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AERODYNAMICS OF THE HUMAN MICROENVIRONMENT

H. E. LEWIS A. R. FOSTER
B. J. MULLAN
OF THE DIVISON OF HUMAN PHYSIOLOGY,
NATIONAL INSTITUTE FOR MEDICAL RESEARCH, LONDON N.W.3

R. N. COX R. P. CLARK
OF THE DEPARTMENT OF AERONAUTICS,
THE CITY UNIVERSITY, LONDON E.C.1

Summary The skin, the boundary between man and his environment, is separated from the ambient atmosphere by a layer of convecting air. This boundary layer has been photographed using colour schlieren cinephotography, a technique which makes use of the fact that this air is warmer, less dense, and has a refractive index different from that of the ambient air. Starting from the feet, there is a layer of air which passes up adjacent to the surface of the body, its thickness progressively increasing as it rises and accelerates. At times the outer part of the boundary layer becomes partly detached. When the layer passes over the face some of it enters the nose with each inspiration. The air flow reaches the orbit, passes over the eye, and clears the cornea by a millimetre or so. The maximum velocity of the boundary layer at head level is about 0·5 m. per second. Preliminary experiments reveal that the human microenvironment has a significantly higher content of microorganisms than the ambient air. The source of bacteria is either the skin and/or the ambient air. Since some of the air of the microenvironment is inhaled during the respiratory cycle, this may be one of the missing links in the natural history of airborne infection; it may also provide a connection between skin disease and respiratory disease. Particles, pollens, and micro-organisms in the air, entrained and concentrated by the boundary layer, could be presented to the nasal orifice and inhaled. There is inevitable dissemination to the ambient air of microorganisms by the human boundary layer, and this may be a mechanism in hospital sepsis. In special circumstances (e.g., transplant surgery, treatment of burns, leukæmia), by isolating the surgeon or nurses in a pneumatic suit, it may be possible to reduce this serious complication.

Introduction

As a result of work on cold environments (Lewis and Masterton 1963) we realised that the layer of air next to the skin must be part of the human microenvironment, and its importance led us to consider methods of visualising it.

Photography of the Microenvironment

The skin (about 33°C) is normally at a higher temperature than the ambient air (20°C or less) and there is a thermal gradient between skin and ambient air. The layer of insulating air next to the skin is thus of a lower density than the ambient air, and since refractive index varies with density, this layer can be visualised with suitable optical methods, based on changes of refractive index (e.g., schlieren techniques). These techniques were introduced in the 19th century by the sheet-glass industry in Germany to detect flaws (*Schlieren*) not apparent to the naked eye. In aeronautical research they are used to visualise regions of density change in high-velocity wind tunnels (Holder and North 1963). We adopted the method to display zones of decreased density immediately around the human body (Lewis 1967).

In our preliminary schlieren cine studies we used two concave mirrors of high optical quality, 1 ft. (30 cm.) diameter, 10 ft. (3 m.) focal length. The source of light was a 12 V motorcar headlamp bulb with a vertical line filament as source. A condenser lens was used to focus an image of this filament at a slit which acted as an optical source for the system (fig. 1). The entry cone of light passed to the first mirror, from which it was reflected and travelled 16 ft. (4·8 m.) or so as a parallel

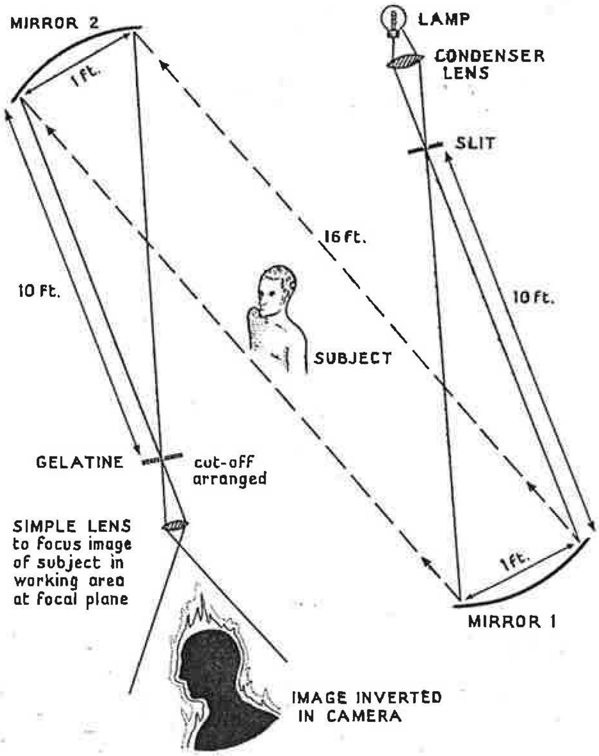


Fig. 1—Schlieren optical system.

beam of rays to fill the surface of the second mirror; from here it was reflected to form an image of the filament at the prinicipal focus of this mirror. The second mirror was arranged in such a way that the 10 ft. (3 m.) convergent cone of rays (i.e., the exit cone of light) was formed to one side, clear of the parallel beam of rays which was the working area.

At the final focus, the vertical edge of a coloured, thin gelatin filter was aligned to the image of the filament. There was a camera beyond this. In order to adapt the size of the image to the desired film size, a simple thin spherical lens was used to focus the image at the film plane of the camera. The system was adjusted so that light passing through the undisturbed region of the working section passed just to one side of the coloured filter. A change in the refractive index of any region of the air within the working section caused some light to be deflected and pass through the filter itself; it was photographed as a coloured image. A hand placed in the working section appeared as a silhouette, and round its contours a boundary of heated air was seen in colour.

The final image on the film was produced by a thin lens which replaced the complex camera lens. Its power, and position in the optical path relative to the object under examination, depended on the magnification required. The camera was loaded with 16 mm. film (speed 16 ASA) and was set at 24 frames per second. This produced an effective exposure-time of 1/50 second. Excellent results were obtained with light from the relatively modest headlamp bulb. In subsequent work a more elaborate source has been necessary to satisfy requirements of faster exposure-times and larger film size.

We systematically observed and filmed the pattern of air movement around the erect human body in a still room (air movement less than 0·25 m. per second). The subject, wearing briefs, stood on a platform that could be raised or lowered so that different regions could be illuminated by the schlieren beam. The area observed was limited to the diameter of the mirror, so about six serial positions were required to photograph a standing man. The ambient air temperature was 15°C.

Results

What Schlieren Photography Revealed

The air, which forms part of the microenvironment, is not a layer of still air but is in constant upward movement. Its extent and velocity depend on the posture of the body and its contours.

Starting at the feet, the major part of the air adjacent to the skin of the dorsa detaches itself and rises from the feet. This is because the dorsal surfaces are nearly horizontal. Part of the flow does, however, remain attached and when the ankle is reached joins the airflow which remains attached to the vertical surface as it rises up the leg, accelerating and becoming thicker as it rises.

As the layer of air, about 1–2 cm. thick, passes over the knee and thigh to the groin, the inner part of the boundary layer continues to accelerate and becomes well established. The outer part of the boundary layer may become partially detached at the convexities and there appear to be regions of reversed flow. This behaviour persists up to the chest level until, in the region of the shoulder where the surface is horizontal, most of the boundary layer breaks away upward. Despite the vigorous general upward flow, there are regions where the air is brought to rest on the surface of the body. These are known as stagnation regions and develop where the flow is constrained by a horizontal surface. Such regions may be found in the perineum, the axilla, under the lobe of the ear, and under the nasal septum.

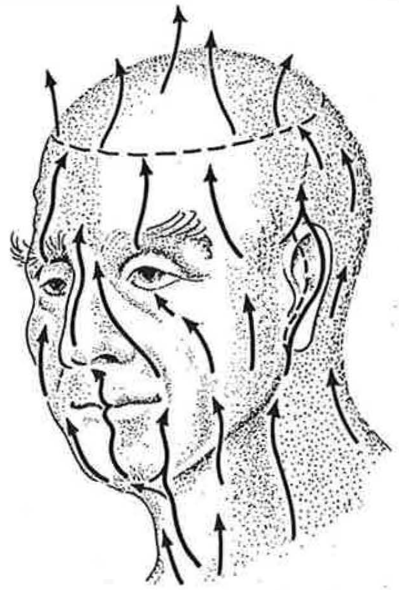


Fig. 2—Routes taken by the naturally convected air over the head.

The air-flow is greatly modified by the contours of the neck, jaw, and face (fig. 2). Part of the rising layer takes the line of least resistance and is deflected up the side of the head while the remaining part follows the undersurface of the chin. The pinna of the ear acts as a deflecting surface and carries away a part of the rising warm air; the rest flows up off the side of the head.

The other portion, following the undersurface of the chin, passes up the front of the face where two important patterns are seen.

Nose.—The layer of warmed air passes up the chin and over the lips, and becomes part of the air which is inhaled (i.e., it is inspired with the ambient air). This might account for about 10% of each tidal inspiration at rest. During expiration through the nose (fig. 3), the pattern of outflowing tidal air is clearly seen as a jet which is directed beyond the area from which the inspired air is drawn—i.e., there is little chance, under ordinary conditions, of entraining expired air during the ensuing inspiration. The direction of the expired jet seems constant for a given individual; subjects showed variations between 10° and 45° with the vertical. As expiration starts, the rising air of the microenvironment halts within a few millimetres

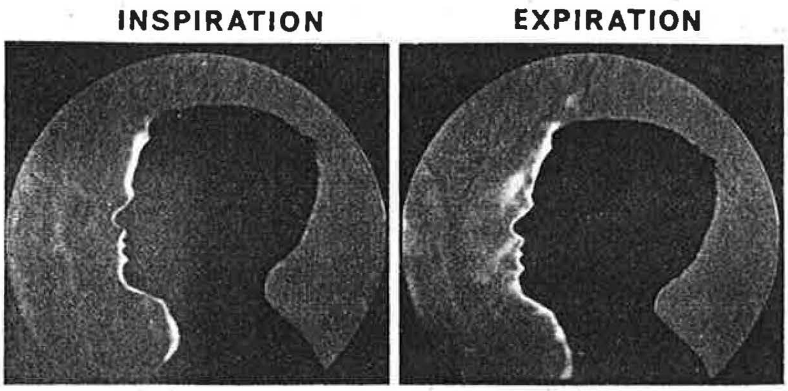


Fig. 3—Profile of face in schlieren beam during respiration.
The white layer around the head is the inner part of the boundary layer.

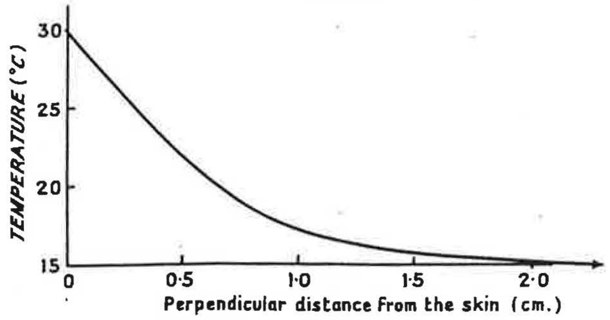


Fig. 4—Smoothed temperature profile in a region of laminar flow (front of leg, height 20 cm.) Each point on the profile is obtained by averaging 50 readings over 100 seconds, because of natural unsteadiness in the flow.

of the external nasal orifice, and during this part of the respiratory cycle it passes to the sides of the nose. Immediately afterwards, with inspiration, air from below again enters the nose.

Eye.—The air layer which has passed over the cheek reaches the orbit; it seems to clear the anterior surface of the cornea by a few millimetres. There is minor separation of the boundary layer, but the flow reattaches by the time it reaches the supraorbital ridge. While passing in front of the eye, the boundary layer thickens. At this level the air velocity, assessed from frame by frame analysis of the cinefilm, is of the order of 0·5 m. per second. The boundary layer flows over the forehead and joins the air which has been rising up the sides and back of the head. A plume can be seen for about 0·5 m. above the hair, after which it disintegrates and is lost in the ambient air.

Temperature Profiles, Air Movement, and their Relation to Schlieren Visualisation

We have done some preliminary experiments on the

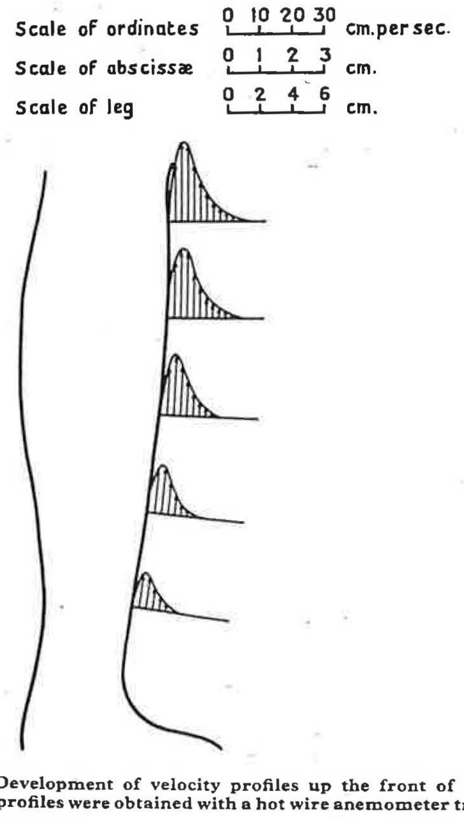


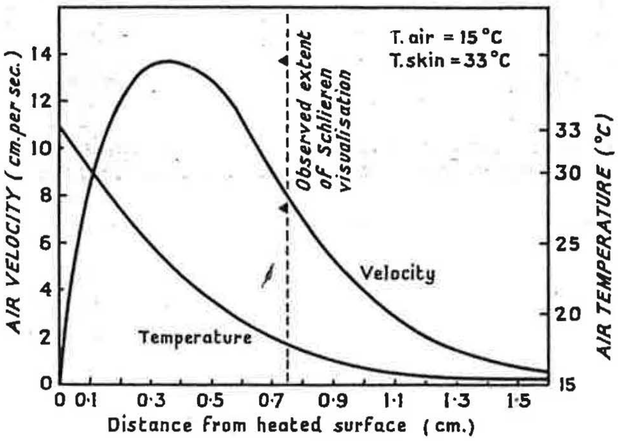
Fig. 5—Development of velocity profiles up the front of the leg. These profiles were obtained with a hot wire anemometer traverse.

velocity and temperature profiles in the thermal boundary layer using hot wire anemometers and thermocouples (Foster 1968).

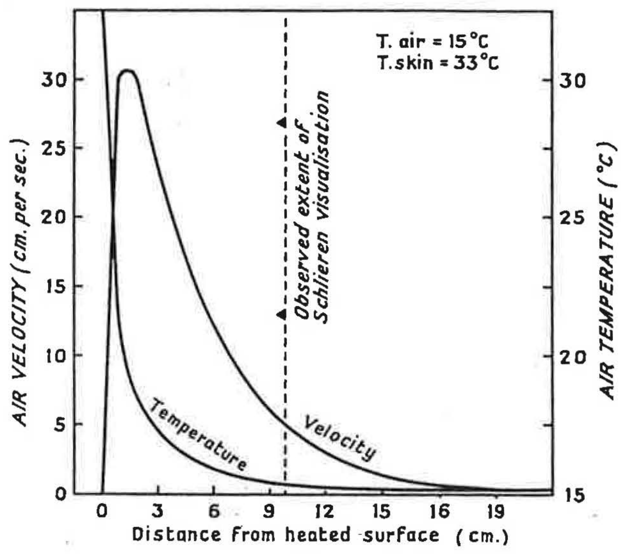
The temperature profile in a typical experiment is shown in fig. 4. The lower-density air initiates air movement, while the temperature gradient controls the heat-transfer rate. The larger the temperature gradient, the greater the heat transfer.

Typical air velocities obtained are illustrated in fig. 5, a series of velocity profiles on the front of the leg, showing that the flow has accelerated and the laminar boundary layer has thickened until, at a height of 30 cm., the boundary layer is 3·0 cm. thick with a peak velocity of 25 cm. per second about 0·5 cm. from the skin.

At about 100 cm. from floor level the boundary layer begins to change from laminar to turbulent flow. Above 150 cm. (mid-chest) fully developed turbulent flow exists. Visualising the boundary layer, whether laminar or turbulent, in the schlieren system depends upon the density gradient (the rate of change of air density with distance from the skin) at that point. With a laminar boundary layer, only the inner part will be visualised by the schlieren system. It is in this region only that the temperature gradient (proportional to density gradient) is



(*a*)



(*b*)

Fig. 6—Relationship of temperature profiles to the schlieren system and consequent visualisation of the higher velocity.

(*a*) Laminar flow. (*b*) Turbulent flow.

sufficiently steep. The schlieren sensitivity limit for the system used is indicated in fig. 6. In the turbulent boundary layer, one can see, besides part of the inner layer, parts of the outer boundary layer when the temperature gradient increases locally over a small region in the turbulent eddies.

The schlieren system cannot conveniently be used for quantitative interpretation. This does not detract, however, from the use of the system as a visual aid, especially since those parts of the boundary layer visualised in the schlieren system will encompass the regions of maximum velocity.

Discussion

FUNCTION OF CONVECTIVE AIR MOVEMENT

Thermal Regulation

The air-flow in the microenvironment is the natural convection thermal boundary layer. It affords a certain amount of thermal protection because the thicker it is the shallower is the thermal gradient, with proportionately reduced heat exchange to the ambient air.

Convection, which includes conduction, accounts for 36% of the total heat loss from a body at rest; radiation (45%) and evaporation (19%) account for the remainder. These values have been substantiated by theoretical analysis on an idealised mathematical model of the human body. Further implications of the convective flow will be discussed elsewhere, but we will consider here the possibilities of transport within the microenvironment.

Potential of the Boundary Layer as a Transport Mechanism

Having seen and measured the movement of air within the human microenvironment, we must consider what might be contained within this boundary layer and suggest some implications relevant to airborne infection.

Our preliminary experiments on the nude standing man (details of which will be reported elsewhere) have shown that his microenvironment contains significantly (30–400%) more microorganisms than does the ambient air. These particles must be entrained from the skin and/or the ambient air.

We have not yet investigated the effects of clothing on the dispersal of microorganisms, but we do know that the boundary layer is re-established on the outside of clothing. One of the missing links in the natural history of respiratory airborne infections may be the role of clothes since they are responsible for harbouring and shedding organisms that will be conveyed to the convecting layer.

Davies and Noble (1962) showed that during activity large numbers of epithelial scales are liberated into the air, and that organisms such as staphylococci are carried on these fragments. As the epithelial cells come to the surface of the skin and are converted to keratin, they dry and then curl up looking rather like a cornflake. Once the flake is ready for shedding, the most likely cause of final detachment is friction from clothes and towelling. When the body is at rest there is also a continuous shear stress exerted by the natural convection boundary layer. However, the levels of wall shear in laminar and turbulent boundary layers are too small (by a factor of 10 or more) to cause the particles to be dragged away from the skin. Nor is it likely that normal levels of forced convection will detach the skin flakes.

Whatever the mechanism, the flakes do detach and fall away from the surface. Larger particles (say greater than 50 μ diameter) are likely to fall to the ground, but smaller particles are entrained and move with the flow. In laminar boundary layers this may be aided by hairs which stir up the flow and cause eddies. In turbulent flow the natural eddying motion is sufficient to maintain the particles in suspension.

IMPLICATIONS

Taking a shower increases the number of organisms in the air immediately and for as long as an hour afterwards (Speers et al. 1965). The explanation may be that during the shower the flow of the boundary layer is disrupted by water droplets in the opposite direction, and its contents are disseminated. After the shower, the defatting of the skin and frictional effect of towelling releases and increases the number of skin flakes and bacteria into the convective boundary layer of the microenvironment from which they contaminate the room.

The convecting layer may also deposit bacteria. Summers et al. (1965) showed that bacteria, especially *Staphylococcus aureus*, are always to be found in the scalp hair of the hospital community, and we believe that they could have been transported in the boundary layer.

It is of interest to note that the highest bacterial counts (Marples 1969 a, b) are associated with the stagnation regions on the body (e.g., axilla and perineum), where the numbers of bacteria could be increased by deposition. The relative absence of air-flow in these regions attenuates evaporation with the result that these areas are moist and suitable for bacteria proliferation.

For the hygiene of rooms generally, it is known that airborne bacteria can be distributed attached to dust particles or in gross droplets expelled from nose and mouth, or in droplet nuclei which result from evaporation of the droplets (Wells et al. 1939, Medical Research Council 1948). After the Medical Research Council report a series of studies on the dispersal of bacteria—reviewed by Williams (1966)—has confirmed the large numbers of organisms to be found in room air associated with bedmaking and dressing. Duguid and Wallace (1948) concluded that dust particles from clothes were as important in airborne infection as droplet nuclei from the respiratory tract.

Since some of the boundary layer is inhaled with each respiratory cycle, organisms find their way into the nose. This flow over the skin surface provides a possible transport mechanism for inhaling a large daily dose of bacteria; this is in contrast to the random inspiration of relatively few organisms in the ambient air. This relationship might also provide a connection between skin disease, such as eczema in children, and asthma which often follows the eruption.

If one considers the boundary layer over the front of the body as a catchment zone, many more particles, pollens, and microorganisms from the ambient air than hitherto suspected may be entrained by the boundary layer and thus conveyed to the respiratory tract with amplified effect.

We also need to know what happens to the microenvironments of individuals who come into close physical proximity with each other in crowded conditions and whether cross-flow occurs in which organisms are exchanged.

A further area to be studied is the effect of ambient temperatures, since a cooler environment increases the velocity of the boundary layer and therefore the transport of organisms to the nose. It is known that the number of respiratory infections increase a few days after air temperature falls.

Schlieren photography reveals a close relationship between the convective boundary layer and the eye. The lower eyelashes cause small areas of turbulence. Bacteria in the microenvironment may be deposited in the conjunctival area by this mechanism. After eye operations, infection by staphylococci is a serious hazard.

Normally, the boundary layer passes up and seems to flow just beyond the anterior surface of the cornea. In proptosis or in exophthalmos, the flow could impinge on the conjunctival surface. This could produce drying which might account for characteristic discomfort and also the deposition of bacteria.

Bacterial transport within the human microenvironment might be of special importance in the problem of hospital infection, since organisms are constantly and inevitably shed by surgeons and nurses in operating-theatres. Attempts have been made to use impermeable garments. However, the comfort and efficiency of the surgical team depends on their own ability to eliminate heat while working. Some operations, especially orthopædic ones, are associated with a large amount of physical work (and thus heat production). In this situation, especially if there is sweating, such garments frustrate the principles of clothing physiology (Lewis 1968, Charnley and Eftekhar 1969). In any event, the bellows action of garments (permeable or not) will drive skin particles and organisms via the tailored openings into the ambient air over the operation site.

It is of interest that Lister's early antiseptic techniques were aimed at sterilising the air of operating-theatres but the carbolic spray was so unpleasant that, in its place, aseptic techniques evolved. The modern routine also takes account of airborne infection but is as yet not very effective.

A relatively inexpensive method could be used to help achieve germfree nursing (e.g., in leukæmia). Although autogenous infection is often responsible for the coup de grace, it is highly desirable to reduce exogenous infection; this could be obtained if the nurse or doctor is equipped with an isolating pneumatic suit when the patient has to be attended to. The development of such a system might certainly spare the patient the mental discomfort of being confined to a small tent for weeks on end.

The incidence of wound infection and cross-infection is higher in the hospital ward than in the operating-theatre, and there is the well-established association with bedmaking and with the changing of dressings. Rountree et al. (1960) examined infection in clean wounds which were closed by a plastic seal and those open to the ward atmosphere (closed with a gauze pad), and found infection-rates of less than 12% and 56%, respectively. The plastic seal excluded the ward bacteria, and when infection did take place in sealed wounds it was autogenous, or arose late in the postoperative period when the seal had been accidentally broken. These observations are consistent with the mechanism we have suggested for airborne infection—i.e., by sealing the wound from the boundary layer one can reduce airborne infection.

The film, Man's Natural Barrier to the Environment (16 mm., colour sound, 6 minutes), is available from the Film Library Department of Audio-Visual Communication, British Medical Association, Tavistock Square, London W.C.1, or from Macqueen Film Organisation Ltd., West Street, Bromley, Kent.

Requests for reprints should be addressed to H. E. L., National Institute for Medical Research, Holly Hill, London N.W.3.

References at foot of next column

MICROANGIOPATHIC HÆMOLYTIC ANÆMIA AND THE PATHOGENESIS OF MALIGNANT HYPERTENSION

A. L. LINTON H. GAVRAS R. I. GLEADLE
H. E. HUTCHISON D. H. LAWSON A. F. LEVER
R. F. MACADAM G. P. MCNICOL
J. I. S. ROBERTSON

FROM THE MEDICAL RESEARCH COUNCIL BLOOD PRESSURE UNIT, THE RENAL UNIT, AND THE DEPARTMENTS OF HÆMATOLOGY AND PATHOLOGY, WESTERN INFIRMARY, GLASGOW W.1, AND THE UNIVERSITY DEPARTMENT OF MEDICINE, ROYAL INFIRMARY, GLASGOW C.4.

Summary The relation between severe hypertension and microangiopathic hæmolytic anæmia (M.H.A.) was explored in detail in nine patients with both conditions. Blood-films were also examined in eighty-seven cases of hypertension. Of twenty-four patients with malignant-phase hypertension, sixteen had evidence of M.H.A.: of the remaining patients none had evidence of M.H.A. A hypothesis is suggested for the relation between M.H.A. and malignant hypertension in which the following are the important steps: high arterial pressure or primary vascular disease increases the permeability of small blood-vessels to fibrinogen; fibrin is deposited in the wall and lumen of vessels, and persists either because the deposition of new fibrin is increased or because fibrinolysis is impaired; fibrin deposits fragment red blood-cells, leading to hæmolysis and further deposition of fibrin.

Introduction

IN the past few years, increasing interest has been taken in the syndrome of microangiopathic hæmolytic anæmia (M.H.A.) (Brain et al. 1962). Several forms have been reported, including an acute illness affecting infants and young children, usually called the hæmolytic-uræmic syndrome (Gasser et al. 1955, Desmit et al. 1966), and a disease with the same hæmatological characteristics complicating acute glomerulonephritis, malignant hypertension, acute renal failure, eclampsia, various collagen diseases, ulcerative colitis, and some carcinomata (Brain et al. 1962, Brain et al. 1968, *Lancet* 1968, Lehtinen et al. 1968, Seligsohn et al. 1968). The disease is usually rapidly progressive and fatal. Brain et al. (1962) suggested that the primary lesion is in the small blood-vessels, as implied in the term "microangiopathy" (fig. 1). This may damage red blood-cells directly (Brain et al. 1962) or it may produce intravascular coagulation with fragmentation of red blood-cells by fibrin strands (Regoeczi et al. 1967, Brain et al. 1968, Bull et al. 1968, Rubenberg et

DR. LEWIS AND OTHERS: REFERENCES

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