot}02 = 13{\cdot}22$. The other cells in Table 10 have been calculated in a similar way.

It is clear that, in any situation, the greater proportion of potential source carriers are disposed similarly to the apparent sources, compare the figures in the bottom row of Table 10 with those in the left hand column. A correction to the distribution of the probable sources for nasal acquisition by patients has been made according to the figures in this table (see below) and is shown in Table 5. The difference from that obtained by using the recognized sources only is insignificant.

Using the distribution of apparent sources in relation to the individual wards and for the four periods of the study given in Tables 5 and 7, we have calculated values for the nasal acquisition rates/1000 patient weeks/source carrier and for the exposure to airborne *Staphylococcus aureus* expressed as the numbers settling/100 m².min./source carrier for carriers in various relations to a potential recipient.

The mean rate of nasal acquisition over the whole investigation was 87·3/1000 patient weeks (Table 4) or $87{\cdot}3 \times \frac{(100-35-11)}{100} = 47{\cdot}1$ from identifiable sources (Table 5). These acquisitions are attributable to the different groups of sources according to the proportions shown in Table 5, e.g. from other patients in the same room $47{\cdot}1 \times \frac{19}{100} = 8{\cdot}9$, etc. Similar calculations have been carried out for the

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Table 10. *Numbers of potential source carriers in relation to a possible recipient*

Recognized apparent sources		Actual number of sources in			
Location	Number	Same room	Other rooms in same ward	Other rooms in adjacent wards	Other rooms in a remote ward
Same room	1·36	1·36	0·40	0·13	0·041
Other rooms in the same ward	6·8	0·32	8·01	0·53	0·16
Other rooms in adjacent wards	10·2	0·11	0·53	13·22	0·53
Other rooms in a remote ward	6·8	0·032	0·16	0·53	8·01
All rooms		1·82	9·10	14·41	8·74

These figures have been obtained by taking an average of the numbers of patients in the different ward situations in relation to a potential recipient. The distribution of unrecognized sources has been taken to follow that of the unrecognized dispersers deduced from Table 9. The average patient carriage rate has been taken as 34 % and allowance has been made for the fact that only 4/5 of the carriers in a room are potential sources for a recipient in that room, i.e. of the average number of 1·70 carriers recognized in a 6-bed room only $1{\cdot}70 \times 4/5 = 1{\cdot}36$ sources are presented to each patient in that room.

numbers of *Staph. aureus* settling from the air using the data in Tables 6 and 7. The values for the nasal acquisition rates and for the settling rates have then been divided by the numbers of apparent sources given in the first column of Table 10. Calculations of this kind have also been carried out for the results obtained from the individual wards and during the four periods into which the investigation has been divided. The resulting rates of nasal acquisition and the corresponding numbers settling, each per single source carrier, are plotted in Figure 7 on a double logarithmic scale as was done for the previous studies. The data are reasonably well represented, over the whole range, by a straight line with a slope of approximately 0·5. It should be noted that the individual points shown are not all independent since they represent different derivations from the same data.

Acquisition rates related to the estimated actual number of sources given in table 10 can also be calculated. This has only been done for the data from the whole investigation taken together. If a_1 is the rate of nasal acquisition from a single patient carrier in the same room, a_2 from one in another room in the same ward, a_3 from one in an adjacent ward and a_4 from one in a remote ward, then:

$$1{\cdot}36a_1 + 0{\cdot}40a_2 + 0{\cdot}13a_3 + 0{\cdot}041a_4 = 47{\cdot}1(19/100) = 8{\cdot}9$$
$$0{\cdot}32a_1 + 8{\cdot}01a_2 + 0{\cdot}53a_3 + 0{\cdot}16a_4 = 47{\cdot}1(38/100) = 17{\cdot}9$$
$$0{\cdot}11a_1 + 0{\cdot}53a_2 + 13{\cdot}21a_3 + 0{\cdot}53a_4 = 47{\cdot}1(12/100) = 5{\cdot}7$$
$$0{\cdot}032a_1 + 0{\cdot}16a_2 + 0{\cdot}53a_3 + 8{\cdot}01a_4 = 47{\cdot}1(3/100) = 1{\cdot}4$$

The solution of these equations gives; $a_1 = 5{\cdot}92$, $a_2 = 1{\cdot}96$, $a_3 = 0{\cdot}31$ and $a_4 = 0{\cdot}08$.

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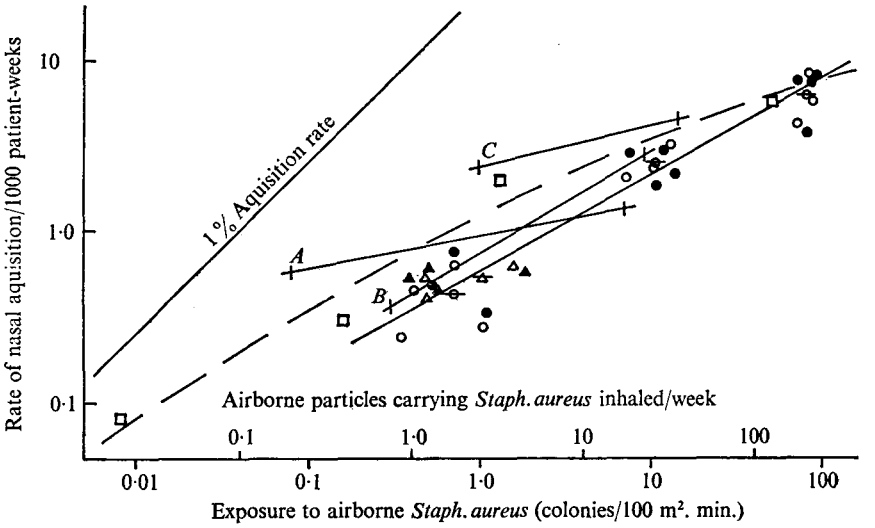

Fig. 7. Exposure to airborne *Staph. aureus* and the rate of nasal acquisition. The vertical scale is the rate of acquisition of a new strain in the nose, per single potential source (carrier) per 1000 patient-weeks. The horizontal scale is the exposure to airborne *Staph. aureus*, per single potential source (carrier), expressed as the number of colony forming particles settling per 100 m² (1080 ft²) min. during daytime hours. Above this scale is given, approximately, the corresponding number of airborne particles carrying *Staph. aureus* which would be inhaled by a patient during one week. For this purpose the mean breathing rate has been taken as 10 l/min. and the exposure during the 12 night hours as one half that during the daytime. All the scales are logarithmic. The acquisition rates from the detected patient sources are shown by circles and those from staff carriers by triangles. The open symbols correspond to data for the three wards taken separately and the filled symbols for the four periods of the investigation. The open symbols crossed by short horizontal bars refer to the average values for the whole investigation. The group of 8 circles in the upper right hand corner of the figure relates to acquisitions from patient sources in the same room as the recipient; the centrally placed group to patient sources in another room of the same ward and the lower left hand group to patient sources in another ward. The 'best' straight line through these points has been drawn by eye. The results of previous calculations of this kind have been included in the figure, for purposes of comparison, as shorter lines on which short vertical bars indicate the range of values covered; *A* (Lidwell *et al.* 1966) *B* Lidwell *et al.* 1970) and *C*, Queen Elizabeth II hospital, Welwyn (Lidwell *et al.* 1971). For acquisition from patient sources at Greenwich, corrected values have been derived which attempt to take account of undetected (missed) possible sources (see text). These have also been plotted on the figure, as squares which correspond, in order of decreasing exposure to airborne *Staph. aureus*, to nasal acquisition from patient sources in the same room as the recipient, in other rooms of the same ward, in rooms in an adjacent ward and in rooms in a remote ward. The curved broken line has been drawn through these four points. Also indicated on the figure is the rate of nasal acquisition which would result if 1/100 of the particles carrying *Staph. aureus* inhaled were to result in acquisition of that strain in the nose.

If these rates of acquisition from single source-carriers are mutliplied by the total numbers of carriers given in the bottom row of Table 10 we have for the estimated actual rate of acquisition from all patient carriers in the same room, $5{\cdot}92 \times 1{\cdot}82 = 10{\cdot}78$, from carriers in other rooms of the same ward $1{\cdot}96 \times 9{\cdot}10 = 17{\cdot}84$, from carriers in adjacent wards $0{\cdot}31 \times 14{\cdot}41 = 4{\cdot}47$ and from carriers in

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remote wards $0{\cdot}08 \times 8{\cdot}74 = 0{\cdot}73$, a total of 33·86. The percentage distribution of these, as a proportion of acquisitions from all recognizable sources, is $10{\cdot}78 \times (100-20-8)/33{\cdot}86 = 10{\cdot}78 \times 2{\cdot}13 = 22{\cdot}9$, $17{\cdot}84 \times 2{\cdot}13 = 38{\cdot}0$, $4{\cdot}52 \times 2{\cdot}13 = 9{\cdot}6$ and $0{\cdot}73 \times 2{\cdot}13 = 1{\cdot}6$ which are the values given, rounded to the nearest whole number, in parentheses in Table 5.

The exposure to airborne *Staph. aureus* from actual sources in known positions has been estimated from the figures for airborne transfer from identified individual sources given in rows ii of Table 8 combined with the average dispersal in a source room. The isolation of 5639 colonies from the 1725 recognized unique sources on the 384 occasions when the highest count was found in samples exposed in the same room as the source corresponds to a settling rate in the same room as a unique source of $\frac{5639}{1725} \times \frac{100}{6{\cdot}5}$ or 50·3/100 m.² min. (each plate exposure was equivalent to 6·5 m.² min.). The figure for other rooms in the same ward is then $50{\cdot}3 \times 25{\cdot}8 \times 10^{-3} = 1{\cdot}3$, for rooms in adjacent wards, 0·16, and for rooms in remote wards, 0·008. These values for exposure to airborne *Staph. aureus* from single source carriers, corrected for the effect of missed carriers, have also been plotted in Figure 7 against the rates of nasal acquisition similarly corrected (a_1, a_2, a_3 and a_4 as calculated above). The increased reliability of these estimates in relation to the degree of exposure to airborne staphylococci and the rates of nasal acquisition from sources in a ward remote from the recipient has made it possible to separate out these from those sources in adjacent wards. The range of values covered by the data is then extended by a factor of more than 10 in the exposure to airborne staphylococci.

The individual points cover a range of 100 : 1 in the risk of nasal acquisition and nearly 10,000 : 1 in exposure to airborne staphylococci. The general trend of these points differs little from that for the uncorrected data although the nasal acquisition rates are somewhat higher for similar exposure to airborne *Staph. aureus*.

For the purpose of comparison the data from the three previous investigations have been included in the figure, as short lines covering the relevant ranges. That from the 1970 report is indistinguishable from the present results. The other two lie within the present results for their highest exposures but deviate from these as the level of exposure to airborne staphylococci is reduced. The flatter response leads to higher rates of nasal acquisition in these circumstances. We know too little about factors that might determine dose-response curves of this kind, or of the errors in these estimates, to attempt any explanation for the differences.

The corrected Greenwich data are, perhaps, best represented by a curved rather than a straight line relation and this, shown as a broken line in Figure 7, could be said to give a reasonable approximation to the data for all four investigations. The dose-response curve appropriate to infection in a non-homogeneous population would be curved in this way (Lidwell, 1963). The rate of infection must approach a constant value as the dose rate is increased and near 100 % of the susceptibles are infected. If the dose is reduced the rate of infection cannot exceed the frequency with which a single dose unit is received. The line corresponding to an infection rate

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of 1 % of this is given on the figure. None of the data presented reach this line and the ultimate limit of the 100 % rate is therefore still more than 100 times above any acquisition rates recorded.

The consistent appearance of a relation between the risk of nasal acquisition and the exposure to airborne staphylococci from individual carrier sources does not prove that this is the mechanism by which nasal acquisition is produced. The numbers of airborne cocci could be an index of exposure to infection by other routes. Measures that reduce exposure to airborne staphylococci will often reduce the risk of bacterial transfer between patients in other ways. Unfortunately the hope that by very greatly reducing the direct airborne transfer of particles between patient rooms the exposure to airborne staphylococci arising from patient sources in other rooms would be similarly reduced was not realized at Greenwich. Probable transfer by non-airborne routes followed by redispersal into the air of another room resulted in exposure to airborne cocci derived from patient sources in other rooms about as great as that observed in naturally ventilated semi-open wards. We have therefore been unable to verify the expectation that reduction in the airborne dose alone would lead to reduction in the risk of nasal acquisition.

A direct experiment has, however, been carried out by Solberg (1974). Nasal carriers of *Staph. aureus* were placed for 10 days in a 4-bed room mechanically ventilated at 3–4 air changes per hour together with three other patients who were not nasal carriers. These non-carriers were nursed by nurses other than those who dealt with the carrier. Among patients exposed to carriers who dispersed more than 100,000 staphylococcal carrying particles in a standard test 30 % became themselves carriers of the same strain. Among those exposed to carriers who disperse no more than 100 particles in the test only 5 % became carriers of the strain. The only difference here between the treatment of the two groups was the degree of exposure to airborne infection and a probable reduction in dose of the order of 1000 fold appeared to lead to a 6-fold reduction in the risk of nasal acquisition. This corresponds to a slope of the dose-response curve as plotted in Figure 7 of about 0·25. It is however possible that the strains carried by patients who disperse greater numbers of *Staph. aureus* into the air may have differed in other respects from those strains dispersed in smaller numbers. If they differed in ability to colonize the nose, then this would imply that the ratio of the nasal acquisition rates observed was not wholly determined by the relative exposure to airborne staphylococci.

Although there was evidence that a substantial proportion of patient carriers were not detected in the present investigation, allowance for these made no significant difference to the apparent dose-response relation. This was due to the fact that these missed carriers were found most frequently in close proximity to observed carriers of the same strain. Had they been distributed at random throughout the ward they would have considerably increased the apparent risk of nasal acquisition in situations remote from the recognized sources, i.e. the slope of the dose-response curve would have been reduced below its true value. An effect of this kind would account for the lower slope of the dose-response curve observed in two of the previous studies but there is no actual evidence to support such an assumption. Even

after allowing for the effect of missed carriers, the slope of the relation observed in the Greenwich study, which was by far the most extensive, is only about 0·5, i.e. a hundredfold reduction in exposure to the airborne strains only leads to a tenfold reduction in the rate of nasal acquisition.

DISCUSSION

However the results are expressed, the pattern and extent of the acquisition of new strains of *Staphylococcus aureus* by patients in the medical wards of the new Greenwich District Hospital from other patients in those same wards did not differ from that observed in open wards of the Nightingale type or in partly divided wards in which the separation between the patient bed areas was largely visual. In spite of the very small extent of direct airborne transfer from one patient room to another of particles of the size normally associated with airborne bacteria, such as *Staphylococcus aureus*, strains of this species, presumptively originating from patient carriers in other rooms and wards, could be found in substantial numbers in the air of many other patient rooms. Since the ventilation system did not result in a great, or perhaps any, reduction in the exposure to airborne organisms the investigation could not provide an answer to the question whether reduction in such exposure would bring about a reduction in the risk of nasal acquisition, as it should do if such acquisitions normally take place by means of the airborne route. It does, however, show clearly that even a well designed ventilation system will not by itself reduce the rate of staphylococcal colonization in a general hospital.

The purpose of our series of studies, of which this is the latest and probably the last, was to explore the environmental determinants of hospital staphylococcal infection, especially in relation to the subdivision of the ward into smaller patient bed units and the provision of mechanical ventilation. Some of the results obtained in these investigations are summarized in Table 11 together with those from some other studies which provided comparable data. The attempts to reduce the spread of infection, in particular the nasal acquisition by patients of new and often antibiotic resistant or 'hospital' strains have not been particularly successful. The low rates of acquisition of antibiotic resistant strains observed in reference 4, an infectious diseases ward with patients in single-rooms opening off a covered and partly enclosed passageway, and in reference 5, a modern very subdivided thoracic surgery ward might suggest that subdivision into small patient units in itself was effective. Similarly low rates were also reported in reference 7, where an open surgical ward had been divided into a pre-operative and post-operative section with mechanical ventilation designed to protect the first section from exposure to strains originating from patients in the second section. This satisfactory result was not maintained, however, when the introduction of a particular strain was followed by its widespread dissemination and acquisition throughout the ward. The varied nature of the strains which may be present in a hospital environment at any particular time is one of the major uncontrollable variables in studies of this kind. Observations made over a favourable period may easily lead to over-optimistic conclusions. Although there appears to be a quantitative relation between the

Table 11. *Nasal acquisition and airborne* Staph. aureus

Ref*	Ward type	Ventilation	Year	Nasal acquisition rate/1000 patient weeks		Airborne *Staph. aureus*/ 100 m.³ min., or /30 m.³
				All strains	T strains	
1	Open	Natural	56/57	95	—	270
2	Open	Natural	56/61	91	—	204
3	Open	Natural	61/62	90 (94)†	37 (63)†	—
4	Verandah	Natural	62/63	64	14	—
5	Sub-divided	Natural	62–64	34	13	38
6	Divided Pre-op	Natural	62	99	20	88
	Divided Post-op	Natural	62	119	42	100
7	Divided Pre-op	Mechanical	63/64	36	11 (8)‡	61
	Divided Post-op	Natural	63/64	57	10 (7)‡	114
8	Divided Pre-op	Mechanical	66/67	71	32 (27)‡	68
	Divided Post-op	Mechanical	66/67	58	38 (33)‡	71
9	Open	Natural	68	84	32	—
	'Race-Track'	Mechanical	68	70	19	—
10	Semi-open	Natural	65/66	77	29	89
11	Sub-divided	Mechanical	70–73	84	40	279

T strain, strain resistant to tetracycline.

All the estimates of airborne *Staph. aureus* were made by volumetric sampling using some form of slit sampler for various sampling times up to 1 hr. except for the last two studies, references 10 and 11 where all-day settle plates were used.

At a particle settling rate of 5 mm/sec. (30 cm/min.) the numbers settling /100 m². min. are equivalent to the numbers /30 m.³ of air.

* References: 1, Shooter *et al.* 1958; 2, Williams *et al.* 1962; Noble, 1962; 3, Parker, 1965; 4, Parker *et al.* 1965; 5, Lidwell *et al.* 1966; 6, Shooter *et al.* 1963; 7 & 8, Lidwell *et al.* 1970; 9, Whyte *et al.* 1969; 10, Lidwell *et al.* 1971; 11, This study.

† Acquisition rates for patients receiving antibiotics.

‡ Acquisition rates for a single epidemic strain (84/85).

exposure to individual airborne strains and the risk of acquiring them in the nose it has proved more difficult than was expected to achieve any significant reduction in this exposure. Because the relation between the inhaled dose and the infection risk appears to be less than proportional, i.e. the risk varies as no more than the square root of the dose, a large reduction in the dose, more than tenfold, would be needed to produce any useful effect.

Other observations (Speers *et al.* 1969; Hambraeus, 1973; Lidwell, Towers, Ballard & Gladstone, 1974) have shown that nurses' clothing is regularly contaminated with strains carried by the patients they nurse. These strains are then easily redispersed into the air and this may occur when the nurse has entered another room. The generation of airborne particles carrying staphylococci derived

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from particular carriers may therefore be both complex and indirect. The medical and nursing staff of the hospital are not only capable of transferring micro-organisms from one patient to another by direct contact when touching or handling but may also be the means for creating an airborne risk to all the patients in a room they enter, not only those they attend to.

If this is so then structural changes or improved ventilation cannot be expected to reduce the risks of transfer of infection, even by the airborne route. They will only be capable of so doing if changes in nursing clothing or methods can be devised and put into practice which reduce, not only direct and indirect contact transmission, but also the dispersal into the air in other parts of the ward of micro-organisms acquired when attending to a patient.

The successful carrying out of this investigation was largely due to the very efficient work of the two research nurses, Mrs M. Fletcher and Mrs D. Faulkner, who took most of the patient and staff specimens and compiled the extensive records required. We cannot overstate our gratitude to them. We are also indebted to the bacteriological staff of the hospital laboratory who handled the large number of specimens involved and must also thank the hospital administration for permitting us to carry out the study and the nursing staff and patients of the wards concerned for their willing co-operation.

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REFERENCES

Bøe, J., Solberg, C. O., Vogelsang, T. M. & Wormnes, A. (1964). Perineal carriers of staphylococci. *British Medical Journal* ii, 280.

Davies, R. R. & Noble, W. C. (1962). Dispersal of bacteria on desquamated skin. *Lancet* ii, 1295.

Foord, N. & Lidwell, O. M. (1975*a*). Airborne infection in a fully air-conditioned hospital. I. Air transfer between rooms. *Journal of Hygiene* **75**, 15.

Foord, N. & Lidwell, O. M. (1975*b*). Airborne infection in a fully air-conditioned hospital. II. Transfer of airborne particles between rooms resulting from the movement of air from one room to another. *Journal of Hygiene* **75**, 31.

Hambraeus, Anna (1973). Transfer of *Staphylococcus aureus* via nurses' uniforms. *Journal of Hygiene* **71**, 799.

Kingston, D., Lidwell, O. M. & Williams, R. E. O. (1962). The epidemiology of the common cold. III. The effect of ventilation, air disinfection and room size. *Journal of Hygiene* **60**, 341

Lidwell, O. M. (1963). Methods of investigation and analysis of results. In *Infection in Hospitals* (ed. R. E. O. Williams and R. A. Shooter), p. 43. Oxford, Blackwell.

Lidwell, O. M. & Brock, B. (1970). Some aspects of the dispersal of *Staphylococcus aureus* in hospital wards. In *Airborne Transmission and Infection*, p. 454. Utrecht: Oosthoek Publishing Co.

Lidwell, O. M., Davies, J., Payne, R. W., Newman, P. & Williams, R. E. O. (1971). Nasal acquisition of *Staphylococcus aureus* in partly divided wards. *Journal of Hygiene* **69**, 113.

Lidwell, O. M., Polakoff, Sheila, Davies, J., Hewitt, J. H., Shooter, R. A., Walker, K. A., Gaya, H. & Taylor, G. W. (1970). Nasal acquisition of *Staphylococcus aureus* in a subdivided and mechanically ventilated ward: endemic prevalence of a single staphylococcal strain. *Journal of Hygiene* **68**, 417.

LIDWELL, O. M., POLAKOFF, SHEILA, JEVONS, M. PATRICIA, PARKER, M. T., SHOOTER, R. A., FRENCH, VALENTINE I. & DUNKERLY, D. R. (1966). Staphylococcal infection in thoracic surgery: experience in a subdivided ward. *Journal of Hygiene* **64**, 321.

LIDWELL, O. M., TOWERS, A. G., BALLARD, J. & GLADSTONE, B. (1974). Transfer of micro-organisms between nurses and patients in a clean air environment. *Journal of Applied Bacteriology* **37**, 649.

NOBLE, W. C. (1962). The dispersal of staphylococci in hospital wards. *Journal of Clinical Pathology* **15**, 552.

PARKER, M. T. (1965). A report from the Public Health Laboratory Service. Infections acquired in medical wards. *Journal of Hygiene* **63**, 457.

PARKER, M. T., JOHN, MADELEINE, EMOND, R. T. D. & MAHACEK, K. A. (1965). Acquisition of *Staphylococcus aureus* by patients in cubicles. *British Medical Journal* i, 1101.

POLAKOFF, SHEILA, RICHARDS, I. D. G., PARKER, M. T. & LIDWELL, O. M. (1967). Nasal and skin carriage of *Staphylococcus aureus* by patients undergoing surgical operation. *Journal of Hygiene* **65**, 559.

SHOOTER, R. A., GIRLING, J. A., MATTHIAS, J. Q. & WILLIAMS, R. E. O. (1960). Staphylococcus infection in a medical ward. *British Medical Journal* i, 1923.

SHOOTER, R. A., SMITH, M. A., GRIFFITHS, J. D., BROWN, MARY E. A., WILLIAMS, R. E. O., RIPPON, JOAN E. & JEVONS, M. PATRICIA (1958). Spread of staphylococcus in a surgical ward. *British Medical Journal* i, 607.

SHOOTER, R. A., THORN, B. T., DUNKERLY, D. R., TAYLOR, G. W., PARKER, M. T., JOHN, MADELEINE & RICHARDS, I. D. G. (1963). Preoperative segregation of patients in a surgical ward. *British Medical Journal* ii, 1567.

SIMON, J. (1863). 6th Report of the Medical Officer of the Privy Council, London.

SMYLIE, H. G., DAVIDSON, A. I. G., MACDONALD, A. & SMITH, G. (1971). Ward design in relation to postoperative wound infection: part 1. *British Medical Journal* i, 67.

SPEERS, R., SHOOTER, R. A., GAYA, H., PATEL, NIRANJANA & HEWITT, J. H. (1969). Contamination of nurses uniforms with *Staphylococcus aureus*. *Lancet* ii, 233.

SOLBERG, C. O. (1965). A study of carriers of *Staphylococcus aureus*. *Acta medica scandinavica* **178**, Suppl. 436.

SOLBERG, C. O. (1974). Spredning av *Staphylococcus aureus* på Sykehus. R³ Symposium Nordiska Föreningen för Renlighsteknik & Rena Rum, Hamar. University of Oslo Congress Service, Box 55, Blindern, Oslo 3, Norway.

WILLIAMS, R. E. O., JEVONS, M. PATRICIA, SHOOTER, R. A., HUNTER, C. J. W., GIRLING, J. A., GRIFFITHS, J. D. & TAYLOR, G. W. (1959). Nasal staphylococci and sepsis in hospital patients. *British Medical Journal* ii, 658.

WILLIAMS, R. E. O., NOBLE, W. C., JEVONS, M. PATRICIA, LIDWELL, O. M., SHOOTER, R. A., WHITE, R. G., THOM, B. T. & TAYLOR, G. W. (1962). Isolation for the control of staphylococcus infection in surgical wards. *British Medical Journal* ii, 275.

WHYTE, W., HOWIE, J. G. R. & EAKIN, J. E. (1969). Bacteriological observations in a mechanically ventilated experimental ward and in two open-plan wards. *Journal of Medical Microbiology* **2**, 335.