J. Hyg., Camb. (1968), **66**, 229
Printed in Great Britain

Thermal comfort during surgical operations

By D. P. WYON*, O. M. LIDWELL and R. E. O. WILLIAMS
Central Public Health Laboratory, Colindale Avenue, London, N.W. 9
and Wright-Fleming Institute, St Mary's Hospital Medical School,
Paddington, London, W. 2

(*Received* 28 *October* 1967)

In spite of much recent discussion and complaints by surgeons that operating rooms are often hot and uncomfortable no direct studies appear to have been made of this environment in Great Britain. Bedford (1936) found that most people in very light industrial work preferred an indoor temperature of 65° F. in winter. A later investigation in a similar environment in summer (Hickish, 1955) indicated a slightly higher preferred temperature, 67·5° F. American surgeons (Houghten & Cook, 1939) appear to prefer a substantially higher temperature, 73° F. but this is also true of North American people generally. However, a recent study among office workers in Great Britain (Black & Milroy, 1966) gave an optimum temperature for comfort as high as 72° F.

Operating room temperatures have often been kept fairly high in the supposed interest of the patient. More recently it has been assumed that this is not necessary (Angus, 1959). Some current physiological studies, however (Mr H. F. Lunn, personal communication) suggest that heat loss from ordinary adult patients during surgical operations is significant. Full control of patients' heat loss by adjustment of the thermal environment in the operating room is unlikely to be practicable, and, if such control is required, it must and can be achieved by direct methods applied to the patient himself. The present study has been concerned solely with the comfort of the operating room staff and was devised to provide guidance for the design of operating suites in the British Isles.

Comfort is a subjective assessment related to, but not entirely determined by, the thermal effects of environment; a good general discussion is given by Bedford (1964). In particular, the perception of comfort, or more accurately of discomfort, is affected by activity, both physical and mental, by clothing, acclimatization and personal idiosyncrasies. These factors may lead to varying responses by the same individual on different occasions in the same physical environment as well as to different responses by different individuals. It is important also to realize the ephemeral element in assessments of comfort. As habits and tolerance change so will the acceptable range of environmental conditions. However, such changes are slow and the factors relevant to the perception of comfort remain relatively constant within a particular situation.

---

* Now at: Statens Institut för Byggnadsforskning, Valhallavägen 191, Stockholm 27, Sweden.

Requests for reprints should be sent to O. M. Lidwell at the Central Public Health Laboratory, Colindale Avenue, London, N.W. 9

METHODS

Organization

A large number of comfort studies have been carried out by repeated observation on a small number of individuals in an experimentally varied environment. This is a satisfactory method for a fundamental study of the relative effects of different environmental variables. It was not considered suitable for this investigation, since we were concerned with comfort assessments under normal working conditions and with the full range of interpersonal variations to be found in practice.

We therefore visited thirty separate operating suites in twenty-eight different hospitals and made environmental observations and questioned the working staff in eighty-five operating rooms in use. In order to allow for the possible effect of season of the year and to study as wide a range of operations as possible, each suite was visited over a period of 3 days (an average of 5 half-day working sessions) in 1 week, on three separate occasions during a year at approximately 4-month intervals. The hospitals were chosen to provide as wide a range of environmental conditions as possible, and therefore included a proportion of older suites with unsatisfactory working conditions. Teaching hospitals and specialized units were avoided since we wished to study conditions in general surgery.

The visits were made by one of us (D.P.W.) accompanied by a nurse. Both changed into operating room clothing and were present in the operating room throughout the whole of each session that was studied. The minute-to-minute progress of a session was recorded, with full details of the number, type and length of operations performed, the number of staff present and the amount of movement in and through the theatre. This part of the study will be the subject of a separate publication. Any occurrence, such as a mishap or a surgical complication, that could have affected the subjective perception of the environment, was recorded. The details of clothing, sex, age, build, etc., for each person were obtained either by observation or by interview, and recorded. At frequent intervals the four principal environmental variables, air temperature, radiation temperature, air velocity and relative humidity were measured at the table and at the periphery of the room, using specially constructed equipment described elsewhere (Lidwell & Wyon, 1968). The apparatus was small and easily portable and its use did not involve any preparation of the operating room in advance.

Between operations, at intervals of about 2 hr., the surgeon, his assistant, the scrubbed-nurse and the anaesthetist, referred to as the operating-room table staff, were interviewed briefly in a standard way. The sequence of questions included separate groups on thermal comfort at each of three levels—head, body and feet. Bedford's seven-point scale of thermal sensation (Bedford, 1936) was used, but it was found convenient to assign a different set of numerical values to the 7 points on the scale, namely: 0, much too cool; 1, too cool; 2, comfortably cool; 3, comfortable; 4, comfortably warm; 5, too warm; 6, much too warm. An estimate was also made of the extent to which the subject was sweating on the forehead during the operation before questioning. Visible sweating was recorded on a 5 point scale:

0, forehead dry; 1, forehead damp; 2, forehead wet showing beads of sweat; 3, forehead wet and needing wiping; 4, clothing also visibly wet. Additional questions referred to 'stuffiness', air movement, noise, humidity, movement of staff and lighting. Replies were coded in a standard way, and care was taken to ensure that the subjects were unaware of the actual thermometer reading in order to avoid obtaining a stereotyped response related to the numerical value of the temperature.

This procedure provided information on all aspects of the session that might have influenced subjective thermal comfort, while taking up the minimum amount of the subject's time. No attempt was made to alter in any way the conditions that were found. Thus the readings are both representative and 'normal' in the sense that the subjects in each suite were used to them. Ample variation for the purpose of analysis was found among the suites visited, although conditions were more often too hot than too cold.

Data recording

In view of the very large number of units of information recorded, some method of mechanically assisted analysis was essential. It would have been preferable to have recorded all the information directly in coded form using a single card for each person-occasion. A great deal of subsequent labour, with the accompanying possibilities of transcription error, would then have been avoided. However, the situation in an operating room during a working session makes all note-taking difficult and this, coupled with the short time usually available for making the observations, made it necessary to use separate field sheets for the different categories of information, e.g. environmental particulars which were usually common to several subjects, subject responses, clothing and other personal details, etc. The basic assembly of information for analysis was that pertaining to a single person-occasion consisting of the results of the interview together with all the other recorded data relevant to this. Over 2500 such records were obtained in the course of 2 years' work between November 1963 and December 1965.

The data recorded on the individual field sheets were worked up so as to produce standardized summaries of the information relevant to each interview. This information together with the interview responses was then transferred on to a coding card, one card being used for each person-occasion. To minimize error in transcription no coding of the data recorded on the field sheets was done at this stage. Coding into integral numerical form suitable for the subsequent analysis was done later and the values written into a second set of spaces provided on the card. Accommodation of all the information finally required needed most of the 160 fields, corresponding to the number of columns on two standard-form punch cards, and the operators were able to punch each pair of cards directly from this second set of spaces.

Paired cards are satisfactory for computer input but present difficulties in carrying out mechanical cross-tabulation. In order to reduce these difficulties, some of the data were included on both of a given pair of cards. Subsequently a third card was prepared and punched by computer. This carried a selection of the data that previous analysis had shown to be of particular interest, together with predicted responses computed from one or other of the regression equations obtained from this analysis.

Analysis

The main bulk of the analysis was carried out by computer, but before the material was submitted to this process mechanical sorting of the cards was used to determine certain preliminary characteristics of the data. The range and distribution of the values of the principal variables was obtained. The continuous and multi-valued variables, including the subjective responses, were found to be distributed sufficiently close to normality to justify analysis by standard methods without transformation of the variables. The non-metric variables were treated as described by Lidwell (1961). As the cooling effect of air movement on a cylindrical or near cylindrical object, such as the human body, is closely proportional to the square root of the air velocity, and as this function has been used in a number of comfort indices (e.g. Webb, 1959; Lee, 1958), we also used it in our analyses. The limited range of air velocity encountered in the operating rooms and the small effect produced by these variations on the comfort responses meant that, from our own observations, we were unable to justify the choice of any particular functional relation between air velocity and comfort response.

Two-way sorting was also used to explore the possibility of strong interactions between any pair of variables. This revealed that the extent to which the comfort vote varied with relative humidity was greater at higher than at lower ambient temperatures. The variation of the comfort vote with differences in the pressure of water vapour in the atmosphere, however, appeared to be independent of temperature over the range studied. All subsequent analysis was therefore carried out using water vapour pressure as the index of humidity.

The general analysis method employed was to determine a linear regression equation between the response as dependent variable and those other variables that gave significant regression coefficients. We included a general comfort response (T_0) obtained by summation of the numerically coded values of the responses for the head, trunk and feet (T_1, T_2 and T_3) and dividing the result by 3, i.e.

$$T_0 = (T_1 + T_2 + T_3)/3.$$

The programme employed was the BMD O2 R (Biomedical Series, 1965) sequential regression analysis by which variables are added to the regression analysis in the order in which they make the biggest reduction in the residual sum of squares until the effect of adding the next variable falls below a specific level of significance.

There were a large number of factors recorded that seemed unlikely to be of major significance or that were only recorded for a proportion of person-occasions. These were not included in the main analysis but were examined subsequently. A third card was prepared, by computer method, for each person-occasion on which were recorded the expected votes, calculated from the regression equations determined by the preceding analysis, together with the actual votes recorded and the data relating to these other factors.

Sequential regression analyses, using the same BMD 02 R programme, were carried out using the differences between the calculated and recorded votes as the dependent variables. These analyses were carried out on the whole of the data, or on a part where the factor in question had only been recorded on a proportion of occasions.

RESULTS

The mean and standard deviation for the major variables recorded are given in Table 1. It can be estimated from these figures that temperatures exceeding 75° F. were recorded on about 25% of occasions and that nearly 20% of the recorded votes indicated that the individuals concerned felt too hot or much too hot, e.g. the upper boundary for comfort is a vote of 4·50, treating the vote as a continuous variable. The mean value of the response at head height, T_1, was 3·69 with a

Table 1. *Mean and standard deviation of the major variables*

Variable	Mean	Standard deviation
1. Ambient temperature (° F.): head	72·6	4·0
trunk	72·3	4·0
feet	71·8	3·9
2. Water vapour pressure (mm. Hg)	10·2	2·4
3. Radiation (° F. excess over ambient): head	4·3	2·8
trunk	2·1	1·5
feet	1·6	1·6
4. Air movement $(\text{ft./min})^{\frac{1}{2}}$: head	4·59 (≡ 21 ft./min.)	1·16
trunk	4·77 (≡ 23 ft./min.)	1·21
feet	5·51 (≡ 30 ft./min.)	1·50
5. Age (yrs.)	38·6	9·3
6. Sex (proportion female)	0·364	—
7. Race (proportion European)	0·836	—
8. Build	2·820	0·78
9. Surgeon (proportion)	0·228	—
10. Surgical assistant (proportion)	0·250	—
11. Scrubbed nurse (proportion)	0·281	—
12. Anaesthetist (proportion)	0·241	—
13. Spring (fraction responses Mar.–May)	0·260	—
14. Summer (fraction responses June–Aug.)	0·187	—
15. Autumn (fraction responses Sept.–Nov.)	0·292	—
16. Winter (fraction responses Dec.–Feb.)	0·261	—
17. Stay in room (hours up to time of questioning)	2·00	1·11
18. Stress	1·46	0·73
19. Proportion wearing glasses during operation	0·287	—
20. Comfort: for head (T_1)	3·69	1·14
for trunk (T_2)	3·51	1·17
for feet (T_3)	3·31	0·97
21. Comfort overall ($T_0 = (T_1+T_2+T_3)/3$)	3·50	0·94
22. Degree of visible sweating on forehead (P)	0·58	0·62

Variables 6, 7, 9–16 and 19 are non-metric so that a standard deviation is not an appropriate measure of dispersion.

Build was recorded in 5 steps from 1, fat, through 3, normal, to 5, thin. The operations were recorded in three categories: 0, minor; 1, normal; 2, major. The coded figure for stress was then taken as the time weighted average of this over the period spent in the operating room up to the time of questioning.

Comfort and sweating were scaled as described in the text.

standard deviation of 1·14. A response of 'too hot' or 'much too hot' therefore exceeds the mean value by 4·50–3·69 = 0·81 which is equal to 0·81/1·14 = 0·71 times the standard deviation. For a normal distribution approximately 24 % of instances depart further in one direction from the mean than this. The mean humidity recorded corresponds very closely to a relative humidity of 50 % at the average temperature recorded.

Table 2. *Coefficients of the regression equations for prediction of the subject's response. Environmental variables only*

	Response				
Variable	T_1	T_2	T_3	T_0	P
1. Ambient temperature (° F.)	0·126	0·134	0·091	0·118	0·038
2. Water vapour pressure (mm. Hg.)	0·066	0·076	0·048	0·062	0·033
3. Radiation (° F.)	0·037	0·095	0·050	0·079	0·025
4. Air movement $(\text{ft./min.})^{\frac{1}{2}}$	NS	−0·073	−0·030	−0·058	NS
Constant	−6·340	−6·848	−3·669	−5·636	−2·694
Multiple correlation coefficient	0·504	0·503	0·394	0·548	0·331
Correlation coefficient with ambient temperature only	0·466	0·452	0·366	0·500	0·262

The regression equations are of the form

$$\text{predicted response} = a + b_1x_1 + b_2x_2 + \ldots$$

and the table gives the values of the coefficients b_1, b_2, etc., and of the constant a. All the coefficients listed exceed twice their standard errors. NS indicates that the variable was not entered into the regression, its effect on the residual sum of squares being insignificant.

T_1, T_2, T_3 are the scale values of the interview response for comfort of head, trunk and feet respectively.

T_0, the general comfort response, $= (T_1 + T_2 + T_3)/3$.

P is the extent of visible sweating on the forehead according to the scale described in the text.

In Table 2 the coefficients of regression equations between the comfort responses and the principal environmental variables are listed. By comparison with the range of values encountered for these variables (see Table 1) and by inspection of the correlation coefficients listed, it is apparent that ambient temperature is by far the most important in determining the comfort response and that air movement in particular played a very small part. This is perhaps a consequence of the very small areas of skin exposed when wearing operating room dress.

The comfort response was significantly affected by a number of other recorded variables of either a personal or environmental nature. The coefficients obtained for the regression equations, on the same comfort responses as those included in Table 2, are given in Table 3 for all the major recorded variables. The increase in the precision of these equations considered as predictive instruments is only very slight compared with the equations defined by the coefficients given in Table 2. For example, the general comfort response T_0, has a variance of 0·88, the square of the standard deviation, 0·94, given in Table 1: 25 % of this variance is removed by the correlation with ambient temperature alone, i.e. the square of the correlation coefficient, 0·500, given in Table 2. The other environmental variables account for another 5 %. The total variance accounted for by all the variables listed in

Table 3 that have significant regression coefficients is just over 33 % ($0{\cdot}576^2$), i.e. an additional 3 % only for all the further variables.

There is, however, one very significant effect revealed by the figures in Table 3. For all the responses listed there is a substantial and consistent difference between surgeons and anaesthetists with the other staff lying somewhere between. These effects are, as is shown in Table 4, equivalent to differences of between 1·7° F. and 4·1° F. in the temperatures needed to evoke a similar comfort response in the two groups, and of as much as 12° F. in the temperature needed to produce the same extent of visible sweating. This difference is also shown in the values for the preferred ambient temperatures calculated from the regression equations of Table 3 and given in Table 6.

Table 3. *Coefficients of the regression equations for prediction of the subject's response. All major variables*

	Response				
Variable	T_1	T_2	T_3	T_0	P
1. Ambient temperature (° F.)	0·120	0·124	0·091	0·111	0·036
2. Water vapour pressure (mm. Hg)	0·065	0·066	0·050	0·056	0·030
3. Radiation (° F.)	0·015	0·051	0·040	0·047	0·009
4. Air movement (ft./min.)$^{\frac{1}{2}}$	NS	−0·056	NS	−0·047	NS
5. Age (for each 5 yr. over 25)	−0·048	−0·028	−0·064	−0·045	−0·041
6. Sex (female)	NS	−0·124	NS	NS	−0·263
7. Race (non-European)	NS	NS	NS	NS	−0·111
8. Build (fat, 1,—thin, 5)	NS	NS	−0·054	NS	−0·042
9. Surgeon	0·235	0·188	0·065	0·184	0·254
10. Surgical assistant	0·007	−0·017	−0·043	0·028	0·011
11. Scrubbed nurse	0·007	0·188	0·065	0·028	−0·057
12. Anaesthetist	−0·239	−0·382	−0·091	−0·236	−0·186
13. Spring (Mar.–May)	NS	0·160	NS	0·128	NS
14. Summer (June–Aug.)	NS	0·166	NS	0·117	NS
15. Autumn (Sept.–Nov.)	NS	NS	−0·166	NS	0·090
16. Stay in room (hr.)	NS	NS	NS	NS	0·042
Constant	−5·622	−5·991	−3·467	−4·929	−2·262
Multiple correlation coefficient	0·520	0·541	0·423	0·576	0·490

The form of the regression equations and the symbols used for responses are as described in Table 2.

The coefficients for the seasons were computed in terms of their differences from Winter, (December–February) as the reference period.

NS indicates that the regression coefficient concerned was not significant.

Table 5 also shows the effect on the response of the other variables compared to the effect of ambient temperature. The relatively small effect of radiation, between $\frac{1}{2}$ and $\frac{1}{4}$ that of a similar ambient temperature difference, is in line with other reported observations, e.g. Koch, Jennings & Humphreys (1960) who give a relative effect of about $\frac{1}{3}$. The very small ($\frac{1}{8}$) apparent effect at head height is probably, in part, an artifact of measurement. The radiation temperature measurements for this purpose were made under the operating room lamp in the most intense part of the lamp beam. The majority of the operating lamps encountered were of the 'Hanau' type, incorporating a number of separately focussed sources, and the surgeon generally placed his head in a gap between two of the beams. A limited number of measurements showed that approximately half the radiation effect at the position of measurement was due to the beam and half to the hot lamp casing. If the surgeon was, in fact, subject only to this latter, then the radiation temperature to which he was exposed would be one half of that recorded and the regression coefficient between this value and the response would be twice the value given in Table 3, i.e. 0·30. The value in Table 5 then becomes 4·0 in place of 8·0 and the ratio to the effect of ambient temperature $\frac{1}{4}$.

Table 4. *Equivalent thermal effect of other variables*

Change in ambient temperature, ° F., required to produce the same response in the specified class of individual as that observed in the population as a whole.

	Response				
Class character	T_1	T_2	T_3	T_0	P
Sex (female)	NS	+1·0	NS	NS	+7·3
Race (non-European)	NS	NS	NS	NS	+3·1
Surgeon	−2·0	−1·5	−0·7	−1·7	−7·1
Anaesthetist	+2·1	+3·1	+1·0	+2·1	+5·2

The responses T_1, T_2, T_3 are the scale values of the interview responses for comfort of head, trunk and feet respectively. T_0, the general comfort response, $= (T_1+T_2+T_3)/3$.

P is the extent of visible sweating on the forehead according to the scale described in the text. The values given have been calculated from the regression equations given in Table 3.

NS indicates that the regression coefficient concerned was not significant.

Table 5. *Equivalent thermal effect of other variables*

Change in the specific variable required to produce the same effect as 1° F. drop in ambient temperature

	Response				
Variable	T_1	T_2	T_3	T_0	P
Water vapour pressure (mm. Hg)	−1·8	−1·9	−1·8	−2·0	−1·2
Relative humidity (at 68° F.)	−10	−10	−10	−11	−7
Radiation (° F.)	−8·0	−2·5	−2·3	−2·4	−4·0
Air movement (ft./min. at 25 ft./min.)	NS	+27	NS	+30	NS
Age (yr.)	+12	+22	+7	+12	+4

For explanation, see Table 4.

Scales of warmth

Various ways of combining the variables so as to provide a single index which will predict the response of individuals under a variety of environmental conditions have been proposed (Bedford, 1964). This is especially important when the range of conditions is much greater than that encountered in our observations. For comparative purposes we have compared the adequacy of a number of these when applied to our data (Table 7). It will be seen that, except for the globe thermometer, they all show some improvement over the simple use of ambient temperature, but that they account for significantly less of the variance than the regression equations on environmental variables given in Table 2.

Table 6. *Preferred ambient temperatures (° F.), T = 3·0 (for mean observed values of the other variables)*

	T_1	T_2	T_3	T_0
Surgeons	64·8	67·1	70·0	66·1
Surgical assistants	66·7	67·4	70·5	67·5
Scrubbed nurses	66·7	67·1	70·0	67·5
Anaesthetists	68·8	71·8	71·6	69·9

T_1, T_2, T_3 are the scale values of the interview response for comfort of head, trunk and feet respectively. T_0, the general comfort response, $= (T_1+T_2+T_3)/3$.

The values given have been calculated from the regression equations given in Table 3 and represent the ambient temperatures at which the highest proportion of the class indicated stated that they were comfortable.

Table 7. *Comparison with other indices of thermal comfort*

Values of the correlation coefficient between the indicated response and the index.

Index	Mean value in these data (° F.)	T_1	P
Ambient temperature	72·6	0·466	0·262
Globe thermometer temperature	76·9	0·448	0·306
Equivalent temperature	72·8	0·482	0·300
Effective temperature	68·1	0·481	0·285
Singapore or Equatorial Comfort Index	67·0	0·481	0·281
Regression (Table 2)	—	0·504	0·331

T_1 is the scale value of the interview response for comfort of the head. P is the extent of visible sweating on the forehead according to the scale given in the text.

The correlation with the Singapore index was calculated from the data for surgeons, surgical assistants and scrubbed nurses only, excluding anaesthetists.

The definitions of the several indices are given in Bedford (1964).

Table 8. *Personal variation, response at head height* (T_1)

Source of variation	Degrees of freedom	Sum of squares	Mean square	F
Regression	4	714	178·53	226·47
Between persons	631	870	1·38	1·75
Residual	1456	1148	0·79	—
Total	2091	2732	1·30	—

F (631, 1456) = 1·23 at the 0·1 % level of significance.

Personal consistency

On a number of occasions we interviewed the same person more than once. From this portion of the data it has been possible to compute a partition of variance between that absorbed by the regression, that due to consistent differences between individuals and the residual representing variation in the response of a single individual. The results of this calculation are given in Table 8. It will be seen that while there are consistent personal differences these are not large. The root mean square between individuals is only 1·32 × the residual

$$[\sqrt{(1{\cdot}38/0{\cdot}79)} = \sqrt{(1{\cdot}75)} = 1{\cdot}32],$$

and the proportion of variance absorbed by the regression for repeated observations on a single individual only rises to 38% [714/(714+1148)]. Somewhat larger values, up to 50–60%, have been recorded for observations on single subjects (Davis, McMillan & Webb, 1965) but the environmental conditions were more closely standardized in these experiments.

Distribution of response

In addition to an estimate of the preferred temperature, defined above as that temperature at which the predicted comfort response has the value 3·0, it is also desirable to know the proportion of persons too hot, comfortable or too cold under the various environmental conditions. For this purpose an *Index Temperature* has been defined. This is directly related to the value of the response predicted by the relevant regression equation. It is that ambient temperature in ° F. which would elicit the same predicted response in the specified population under the following standardized conditions: radiation temperature equal to the ambient temperature, relative humidity 50%, air movement 25 ft. per minute. These standard conditions have been deliberately chosen to lie near to the mean values observed so as to avoid unreal extrapolation. In making use of the term index temperature we do

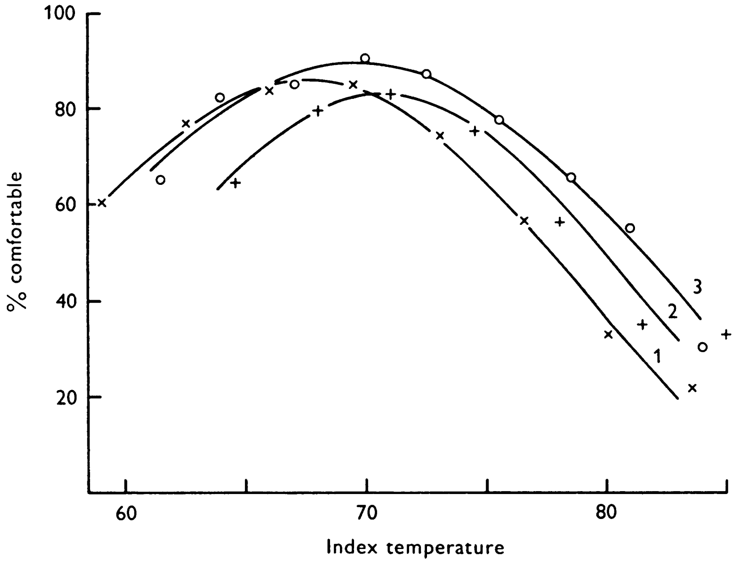

Fig. 1. Relation between index temperature and the proportion of individuals comfortable for different parts of the body. Curve 1, ×, comfortable at head. Curve 2, +, comfortable at trunk. Curve 3, ○, comfortable at feet. See text for definition of index temperature.

not intend to add yet another to the already considerable published array of comfort indices. This form of expression is, however, convenient for the exposition of the present body of data and the method is equally applicable to other specialized situations. The index temperature as we shall use it here relates to a defined population in a particular situation, and its relation to ambient temperature and to other environmental values will depend on these specified conditions and be deducible from the relevant regression equation or equations.

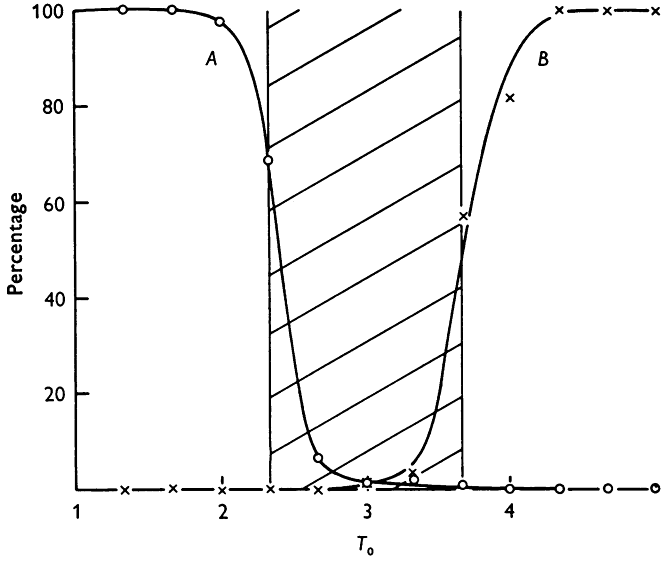

Fig. 2. Proportion of general comfort responses which included at least one 'too cold' or 'too hot' response. Curve *A* shows the proportion of the responses at a given value of T_0, the general comfort response, which included at least one 'too cold' vote, scale value 0 or 1, from either T_1, head, T_2, trunk, or T_3, feet. Curve *B* shows similarly the proportion with at least one 'too hot' vote, scale value 5 or 6. The hatched area shows the range defined as comfortable.

Figure 1 shows the proportion of individuals who stated that they were comfortable, response 2, 3 or 4, as a function of the index temperature. The proportions are shown separately for comfort of head, trunk and feet. The distributions are approximately symmetrical about the maxima and the preference for appreciably cooler temperatures about the head is clearly shown.

It is not immediately obvious how the values of the general comfort response (T_0) should be classed as comfortable, too hot or too cold. Any particular value can arise from a large number of combinations of response at head, trunk and feet, e.g. a value of 2·33 could arise from votes of 3, 3 and 2 or 1, 3 and 4 or even 1, 2 and 5. The first combination includes only votes within the comfort range, the second one 'too cold' response and the third the 'contradictory' pattern of simultaneous 'too hot' and 'too cold' responses. Each individual T_0 response was therefore examined. T_0 can only take integral or thirds values and for each possible value we determined the proportion of responses which included contributing votes, either T_1, T_2 or T_3, lying outside the comfort range of 2, 3 or 4. The results are shown in Fig. 2. From the figure it is clear that values of T_0 of 2 or lower nearly always included at least one 'too cold' response and can therefore reasonably be taken as indicating a general response 'too cold'. Similarly, values of T_0 of 4 or more nearly always included at least one 'too hot' response and have been taken as defining a general response of 'too hot'. The range 2·33–3·66 inclusive has therefore been taken as the comfortable range. At the limits of this range there is little more than a 50% chance of any individual response lying outside the values 2, 3 and 4. Only 7 out of the more than 2500 values involved simultaneous 'too hot' and 'too cold' responses and these have been excluded from the analysis.

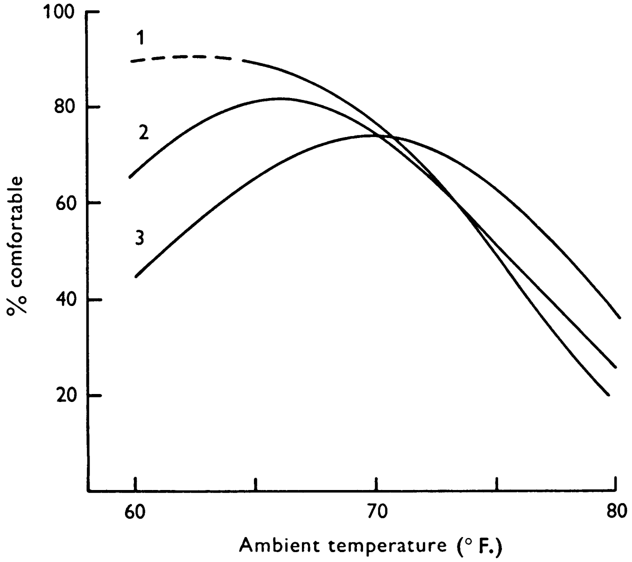

Fig. 3. Proportion of individuals comfortable, general comfort response T_0, at various ambient temperatures. Curve 1 refers to surgeons. Curve 2 refers to surgical assistants and scrubbed nurses. Curve 3 refers to anaesthetists.

The distribution of values of T_0, grouped into 'too cold', comfortable and 'too hot' in this way, is shown in Figs. 3 and 4. Figure 3 shows the proportion comfortable for surgeons, anaesthetists and other table staff, considered separately, as a function of simple ambient temperature. In order to obtain these curves the probits of the proportions 'too hot' and 'too cold' were first plotted against the temperature. This transformation gives a straight line relationship. Smoothed estimates of the proportions 'too hot' and 'too cold' were then obtained from these lines and the proportion 'comfortable' obtained by difference, i.e. those neither 'too hot' nor 'too cold'. The relatively low temperature preferred by surgeons compared with the anaesthetists is apparent. In Fig. 4 the same data for all categories of table staff combined are shown as a function of index temperature. The proportions 'too hot' and 'too cold' have been plotted as probits while the proportion comfortable is given as a simple percentage. The line for the proportion too hot can be used to estimate the index temperature required to be attainable in order to ensure that no more than a specified proportion of the potential occupants will feel too hot. For no more than 5 % of operating room table staff this is 67° F. and for no more than 1 % 63·5° F. In specifying the environmental conditions that should be attainable in an operating room, where the comfort of only one or a few individuals is involved, these values are more important than the value at which the largest proportion of persons is comfortable.

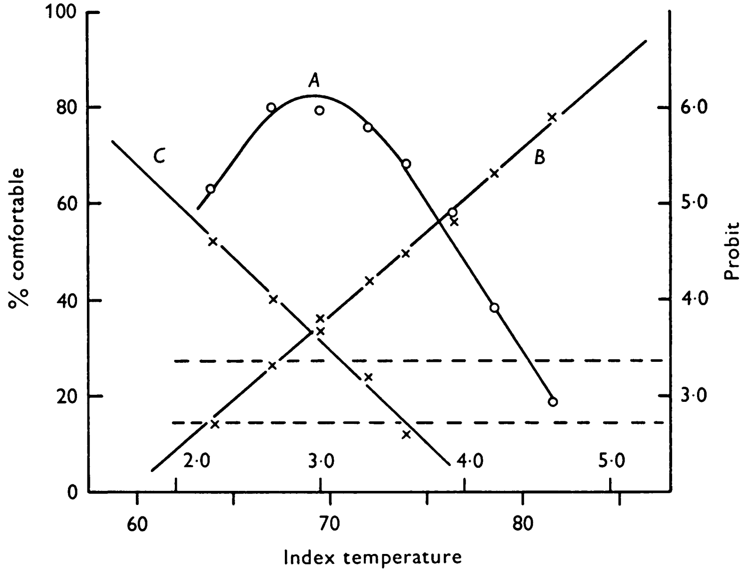

Fig. 4. Proportion of individuals comfortable, general comfort response T_0, at various index temperatures together with the proportion 'too hot' and 'too cold'. Curve *A* shows the percentage comfortable. (L.H. scale). Curve *B* shows the probit of the percentage 'too hot'. (R.H. scale). Curve *C* shows the probit of the percentage 'too cold' (R.H. scale). The figures above the index temperature scale give the equivalent predicted values of T_0. Curve *A* has been calculated from the probit lines *B* and *C*. Definition of the comfort range boundaries is given in the text. The broken lines indicate the 1 and 5 % probit levels (R.H. scale).

Sweating

There is, of course, no preferred level of sweating and these data have been dealt with somewhat differently. The regression equations show that observed sweating is a sensitive index of personal difference and responds to changes in the environmental variables in a similar way to the comfort response. This is of considerable interest since, unlike the comfort response, it is an objective estimate of response to thermal conditions. It is, of course, one-sided. Conditions that are too hot evoke a response but not those that are too cold. The fact that conditions in the operating rooms we observed were much more often too hot than too cold undoubtedly contributes to the regular behaviour of this response. A limited number of actual measurements of the amount of sweat produced were made on the upper arm and on the forehead. These will be reported in more detail elsewhere. They confirmed, however, the opinion that a large part of the sweating observed in the operating room, although related to the thermal environment, is also substantially a response to stress (Kuno, 1956). This is shown by the much higher rate of sweat production by the surgeons and the much greater rate observed on the forehead compared to the upper arm. In Fig. 5 the proportion of individuals who were visibly sweating to each of the four recorded levels is shown plotted against index temperature.

By comparison of the regression coefficient for temperature with the status coefficients which are given for visible sweating, *P* in Table 3, it will be seen, as is also shown in part in Table 4, that the equivalent index temperatures for surgeons are 7° lower, but for scrubbed nurses are 2° higher and for anaesthetists are 5° higher, than the average for all table staff. Under the standard conditions of 50 % relative humidity, 25 ft. per minute air movement and no excess radiant temperature, this means that, while 50 % of all table staff were visibly sweating at an ambient temperature of 72° F., 50 % of surgeons were sweating at only 65° F. A temperature of 77° F., however, had to be reached before 50 % of the anaesthetists were sweating. Similarly , while 80 % of all staff were visibly sweating at a temperature of 82° F. under the standard conditions, this proportion of surgeons was visibly sweating under the same conditions at only 75° F., at which temperature 5 % of the surgeons were sweating to such an extent (grade 3) that the accumulated sweat had to be wiped from their foreheads.

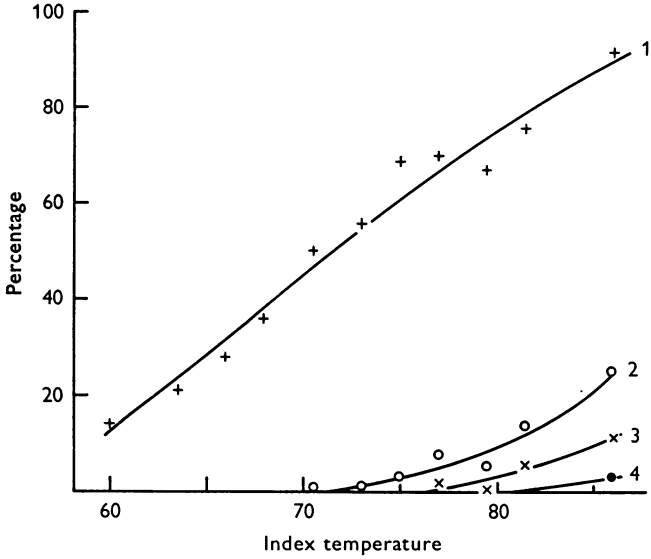

Fig. 5. Proportion of individuals sweating. Curve 1, proportion visibly sweating. Curve 2, proportion with beads of sweat on the forehead. Curve 3, proportion from whose forehead sweat had to be wiped away. Curve 4, proportion whose clothing was wetted through with sweat.

Although the effect of the radiant heat from the operating lamp, to which the surgeons are exposed, is to lower still further the ambient temperature at which surgeons sweat, the reduction is only slight, as is reflected in the small value of the corresponding regression coefficient in Table 3.

Other factors affecting comfort

The analysis of the effect of the large number of other factors that were recorded produced only a limited number of results which added anything to those already described. In particular, the regression on interview responses such as stuffiness, air movement, noise, etc., were not such as to contribute further to our understanding of the problems of thermal comfort. A few of the factors which were investigated as described earlier, by examining the differences between the responses predicted by the regression equations given in Tables 2 and 3 and those actually recorded did, however, show some interesting relationships. These are shown in Table 9, in terms of their equivalent thermal effect. There was more sweating and the staff felt hotter when the 'atmosphere' in the operating room was tense and when there were more frequent exits from and entries to the operating room. These two conditions tended to be associated with each other. On the other hand, when there was more movement in the room and when the noise level was raised, usually by talking, the more relaxed atmosphere implied by these activities was associated with less sweating. The response to 'mistakes' or to the carrying out of a major operation was not, however, consistent. These observations emphasize the subjective elements in comfort and sweating.

Table 9. *The response to some environmental circumstances*

	Change in ambient temperature, ° F., which would produce a similar response to that caused by the specified circumstance	
Circumstance	Comfort at head (T_1)	Sweating (P)
1. Tense atmosphere	0·9	2·7
2. Major operation	NS	1·1
3. Mistake in procedure	−0·6	NS
4. 50 % more entries and exits per hour than average	NS	0·8
5. 50 % increase in movement	NS	−1·1
6. 5 phons increase in noise	NS	−1·4

The average number of exits and entries from and into an operating room was 122/hr. Movement in the operating room was recorded in terms of the number of movements between a limited number of arbitrarily chosen focal points in the room. Noise here represents that level which was reached or exceeded for 20 % of the record. This level averaged approximately 60 phons.

NS indicates that no significant regression coefficient was obtained in the analysis.

The atmosphere in the operating room was recorded as: 0, tense; 1, normal; 2, relaxed. Operations were classified as average, major or minor.

An increase in the variability of the velocity of air movement was also shown to influence the perception of comfort for the head. The average value of the mean deviation of the individual measurements of air velocity about their mean value on any occasion was 4·3 ft./min. (The individual readings had been taken in groups of two at 5 sec. intervals and the time constant of the recording instrument was of the same order, about 5 sec.). A doubling of this, i.e. to a mean deviation of 8·6 ft./min., was accompanied by a fall in the scale value of the response for comfort for the head equivalent to a drop of 0·9° F. in ambient temperature.

No significant effect on response could be attributed to the temperatures in the ancillary rooms of the operating suite, nor to the average outdoor temperature during the previous fortnight.

Index temperature

A substantial proportion of the results discussed have been related to a so-called index temperature. In using the regression equations to convert this to actual environmental conditions for a given class or group of operating room staff, it is important to remember that while the index temperature is defined in terms of 50% relative humidity, the regression equations are given in terms of water vapour pressure (mm. Hg). Regression equations in terms of relative humidity would be more complex in view of the interaction between relative humidity and temperature referred to in the section on analysis. In order to facilitate the conversion, Fig. 6 has been drawn to show the relationship between index temperature and ambient temperature for the general comfort response, T_0.

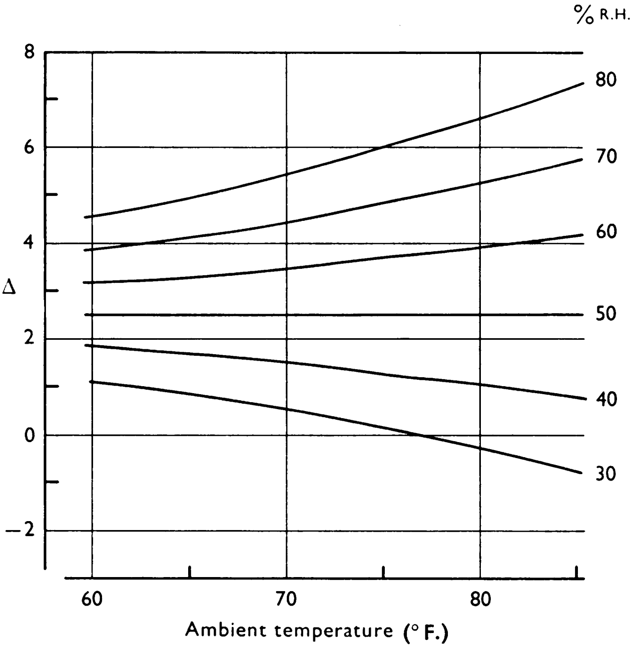

Fig. 6. Relation between index and ambient temperature for the general comfort response, T_0. The value of the index temperature is given by: index temperature = ambient temperature + $\Delta - \frac{1}{2}\sqrt{v} + \frac{1}{2}R + A$, where Δ is read from the figure, v is the air velocity in feet per minute, R is the excess of radiation temperature over ambient air temperature in ° F. and A is a constant which is zero for the reference population (average of all operating room table staff) and takes the value 1·6 for surgeons, 0·25 for surgical assistants and scrubbed nurses and −2·1 for anaesthetists. All temperatures are in ° F.

The effect of humidity on the comfort responses at head, trunk and feet, T_1, T_2 and T_3, is practically identical with that on T_0 so that the figure may also be used for calculations relating to these. The coefficients of the effects of air movement, $\sqrt{v}$, thermal radiation, R, and individual function, the constant A, will, however, differ and must be estimated from the regression equations given in Table 3 by dividing the appropriate coefficient by the coefficient for ambient temperature in the same regression equation.

DISCUSSION

This investigation has established that an index temperature, as defined earlier, of 69° F. is that at which the highest proportion of operating room staff in Britain are comfortable. This figure is not, however, in itself of much significance since there is, in the first place, a substantial difference in the temperature preferences of surgeons, anaesthetists and other table staff. Equally important, the requirements for specifying a comfortable thermal environment in an operating room differ from those in offices, factories and those other environments to which most previous thermal comfort studies have been directed. These environments are occupied simultaneously by a large number of individuals and the problem is to specify those conditions which will be comfortable to the highest possible proportion of these. The operating room is occupied by only a small number of persons at any one time, and the comfort of only one or a few of these, the surgeons, may be considered the most important. In these circumstances, it is desirable to specify those thermal conditions which must be capable of being attained in order that no more than a small proportion of these persons need be uncomfortable. In the operating room environment sufficient warmth is no problem, so that we need to specify how low a temperature must be attainable. If we can allow no more than 5% (1 in 20) of individuals to be too hot, Fig. 4 shows that the index temperature must be capable of being held down to no more than 67° F. but if only 1 in 100 may be too hot then the figure is probably about 63·5° F. For surgeons the equivalent index temperatures are rather more than 1·5° lower than for the average of all staff, and in addition it is necessary to make some allowance for radiation from the operating lamp, probably about 1°. These two effects together amount to about 2·5°, so that for no more than 1 surgeon in 20 to be uncomfortably hot an equivalent index temperature of 64·5° F. must not be exceeded, i.e. 64·5° F. at 50% relative humidity and 25 ft./min. air movement. The index temperature should probably not exceed 61° F. if no more than 1 in 100 is to be uncomfortably hot.

Surgical assistants and scrubbed nurses are also exposed to thermal radiation from the operating room lamp and will generally prefer temperatures about 1° F. higher than the principal surgeon. This difference is not large enough to be significant. Anaesthetists, however, are usually more remote from the operating lamp and in addition prefer temperatures nearly 2° F. above the average for all staff, i.e. an index temperature of about 71° F., corresponding to an ambient temperature about 4° F. warmer than that preferred by most surgeons.

At the relatively low temperatures needed to prevent the more heat-sensitive surgeons from feeling too hot a substantial proportion of the other table staff will feel too cold. At 64·5° F. ambient temperature, for example, with average radiant heat conditions and 25 ft./min. air movement at 50% relative humidity, over one-third of surgical assistants and scrubbed nurses and nearly one-half of the anaesthetists would have felt too cold. At 61° F. the proportions would be nearly two-thirds and three-quarters respectively. The only way of reconciling these differences would seem to be for the anaesthetists and perhaps some others of the table staff to wear rather warmer clothing in operating rooms which can be kept down to the surgeon's preferred temperature. Recent work on the dissemination of bacteria from various forms of clothing shows that, even if the additional clothing were not sterile, it should not lead to any increased risk of infection for the patient (Bethune, Blowers, Parker & Pask, 1965).

It is not possible to estimate how often regulation of temperature conditions by the anaesthetist, who can do this readily where open controls are provided, may have contributed to complaints of overheating by surgeons. It is, however, probably just coincidence that the mean temperature recorded during these observations, approximately 72° F., lies so close to that preferred by most anaesthetists (see Fig. 3).

The effect of all the other variables observed was small in comparison with that of ambient temperature. In particular the effect of air movement was slight and not always significant. This is perhaps related to the very small skin areas exposed. The observed extent of visible sweating provides a good objective index of thermal discomfort in too hot conditions. This too is not greatly affected by environmental conditions other than ambient temperature. The effect of race and sex is however more pronounced on visible sweating (Table 4) than on the expression of comfort. Almost all the sex difference, however, depends on observations on anaesthetists, the only class which included a substantial proportion of both sexes. The much greater extent of sweating among surgeons is almost certainly a reflexion of nervous tension. Observations on the actual amount of sweat produced showed that this was almost entirely confined to the forehead. Upper arm sweating was very slight under the conditions investigated.

Although the other environmental variables exert individually only small effects their combined influence is not necessarily negligible. Thus, a reduction of 10% in relative humidity and 2° F. in the radiation temperature, accompanied by an increase of 15 ft./min. in the air velocity in the operating room, with some increase in the variability of this rate of air movement, will usually be equivalent in its effect on comfort and sweating to a drop of between 2 and 3° F. in the ambient temperature. This calculation assumes that the initial conditions are close to the average values of Table 1.

The figures given above define the requirements for thermal comfort of surgeons working in the British Isles under present-day surgical conditions. If the well-being of the patient calls for higher temperatures, or inadequate plant makes these inevitable, some amelioration of the consequent discomfort to the surgeons may be achieved by other methods. Surgical clothing, including the wearing of masks, undoubtedly imposes a thermal load on the wearer. The extent of this does not appear to be known, particularly the extent to which masks promote re-breathing and warm and humidify the inspired air. Modifications in design may be able to lighten this thermal load, although the bacteriological requirement for closely woven materials impermeable to small particles (Bernard, Speers, O'Grady & Shooter, 1965; Blowers & McCluskey, 1965) does not help. Charnley (1965) has approached the problem in a more radical way by furnishing the surgeon with an independent piped air supply and extract to the inside of his suit and mask.

This investigation largely substantiates the claim that conditions in British operating rooms often reach temperatures above those at which surgeons are comfortable. The average temperature observed in this series was over 72° F., nearly 6° F. higher than the value most generally preferred by surgeons. A temperature of 64·5° F., which seems to be necessary if no more than 5 % of surgeons are to be uncomfortably hot, cannot be attained without some degree of cooling over part of the year, even if extraneous heat is kept to a minimum.

SUMMARY

Visits have been made to thirty operating suites in the British Isles. Each suite was visited three times at approximately 4-month intervals and observations made on an average of five half-day working sessions on each occasion. Measurements were made of air temperature, humidity, air movement and radiation temperature and many details of the suites and working conditions recorded. At suitable intervals the operating room staff were questioned as to their feelings of thermal comfort using Bedford's 7-point scale. Over 2500 sets of replies were obtained. Visible sweating was also noted.

The effect on comfort and the extent of visible sweating of the many items recorded was then explored by means of a sequential multiple regression analysis. Although air temperature was by far the most important factor affecting thermal comfort, all the variables named above exerted a significant effect. In addition, a number of other conditions including age, sex and race produced minor differences.

Surgeons and anaesthetists were found to differ from other staff in their thermal preferences, the surgeons liking a cooler and the anaesthetists a warmer environment. Although most surgeons were comfortable at temperatures around 66·5° F. (19° C.), at 50 % relative humidity and 25 ft./min. air movement with the average amount of thermal radiation from the operating room lamp, it would be necessary to keep the temperature down to 64·5° F. (18° C.) if no more than one surgeon in twenty was to be uncomfortably hot. At this temperature nearly half the anaesthetists, who mostly preferred temperatures around 71° F. (21·5° C.), would feel too cold. Variation in the clothing worn by different staff members seems to be the only way of resolving this difficulty.

The average temperature in the operating rooms visited was over 72° F. (22° C.), and 75° F. (24° C.) was exceeded on about 25 % of occasions.

We should like to thank all those, operating room staff and others, whose help and collaboration made this investigation possible.

This work includes part of the material contained in a thesis to be submitted by one of us (D.P.W.) for the Ph.D degee of the University of London.

REFERENCES

ANGUS, T. C. (1959). Air conditions in operating theatres. *Med. Press* **242**, 113.

BEDFORD, T. (1936). The warmth factor in comfort at work. *Rep. Industr. Hlth Res. Bd., London*, no. 76.

BEDFORD, T. (1964). *Basic Principles of Ventilation and Heating*, 2nd ed. London: H. K. Lewis and Co. Ltd.

BERNARD, H. R., SPEERS, R., O'GRADY, F. & SHOOTER, R. A. (1965). Reduction of dissemination of skin bacteria by modification of operating-room clothing and by ultra-violet irradiation. *Lancet* ii, 458.

BETHUNE, D. W., BLOWERS, R., PARKER, M. & PASK, E. A. (1965). Dispersal of *Staphylococcus aureus* by patients and surgical staff. *Lancet* i, 480.

BIOMEDICAL SERIES (1965). Health Sciences Computing Facility, University of California, Los Angeles.

BLACK, F. A. & MILROY, E. A. (1966). *Building Research, Design Series*, no. 51. Building Research Station, Garston, Watford, England.

BLOWERS, R. & MCCLUSKEY, M. (1965). Design of operating-room dress for surgeons. *Lancet* ii, 681.

CHARNLEY, J. (1965). Operating room conditions. *Lancet* ii, 907.

DAVIS, J. E., MCMILLAN, A. D. & WEBB, C. G. (1965). Order in thermal comfort data. Building Research Station Note no. EN91/65 (unpublished). Garston, Watford, England.

HICKISH, D. E. (1955). Thermal sensation of workers in light industry in summer. *J. Hyg., Camb.* **53**, 112.

HOUGHTEN, F. C. & COOK, W. L. (1939). Cooling requirements of operating room and recovery ward. *Trans. Am. Soc. Heat. Vent. Engrs.* **45**, 161.

KOCH, W., JENNINGS, B. H. & HUMPHREYS, C. M. (1960). Is humidity important in the temperature comfort range? *ASHRAE Jl* **2**, (4), 63.

KUNO, Y. (1956). *Human Perspiration*, pp. 103–7. Thomas, Springfield Ill. U.S.A.

LEE, D. H. K. (1958). Proprioclimate of man and domestic animals. *Arid Zone Res.* **10**, 102.

LIDWELL, O. M. (1961). Multiple regression analysis applied to records of post-operative hospital sepsis. *J. Hyg. Camb.* **59**, 259.

LIDWELL, O. M. & WYON, D. P. (1968). A rapid response radiometer for the estimation of mean radiant temperature in environmental studies. *J. scient. Instrum.* (In the press.)

WEBB, C. G. (1959). An analysis of some observations of thermal comfort in an equatorial climate. *Br. J. Ind. Med.* **16**, 297.