35. Erde, A., Experience with Moderate Hypothermia in the Treatment of Nervous System Symptoms of Decompression Sickness, in Proceedings of Second Symposium Underwater Physiology, C. J. Lambertson, L. J. Greenbaum, Jr., (eds.). NAS-NRC-1181, National Academy of Sciences - National Research Council, Washington, D. C., 1963, pp. 66-73.

36. Ferris, E. B.,Jr., Engel, G. L., The Clinical Nature of High Altitude Decompression Sickness, in Decompression Sickness, J. G. Fulton, (ed.). Philadelphia, W. B. Saunders Co., 1951, pp. 4-52.

37. Ferris, E. B. Jr., Molle, W. E., Engel, G. L., Brown, E., Comparative Study of Decompression Sickness Under Varied Conditions of Exercise, Altitude and Denitrogenation. NAS-NRC-CAM-363, National Academy of Sciences - National Research Council, Committee on Aviation Medicine, Washington, D. C., 1944.

38. Flinn, D. E., Womack, G. J., Neurological Manifestations of Dysbarism: A Review and Report of a Case with Multiple Episodes, Aerospace Med., 34:956-962, 1963.

39. Fryer, D. I., Decompression Sickness at 18,500 feet: A Case History with Comment. FPRC/Memo 199, Flying Personnel Research Committee, Royal Air Force Institute of Aviation Medicine, Farnborough, England, 1963.

40. Goodman, M. W., Decompression Sickness Treated with Compression to 2-6 Atmospheres Absolute. Aerospace Med., 35:1204-1212, 1964.

41. Gowdey, C. W., Philp, R. B., Etiology and Treatment of Experimental Decompression Sickness with Special Reference to Body Lipids. Milit. Med., 130:648-652, 1965.

42. Gray, J. S., Constitutional Factors Affecting Susceptibility to Decompression Sickness, in Decompression Sickness, J. G. Fulton, (ed.). Philadelphia, W. B. Saunders Co., 1951, pp. 182-191.

43. Gray, J. S., Aeroembolism Induced by Exercise in Cadets at 23,000 Feet. AF-SAM-227-1, U. S. Air Force Sch. Aviation Med., Randolph Field, Texas, 1944.

44. Gribble, M. de G., A Comparison of the "High-Altitude" and "High-Pressure" Syndromes of Decompression Sickness. Brit. J. Industr. Med., 17:181-186, 1960.

45. Harris, R. I., Fat Embolism. J.A.M.A., 105:1013-1016, 1935.

46. Harvey, E. N., Decompression Sickness and Bubble Formation in Blood and Tissues. Bull. N. Y. Acad. Med., 21:505-536, 1965.

47. Haymaker, W., Johnston, A. D., Pathology of Decompression Sickness: A Comparison of the Lesions in Airmen with Those in Caisson Workers and Divers. Milit. Med., 117:285-306, 1965.

48. Hetherington, A. W., Miller, R. A., The Effect of Intravenous Nitrogen on the Respiration and Circulation of the Cat. Fed. Proc., 5:46, 1946.

49. Henn, R. H. E., Wünsche, O., Experimental Study of Fat Embolism, in XI. European Aeronautical and Cosmonautical Medical Congress. DVL-273, Deutsche Versuchsanstalt für Luftund Raunfahrt, E. V., 1963.

50. Henry, F. M., Aviators' "Bends" Pain as Influenced by Altitude and In-Flight Denitrogenation. WADC-TR-53-227, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1953.

51. Henry, F. M., Effects of Exercise and Altitude on the Growth and Decay of Aviators' Bends. J. Aviat. Med., 27:250-259, 1956.

52. Henry, F. M., Cook, S. F., Stratman, E., Lund, D. W., Effectiveness of Preflight Oxygen Breathing in Preventing Decompression Sickness. NAS-NRC-CAM-384, National Academy of Sciences - National Research Council, Committee on Aviation Medicine, Washington, D. C., 1944.

53. Holstrom, F. M. G., Beyer, D. H., Decompression Sickness and Its Medical Management: A Team Approach to the Study of Aviator's Hemocirculatory Collapse. AF-SAM-TR-65-21, U. S. Air Force Sch. Aerospace Med., Brooks AFB, Texas, 1965.

54. Höök, O., Dysbarism Manifested by Anterior Spinal Artery Syndrome: Further Report of a Case with Recovery. J. Aviat. Med., 29:540-543, 1958.

55. Ivy, A. C., cited by Ferris, E. B. Jr., Engel, G. L., (see ref. 36).

56. Jones, H. B., Respiratory System: Nitrogen Elimination, in Medical Physics, O. Glasser, (ed.). Chicago, Year Book Publishers, 1950, Vol. II, pp. 855-871.

57. Jones, H. B., Preoxygenation and the Rate of Nitrogen Elimination with Regard to Decompression Sickness. NAS-NRC-CAM-491, National Academy of Sciences - National Research

Council, Committee on Aviation Medicine, Washington, D. C., 1945.

58. Kellett, G. L., Coburn, K. R., Hendler, E., An Investigation of Decompression Hazards Following Equilibration in a Simulated Spacecraft Atmosphere of 50%O_2-50%He at 380 mm Hg. NAEC-ACEL-540, U. S. Naval Air Engineering Center, Aerospace Crew Equipment Laboratory, Philadelphia, Pennsylvania, 1965.

59. Kern, J. D., Etiology and Pathological Physiology of Decompression Sickness. NMRL-345, U. S. Naval Medical Research Laboratory New London, Connecticut, 1960.

60. Kindwall, E. P., Boreus, L. O., Westerholm, B., Failure to Show Change in Rat Tissue Histamine and Serotonin After Rapid Decompression. Amer. J. Physiol., 203:389-390, 1962.

61. Labout, H., Barthelemy, L., Perrimond-Trouchet, R., Action de l' Héparine dans le Traitement des Accidents de Decompression. (Action of Heparin in the Treatment of Decompression Accidents.) Révue Agressologie, 2:229-236, 1961.

62. LeQuire, V. S., Shapiro, J. L., LeQuire, C. B., A Study of the Pathogenesis of Fat Embolism Based on Human Necropsy Material and Animal Experiments. Amer. J. Path., 35: 999-1015, 1959.

63. Leverett, S. D., Bitter, H. L., McIver, R. G., Studies in Decompression Sickness; Circulatory and Respiratory Changes Associated with Decompression Sickness in Anesthetized Dogs. AF-SAM-TDR-63-7, U. S. Air Force Sch. Aerospace Med., Brooks AFB, Texas, 1963.

64. Luft, U. C., Aviation Physiology - The Effects of Altitude, in Handbook of Physiology, Section 3: Respiration, Vol. II. American Physiological Society, Washington, D. C., 1965.

65. Malette, W. G., Fitzgerald, J. B., Cockett, A. T. K., Dysbarism: A Review of 35 Cases with Suggestion for Therapy. AF-SAM-Rev-3-61, U. S. Air Force Sch. Aviation Med., Brooks AFB, Texas, 1961.

66. Marbarger, T. P., Kemp, W. E., Kadetz, W., Hansen, J., Studies in Aeroembolism. J. Aviat. Med., 29:291-300, 1958.

67. Marotta, S. F., Marbarger, J. P., Andersen, N., Incidence of Bends Following Partial Denitrogenation at Simulated Altitude.

Aerospace Med., 32:289-295, 1961.

68. Masland, R. L., Injury of the Central Nervous System Resulting From Decompression to Simulated High Altitude. AF-SAM-481-1, U. S. Air Force Sch. Aviation Med., Randolph Field AFB, Texas, 1946.

69. Masland, R. L., Injury of the Central Nervous System Resulting From Decompression to Simulated High Altitudes. Arch. Neural. Psychiat., 59:445-456, 1948.

70. McIver, R. G., Medical Problems Encountered at High and Low Barometric Pressures. Illinois Med. J., 123:611-618, 1963.

71. McIver, R. G., Kronenberg, R. S., Treatment of Altitude Dysbarism with Oxygen Under High Pressure: Report of Three Cases, (Presented at Fourth Internat. Biometeorological Congr., New Brunswick, New Jersey), 1966.

72. McIver, R. G., Leverett, S. D., Jr., Studies in Decompression Sickness: Cardiorespiratory Responses of Anesthetized Dogs to Compression Therapy Following Experimental Decompression Sickness. AF-SAM-TDR-63-94, U. S. Air Force Sch. Aerospace Med., Brooks AFB, Texas, 1963.

73. Murray, G., Fat Embolism and a Fat Center. Amer. J. Surg., 100:676-681, 1960.

74. National Aeronautics and Space Administration, Bioastronautics Data Book, P. Webb, (ed.). NASA-SP-3006, National Aeronautics and Space Administration, Washington, D. C., 1964, p. 97.

75. Nims, L. F., Environmental Factors Affecting Decompression Sickness, in Decompression Sickness, J. G. Fulton, (ed.). Philadelphia, W. B. Saunders Co., 1951, pp. 192-222.

76. Odland, L. T., Fatal Decompression Illness at an Altitude of 22,000 Feet. Aerospace Med., 30:840-846, 1959.

77. Parsons, V. A., A Brief Review of Aviator's Decompression Sickness and the High Altitude Selection Test. J. Roy. Nav. Med. Serv., 44:2-13, 1958.

78. Peltier, L. F., An Appraisal of the Problem of Fat Embolism. Int. Abstr. Surg., 104:313-324, 1957.

79. Rait, W. L., The Etiology of Post-Decompression Shock in Aircrewmen. Armed Forces Med. J., 10:790-805, 1959.

80. Robie, R. R., Lovell, F. W., Townsend, F. M., Pathological Findings in Three Cases of Decompression Sickness. Aerospace Med., 31:885-896, 1960.

81. Roth, E. M., Space-Cabin Atmospheres. Part III. Physiological Factors of Inert Gases. NASA-SP-117, National Aeronautics and Space Administration, Washington, D. C., 1966.

82. Schneck, S. A., Decompression Sickness at Medium Altitude. Armed Forces Med. J., 8:1366-1370, 1957.

83. Thomas, S., Williams, O. L., High Altitude Joint Pains; Their Radiographic Aspects. NAS-NRC-CAM-395, National Academy of Sciences - National Research Council, Committee on Aviation Medicine, Washington, D. C., 1944.

84. Webb, J. P., Ferris, E. B., Engel, G. L., et al, Radiographic Studies of the Knee During Bends. NAS-NRC-CAM-305, National Academy of Sciences - National Research Council, Committee on Aviation Medicine, Washington, D. C., 1944.

85. Weeth, J. B., Crippling Effects of Decompression Sickness: Report of Ten Cases. Southern Med. J., 58:657-660, 1965.

86. Whiteley, J. H., The Relation Between Tissue Injury and the Manifestations of Pulmonary Fat Embolism. J. Path. Bact., 67:521-530, 1954.

87. Whitten, R. H., Scotoma as a Complication of Decompression Sickness. Arch. Ophthal., 36:220-224, 1946.

88. Wise, D. A., Constitutional Factors in Decompression Sickness. NEDU-RR-2-63, U. S. Navy Experimental Diving Unit, Washington, D. C., 1963.

89. Wittmer, J. F., Pathogenic Mechanisms in Gas and Fat Embolism. AF-SAM-Rev-4-62, U. S. Air Force Sch. Aerospace Med., Brooks AFB, Texas, 1962.

90. Womack, G. J., Evidence for the Cerebral Vasoconstrictor Effects of Breathing One Hundred Per Cent Oxygen, with Special Reference to the Treatment of Neurocirculatory Collapse as Seen in Cases of Dysbarism. Aerospace Med., 32: 328-332, 1961.

CHAPTER 5

AEROTITIS MEDIA AND AEROSINUSITIS

Aerotitis media and aerosinusitis are well known, occasionally incapacitating medical problems which result usually from an elevation of the ambient atmospheric pressure. Their occurrence during routine operations in space is considered unlikely; any cases will probably be attributed to certain predisposing factors. Since there has been a vast amount of detailed writing in this area, the discussion which follows will be brief, citing major works and presenting information which is pertinent only to missions in space.

Aerotitis Media

The generally accepted definition of aerotitis media was originally stated by Armstrong and Heim [2] as: "an acute or chronic traumatic inflammation of the middle ear caused by a pressure differential between the air in the tympanic cavity and that of the surrounding atmosphere". The non-infectious character of this condition must be emphasized, for only in very rare instances is infection a secondary complication [14, 25, 27, 33, 35, 39].

Pathophysiology

An astronaut might fail or be unable to open voluntarily one or both Eustachian tubes and so provide adequate middle ear ventilation during a recompression in space. Pressure in the middle ear might then become sufficiently negative relative to that of the ambient atmosphere to traumatize tissues surrounding this "semi-rigid" cavity. For all practical purposes, positive pressure differentials, even during "explosive" decompressions in space, should not be great enough to produce damage, provided that astronauts' Eustachian tubes have reasonably normal patency [1, 14, 33].

The anatomy and physiology of the Eustachian tube has been discussed in detail by many authors [1, 14, 24, 26, 32]. Pertinent to this discussion is the fact that the tube has a flutter valve action which

opposes the passage of air from the nasopharynx into the middle ear cavity unless the tube is opened by contraction of its dilator muscles. This must be accomplished voluntarily by various acts such as swallowing, yawning, grinding movements of the lower jaw or the Valsalva maneuver. It is apparently impossible for these muscles to overcome a negative pressure differential of more than 80 to 90 mm Hg. (1, 2).

Either failure or inability of an astronaut to open the Eustachian tube during recompressions in space might occur under a variety of circumstances. A rapid recompression may not allow sufficient time or he might be too preoccupied to perform an adequate equalizing maneuver. Notably, maximum negative pressure differentials developed in the middle ear on recompressions from the present space suit atmospheric pressure of 3.7 psia (191 mm Hg) to possible spacecraft cabin atmospheric pressures of either 5.0 psia (259 mm Hg) or 7.0 psia (362 mm Hg) will be such that the astronaut should be only able to equalize immediately after recompression to 5 psia. Rapid emergency recompression modes which follow large decompressions of either space suit or spacecraft cabin might also lead to excessive negative pressure differentials. Inability to perform the highly effective Valsalva maneuver while in a "closed" space suit will undoubtedly be a factor predisposing to middle ear trauma from rapid suit or suit to cabin recompressions. Finally one should keep in mind that an unconscious astronaut and probably most semi-conscious astronauts will be incapable of equalizing.

The question arises as to whether a common cold or any other nonspecific acute or chronic upper respiratory infection predisposes to aerotitis media. Such a condition might produce inflammatory swelling, especially in and around an otherwise normal Eustachian tube, sufficient to impair tubal function. A positive correlation between the incidence of aerotitis media and both the size of the adenoid and the presence of lymphoid tissue has been noted, but the magnitude of this relationship did not allow accurate prediction in individual cases (31). The role of infection could not be separated from that of lymphoid tissue in obstruction of the Eustachian tube (14). Extensive studies on

flying and diving personnel have failed to reveal a significant correlation between the incidence of aerotitis media and upper respiratory infections [11, 16, 17, 33]. Another study even added the number of individuals excused from altitude chamber operations because of severe upper respiratory infection to the number who suffered from aerotitis media, but still failed to establish a definite relationship [33]. The possibility that an astronaut might experience increased difficulty in ventilating his middle ears if his nasopharynx becomes inflamed cannot be denied, however. Accordingly, an upper respiratory infection might predispose to aerotitis media under certain circumstances in space, such as a rapid recompression or inability of an astronaut to perform the Valsalva maneuver during recompression.

So-called "secondary" or "delayed" aerotitis media can be caused by the absorption of oxygen from the middle ear; increase of the atmospheric pressure per se does not play a causative role [1, 4, 14, 27, 38]. It usually appears in aviators who have breathed oxygen during descent and have failed to ventilate their middle ears adequately after descent, and is attributed to the effect of a high pressure gradient for oxygen being established between the middle ear cavity and the well perfused, metabolically active tissues of the middle ear. Clinical manifestations due to development of negative pressure in the middle ear usually appear some 2 to 6 hours after descent, in most cases while asleep during which the frequency of swallowing, and therefore of equalizing is reduced [1]. Also of note is the fact that the absorption of oxygen can aggravate aerotitis media caused by an atmospheric pressure change [14].

Astronauts will undoubtedly run a risk of developing "delayed" aerotitis media after being recompressed in 100 percent oxygen from a space suit atmospheric pressure of 3.7 psia (191 mm Hg) to a spacecraft cabin atmosphere containing 50 percent nitrogen and 50 percent oxygen at a total pressure of 7.0 psia (362 mm Hg). The risk following suit recompression to a 100 percent oxygen atmosphere at 5.0 psia (259 mm Hg) should be essentially no different than that for continuous exposure to such a cabin environment. It has been shown that the continuous

absorption of oxygen from the middle ear (commonly referred to as "aural atelectasis" if no signs of aerotitis media are present) while living in this atmosphere is sufficiently rapid to cause discomfort after a period of several hours of sleep [12, 13]. Equalizing maneuvers were successful, so that "delayed" aerotitis media did not develop. Prolonged exposures to oxygen atmospheres at other pressures have presented a similar picture [19, 20]. Therefore, even though aural atelectasis commonly occurs in pure oxygen atmospheres, it appears from experience to date that there may be only a remote risk of serious "delayed" aerotitis media from exposure to such atmospheres during space missions.

The probable sequence of events responsible for producing the clinical picture of aerotitis media has been determined from animal experiments [7, 11]. The pathologic changes in the middle ear appear to be primarily vascular in nature, for some degree of hyperemia is nearly always present both in the tympanic membrane and in the mucosa of the middle ear. Mucosal edema and hemorrhage may occur singly or together, the hemorrhagic areas varying from tiny petechiae to large, confluent areas [14]. These effects are probably caused by a combination of factors attributable to negative pressure. These factors include vasodilatation sufficient to produce a temporary vascular paralysis, a stagnation of tissue blood flow, imbalance of osmotic and hydrostatic forces between vessel and tissue fluids, a disruption of overdistended small vessels and the tearing apart of mucosal and fibrous tissue layers. As this condition progresses, a non-inflammatory sterile fluid transudate appears in the middle ear cavity; there may even be gross hemorrhage [30, 36]. Since fluid and blood are space filling, the negative pressure differential decreases and consequently the progression of pathologic changes is arrested. Although the transudate and blood in the middle ear cavity are usually completely reabsorbed, blood in middle ear tissues can organize and hence possibly lead to some degree of permanent hearing loss.

It has been reported that at about a 200 mm Hg negative pressure

differential, the tympanic membrane may disrupt [1]. However this event apparently occurs at this level of pressure only in individuals with previous tympanic membrane disease, so that the critical pressure of a normal tympanic membrane might be considerably higher [1, 28]. Although negative pressure differentials sufficient to produce disruption will probably not be attainable during the space suit to spacecraft cabin recompressions in space discussed above, it is apparent that such pressures might be reached during large emergency recompressions of either the space suit or spacecraft cabin.

Clinical Manifestations

Aerotitis media may be acute or chronic, unilateral or bilateral and mild or severe, depending on the degree and frequency of pressure differential insults on the ear. The incidence of monaural or binaural involvement is often about equal, although in monaural cases, signs of trauma from negative pressure are usually noted in the other asymptomatic ear [15, 16]. The clinical manifestations of acute aerotitis media may begin during or immediately following recompressions [1]. Symptoms of "delayed" aerotitis media usually appear some 2 to 6 hours after recompression while breathing oxygen.

The negative pressure which develops in the middle ear during recompression produces discomfort in the involved ear, then pain which may radiate to the temporal region, cheek, and parotid gland on the affected side [1]. The pain occurs usually when the pressure differential reaches 100 mm Hg and is usually stabbing in character; it can begin gradually or suddenly and vary from mild to unbearable [1]. Its intensity does not necessarily parallel objective findings, for afflicted individuals have complained of severe pain and yet on examination were found to have no changes indicating the presence of aerotitis media [34]. Conversely, slight or even no pain has been reported in instances of tympanic membrane disruption [23]. Pain is usually relieved on early ventilation of a mildly traumatized middle ear.

More severe trauma is followed by a sense of soreness in the ear and an occasional sharp pain caused by movement of the inflamed tympanic membrane [1]. Disruption of the tympanic membrane is accompanied by a sharp piercing pain, a loud "explosive report" which is felt and heard in the affected ear; associated vertigo and nausea may persist for many hours. With disruption, acute pain quickly subsides, but a dull ache may remain for up to 2 days.

Partial deafness is the most frequent complaint of individuals suffering from aerotitis media [14, 23, 27]. A conduction type of hearing loss of up to 15 to 30 decibels can persist from a few hours to many days in duration, depending mainly on such factors as the degree of immobilization of the tympanic membrane by a persisting pressure differential and by edema and blood which accumulates in the membrane, and whether a fluid transudate or blood accumulates in the middle ear cavity [1, 10, 15, 31].

This loss may be fairly uniform for the various frequencies or may in certain individuals affect principally the lower or the higher frequencies [1, 27]. In general, hearing for the lower frequencies seems to be depressed first, and as more fluid is drawn into the middle ear cavity, the high frequencies become more and more effected [27]. It is noted that permanent perceptive type of deafness may rarely occur, presumably due to labyrinthine hemorrhage [10].

There are always temporary sensations of "fullness" and "stuffiness" in an involved ear [27]. These symptoms are often accompanied by a feeling of fluid in the ear [14]. Tinnitus occurs infrequently. Vertigo is also uncommon; when present, it is usually unilateral [18]. Bubbling sounds may be heard on blowing the nose, swallowing or yawning [27]. Another symptom which occasionally appears is autophony, in which the individual's own voice and breathing sounds unusually loud to him [1, 27].

The appearance of the tympanic membrane in aerotitis media often, but not always correlates with symptoms of this condition fairly closely [14]. A classification of progressive pathologic changes

visualized on otoscopy has been advanced by Teed [34], and is somewhat altered here to correspond with the excellent account of otoscopic findings presented by Armstrong [1]. It is noted that the tympanic membrane may or may not be retracted at the time of otoscopic examination.

> Grade 1 - injection of the blood vessels running over the pars flaccida and along the handle of the malleus. At a more advanced stage, there is erythema of the upper and posterior portion of the tympanic membrane.
>
> Grade 2 - redness of the entire tympanic membrane and adjacent portions of the external auditory canal. The tympanic membrane develops a translucent appearance, and small droplets of fluid may be seen on its medial surface.
>
> Grade 3 - gross fluid and bubbles in the middle ear; this may be temporarily concealed by congestion and edema of the tympanic membrane.
>
> Grade 4 - hemorrhage into the substance of the tympanic membrane and/or into the middle ear; this may be temporarily concealed by congestion of the tympanic membrane. If it occurs, a traumatic rupture of the tympanic membrane will usually be linear, quite extensive, and may involve any portion of this structure; the margins of a fresh rupture are red, the whole tympanic membrane is intensely inflamed and there is usually a small amount of blood in the external auditory canal.

Acute aerotitis media has generally a good prognosis, provided that treatment is adequate and sufficient time is allowed for complete recovery [14]. The recovery period may vary from a few hours to 3 or 4 weeks in duration. Both the rapidity with which treatment is initiated following exposure and the type of treatment employed may affect the prognosis. As mentioned above, middle ear infection is a very uncommon complication of acute aerotitis media.

Finally, it should be pointed out that repeated insults on the middle ear can lead to a chronic form of aerotitis media [1, 37]. This is probably caused by a partial stenosis of the Eustachian tube preventing adequate pressure equalization [1]. Symptoms are aggravated by

repeated recompression, and include continuous feelings of "fullness" and "stuffiness", occasionally tinnitus, and rarely pain in the affected ear. Whether hearing acuity is diminished in this condition is not known, but it has been observed that atmospheric pressure changes are capable of producing permanent injury to both the middle ear and cochlea portion of the middle ear [1, 37]. Signs of chronic aerotitis media include a dull, lusterless and slightly thickened tympanic membrane, and a diminished or absent light reflex [1].

Diagnosis

History of recompression exposure and the associated appearance of symptoms and otoscopic findings discussed above usually make the diagnosis of aerotitis media easy. Asymptomatic injection of vessels in the tympanic membrane can appear in association with upper respiratory tract disease, after performing the Valsalva maneuver and in 50 percent of all individuals exposed to large rapid recompressions [1, 33]. However, the presence of only Grade 1 changes and the absence of symptoms in these situations should allow differential diagnosis.

Prevention

Normal upper respiratory passages, middle ears and Eustachian tubes, and a proven capability to equalize during reasonably rapid recompressions by the simple maneuvers, such as swallowing, yawning, or grinding movements of the lower jaw, are prerequisites for astronaut selection. It is important to note again that the astronauts are unable to perform the Valsalva maneuver while in a "closed" space suit.

If difficulty with equalization occurs during recompression from a space suit to spacecraft cabin atmospheric pressure, adequate voluntary control might be attained by decompressing to a pressure which provides relief, then by recompressing more slowly. However, in an emergency recompression, an astronaut who cannot equalize will have to suffer the consequences of having a negative pressure develop

in one or both of his middle ears.

An astronaut with an upper respiratory infection should if possible avoid decompression-recompression operations. As noted above, an inflammatory reaction in and around the Eustachian tube might predispose to difficulty in ventilating the middle ear, especially if he is unable to perform the Valsalva maneuver. Prophylactic administration of a topical or oral decongestant agent to be mentioned below might be considered. Even though this procedure was unsuccessful in two large scale studies, more potent and specific drugs are presently available [21, 31]. This area therefore requires further study.

"Delayed" aerotitis media after recompression to an atmosphere containing an inert gas can be prevented by ventilating the middle ear, especially if a sleep period is soon to follow. Armstrong [1] suggests that adequate ventilation can be accomplished by performing about six reverse Valsalva maneuvers (taking a mouthful of water, holding the nostrils closed and swallowing). If there is a risk of "delayed" aerotitis media from living in a 100 percent oxygen environment, no preventive measures can be suggested other than short sleep periods, periodic equalization (even though no requirement might be felt), and optimum hydration to promote adequate salivation and thus frequent Eustachian tube opening through swallowing.

Treatment

The majority of cases of acute aerotitis media in aviators are mild, requiring either no therapy or minimum conservative therapy [1, 14, 27]. This should not be taken to mean, however, that a similar situation will always exist in space, for failure of highly experienced astronauts to equalize will probably in most instances result from the predisposing events discussed above, and could lead to serious cases of aerotitis media unless negative pressure differentials are immediately equalized.

Relief of negative pressure in the middle ear may be attempted

first by shrinking the nasal mucous membrane, including that in around the Eustachian tube orifice, with a suitable vasoconstrictor or decongestant spray, such as 1/1000 epinephrine, or oral preparation, such as pseudoephedrine or triprolidine. The Valsalva maneuver should then be performed again. If this attempt at equalization fails, inflation of the Eustachian tube might be tried with a technique which uses air delivered at a controlled positive pressure, if such is available in space, according to the same principles as politzerization (14, 21, 22, 23). The control valve should be set initially to deliver a pressure of 20 mm Hg and if this is not sufficient to provide relief, this pressure can be raised by 5 or 10 mm Hg increments (14).

Paracentesis or myringotomy should be performed only in cases which fail to respond to methods of vasoconstriction and inflation. They are highly skilled procedures which demand extreme care to avoid implanting infectious organisms into a culture medium which would otherwise remain sterile (1). Cleansing and sterilization of the external auditory canal and tympanic membrane might be accomplished with an antiseptic agent such as hexachlorophene on a cotton-tipped applicator. Local anesthesia is ineffective. Paracentesis is the procedure of choice. Aspiration of transudate or blood from the middle ear cavity should be carried out when indicated, for it appears to hasten recovery and may prevent the formation of adhesions with subsequent permanent hearing impairment (1, 14, 27, 36). If only paracentesis is to be performed, a short-bevel 22 gauge needle might suffice. If aspiration is indicated, a double-barreled paracentesis needle, which allows a compensatory passage of air into the middle ear while fluid is being withdrawn, should be used (29). Myringotomy might be performed with a larger needle or a myringotomy knife. The prophylactic administrati of a systemic antibiotic might be indicated following either of these procedures.

Catheterization of the Eustachian tube is not a recommended procedure to be attempted in space. The most important objection to it is the great possibility of producing serious permanent damage to

the tissues at the Eustachian orifice [9, 14, 27].

Other possible therapeutic requirements include a suitable analgesic or sedative for the control of pain, and an antibiotic for secondary infection.

A ruptured tympanic membrane requires no specific treatment, unless secondary infection occurs [1]. Except in emergency situations, decompression-recompression maneuvers should not be carried out until healing is complete.

Aerosinusitis

As on Earth, the potential incidence of aerosinusitis in space will probably be much less than that of aerotitis media [1, 6]. Therefore this clinical entity will be discussed only briefly here.

Aerosinusitis is also acute or chronic inflammation caused by a pressure differential, usually negative, but in this case existing between a semi-rigid nasal cavity, or nasal sinus, and the ambient atmosphere [6]. Usually only one sinus is involved - the frontal most frequently, then the maxillary sinus and rarely the ethmoid sinus [1, 6, 8].

The pathophysiologic mechanisms responsible for producing aerosinusitis have been elucidated by Campbell [5, 6]. Aerosinusitis in an otherwise normal nose is most commonly due to inflamed tissue blocking a sinus ostium or, in the case of the frontal sinus, the duct connecting the nasal cavity with the sinus. This tissue has a ball valve effect in that air is allowed good exit into the sinus but poor entry during pressure change. This effect is undoubtedly enhanced by viscous sticky secretions in the area. The pathologic changes which can be produced by a negative pressure differential in a sinus are similar to those described previously for aerotitis media. Of note, however, is the fact that infection appears to be a common complication of aerosinusitis, in most cases no doubt due to either an extension of the infection which caused the blockage,

or infection already existing in a sinus.

Readily apparent factors predisposing to aerosinusitis include upper respiratory infection involving the nasal mucous membrane and rapid recompression if partial stenosis of an ostium or duct exists. Aerosinusitis as a consequence of living in a 100 percent oxygen environment has not been described, but is considered possible.

Clinically, aerosinusitis is characterized by persistent pain which often begins suddenly and is usually localized over the affected sinus [1, 6]. Lacrimation can occur [1]. Infection of a sinus may be accompanied by severe throbbing pain, and possibly fever and general malaise. Nasal bleeding might follow severe trauma to the sinus mucous membrane [5]. On examination, local tenderness can often be elicited over the affected sinus, and redundant tissue and a purulent discharge might be seen about the sinus opening.

The most important measure preventing the occurrence of aerosinusitis in space is obviously the selection of astronauts with normal nasal and sinus cavities and most particularly, adequate sinus openings. Other preventive measures are those which were discussed for "Aerotitis Media".

The treatment of aerosinusitis is directed at the relief of the obstruction with an appropriate decongestant, the control of pain and the treatment of concurrent or secondary infection [1, 5, 6].

REFERENCES

1. Armstrong, H., Aerotitis Media and Aerosinusitis, in Aerospace Medicine, H. Armstrong, (ed.). Baltimore, Williams and Wilkins Co., 1961, pp. 162-174.

2. Armstrong, H. G., Heim, J. W., Effect of Flight on the Middle Ear. J.A.M.A., 109:417-421, 1937.

3. Aschan, G. K., Aero-otitis Media and Aerosinusitis; Experimental Histopathological Changes Due to Oxygen Deficiency and Oxygen Poisoning. Acta Otolaryng., Suppl.69:1-93, 1948.

4. Bowen, W. J., Delayed Acute Aero-otitis Media and Methods of Prevention. U. S. Naval Med. Bull., 44:247-252, 1945.

5. Campbell, P. A., Aerosinusitis. Acta Otolaryng., 35:107-114, 1942.

6. Campbell, P. A., Aerosinusitis - Its Cause, Course, and Treatment. Ann. Otol., 53:291-302, 1944.

7. Chang, H., Margaria, R., Gelfan, S., Pressure Changes and Barotrauma Resulting from Decompression and Recompression in the Middle Ear of Monkeys. Arch. Otolaryng., 51:378-399, 1950.

8. Dickson, E. D. D., King, P. F., Results of Treatment of Otitic and Sinus Barotrauma. J. Aviat. Med., 27:92-99, 1956.

9. Farrior, J. B., Histopathologic Considerations in Treatment of the Eustachian Tube. Arch. Otolaryng., 37:609-621, 1943.

10. Fowler, E. P., Jr., Causes of Deafness in Fliers. Arch. Otolaryng., 42:21-32, 1945.

11. Haines, H. L., Harris, J. D., Aerotitis Media in Submariners. Ann. Otol., 55:347-371, 1946.

12. Helvey, W. M., Albright, G. A., Benjamin, F. B., et al, Effects of Prolonged Exposure to Pure Oxygen on Human Performance. RAC 393-1 (ARD-807-701), Republic Aviation Corporation, Farmingdale, Long Island, New York, 1962.

13. Herlocher, J. E., Quigley, D. G., Behar, V. S., et al, Physiologic Response to Increased Oxygen Partial Pressure. I. Clinical Observations. Aerospace Med., 35:613-618, 1964.

14. Hyde, R. W., Aerotitis Media: A Critical Review. Ann. Otol., 61:937-975, 1952.

15. Kos, C. M., Effect of Barometric Pressure Changes on Hearing. Trans. Amer. Acad. Ophthal. Otolaryng., 49: 75-81, 1944.

16. Lieberman, A. T., Aero-otitis Media in Pressure Chamber "Flights". Arch. Otolaryng., 43:500-507, 1946.

17. Melvin, W., cited by Hyde, R. W., (see ref. 14).

18. Merica, F. A., Vertigo Due to Obstruction of the Eustachian Tubes. J.A.M.A., 118:1282-1284, 1942.

19. Michel, E. L., Langevin, R. W., Gell, C. F., Effect of Continuous Human Exposure to Oxygen Tension of 418 mm Hg for 168 Hours. Aerospace Med., 31:138-144, 1960.

20. Morgan, T. E., Jr., Ulvedal, F., Welch, B. E., Observations in the SAM Two-Man Space Cabin Simulator. II. Biomedical Aspects. Aerospace Med., 32:591-602, 1961.

21. Ogden, F. W., A Study of the Effects of Vasoconstrictor Solutions on Altitude Chamber Aero-otitis Media. NAS-NRC-CAM-170, National Research Council, Committee on Aviation Medicine, Washington, D. C., 1943.

22. Ogden, F. W., Modified Politzerization in Treatment of Aero-otitis Media. Proj. No. 173, U. S. Air Force Sch. Aviation Med., Randolph Field, Texas, 1943.

23. Perlman, H. B., Quantitative Tubal Function. Arch. Otolaryng., 38:453-465, 1943.

24. Perlman, H. B., Mouth of Eustachian Tube: Action During Swallowing and Phonation. Arch. Otolaryng., 53:353-369, 1951.

25. Requarth, W. H., Aero-otitis Media in Compressed Air Workers: Treatment with Helium-Oxygen Mixtures. J.A.M.A., 116:1766-1769, 1941.

26. Rich, A. R., Physiological Study of Eustachian Tube and Its Related Muscles. Bull. Hopkins Hosp., 31:206-214, 1920.

27. Schechter, D. C., Aerotitis Media. Arch. Otolaryng., 66:117-126, 1957.

28. Schubert, H., Über die Widerstandsfähigkeit des Trommelfells gegen Überdruck der Aussenluft. (The Capacity of the Tympanic Membrane to Resist High Atmospheric Pressure.) Exerpta Medica, Section II, (Physiology, Biochemistry and Pharmacology), 3:945, 1950.

29. Seltzer, A. P., Newly Designed Paracentesis Needle for Use in Aerotitis Media. Arch. Otolaryng., 53:672-674, 1951.

30. Senturia, B. H., Gessert, C. F., Carr, C. D., Baumann, E. S., Aerotitis Media. Arch. Otolaryng., 74:141-149, 1961.

31. Shilling, C. W., Haines, H. L., Harris, J. D., Kelly, W. J., The Prevention and Treatment of Aerotitis Media. U. S. Naval Med. Bull., 46:1529-1558, 1946.

32. Simkins, C. S., Functional Anatomy of the Eustachian Tube. Arch. Otolaryng., 38:476-484, 1943.

33. Stewart, C. B., Warwick, O. H., Bateman, G. L., Acute Otitic Barotrauma Resulting from Low-Pressure Chamber Tests. J. Aviat. Med., 16:385-408, 1945.

34. Teed, R. W., Factors Producing Obstruction of the Auditory Tube in Submarine Personnel. U. S. Naval Med. Bull., 42:293-306, 1944.

35. Teed, R. W., A Contribution of War Experience to the Etiology of Otitis Media. Trans. Amer. Acad. Ophthal. Otolaryng., 53:254-260, 1949.

36. Trowbridge, B., A New Treatment of Acute Aero-otitis Media. Arch. Otolaryng., 50:255-263, 1949.

37. Vail, H. H., Traumatic Conditions of the Ear in Workers in an Atmosphere of Compressed Air. Arch. Otolaryng., 10:113-126, 1929.

38. Wiseheart, R. H., A New Method for Treatment of Acute Aero-otitis Media. Ann. Otol., 52:581-588, 1943.

39. Wright, R. W., Aero-otitis Media; A Further Report of Purulent Otitis Media Complicating Aero-otitis Media. Ann. Otol., 54:499-511, 1945.

CHAPTER 6

HEAT DISORDERS, INCLUDING DEHYDRATION

The heat disorders are clinical manifestations of disordered physiology resulting from the imposition of an excessive heat load on the body. The heat load may be either metabolic or environmental heat, or both.

The most likely cause of any heat disorder suffered in space is thought to be an inadequacy or failure of the temperature control system of a space suit during an extravehicular operation. However, even with the highly effective temperature control systems currently being developed for space suits, it is thought that there will still be a risk of a heat disorder occurring during future space missions [30].

This chapter very briefly discusses various aspects of the heat disorders considered pertinent to the space situation. Greater detail on these disorders can be obtained from the excellent reviews of Leithead and Lind [24], Minard and Copman [27], Webb [33] and other literature to be cited here.

Classification

The classification of the heat disorders presented by Leithead and Lind [24] is well oriented from a clinical standpoint. It outlines these disorders in terms of cause, and points out that signs and symptoms associated with the physiologic compensatory mechanisms are just as much heat disorders as are the clinical manifestations caused by the actual failure of thermoregulation. This classification follows:

1. The disorders which result from, and may complicate the processes of thermoregulation:
   a) Due to circulatory instability - heat syncope.
   b) Due to water and electrolyte imbalance - heat edema, water-depletion heat exhaustion, salt-depletion heat exhaustion, heat cramps.
   c) Due to skin changes - prickly heat, anhidrotic heat exhaustion.

2. The disorders which result from failure of thermoregulation: heatstroke, heat hyperpyrexia.

3. The disorders which are characterized by apathy

or fatigue, or deterioration in the performance of skilled tasks without any evidence of the entities listed above: acute heat fatigue.

It should be kept in mind that one or more of the above heat disorders can be suffered at the same or different times, during or after exposure to a heat load. Since many heat disorders share common clinical manifestations, an accurate diagnosis in the absence of certain laboratory measures might be difficult. Fortunately, however, most of them respond rapidly to the same treatment.

Clinical Manifestations

Heat Syncope (Heat Collapse, Heat Prostration, Heat Exhaustion).

Heat syncope characteristically follows sudden exposure to a severe heat load. Although some degree of water depletion may play a role in its genesis, this syndrome has been attributed primarily to heat-induced peripheral vasodilatation which leads to systemic arterial hypotension [33]. The associated deficiency of cerebral blood flow might be indicated at first by lightheadedness or dizziness. Acute fatigue, restlessness, nausea and blurring of vision might also precede syncope, and may be severe enough to render the afflicted individual incapable of undertaking a life-saving action. Rectal temperature is usually not significantly elevated, unless the individual who suffers heat syncope has been exercising.

Heat syncope is more apt to occur in individuals who are unused to heat or the combined stresses of heat and work [33]. It would probably not be expected to occur in physically fit astronauts, especially if they are repeatedly exposed to the range of thermal conditions expected in emergency situations in space [33].

In the weightless environment, syncope provoked by a sudden postural change should not occur. For this reason, syncope in this environment will probably be a manifestation of a more serious circulatory impairment than syncope while sitting or standing in the gravity environment. As was pointed out in Chapter 10, both simulation studies to determine how the body responds to weightlessness and experience to date in space indicate

that prolonged exposure to weightlessness will lead to a temporary, and possibly a permanent decrease of blood volume. This and other cardiovascular adaptations to weightlessness appear to enhance the tendency to orthostatic tolerance (Chapter 10). Hence one would expect that cardiovascular adaptations to weightlessness would increase an astronaut's susceptibility to the hypotensive effect of heat stress imposed either during operations in a gravity environment, such as while exploring a lunar or planetary surface, or when accelerative forces are applied in the head-to-foot direction during landing and take-off operations. The various methods under study for assuring normal orthostatic tolerance on return to a gravity environment are discussed in Chapter 10.

Heat Edema

This condition usually is a trivial consequence of a prolonged exposure to heat. Mild edema usually occurs in the feet. Since the gravitational component of intravascular hydrostatic pressure determines its production and distribution on Earth, heat edema may not occur in space. However, it is possible that mild venous occlusion produced by garment cuffs around extremities could predispose to heat edema, especially if an astronaut must endure a heat load for a prolonged period of time. This condition conceivably might develop after prolonged extravehicular activities in a gravity environment.

Water-Depletion Heat Exhaustion (Water-Deficiency Heat Exhaustion, Dehydration).

Water-depletion heat exhaustion, more commonly referred to as "dehydration", results from failure to replace body water, lost in this case by sweating, through the inability to find or ensure an adequate intake of fluids. A "space-oriented" review of pertinent literature in this area has recently been completed by Webb [33]. Other information can be obtained from the major references cited in this chapter.

Signs and symptoms of dehydration have been summarized in chart form, as shown in Figure 6.1. It is important to note that such clinical manifestations, especially fatigue, can appear quite suddenly and with such severity as to lead to a serious decrement in task performance. One must also keep in mind that,as military experience in hot climates has shown, small amounts of dehydration can easily become cumulative if continued day after day.

Of interest is the well known fact that men working in heat fail to drink back water as fast as it is lost. Attempts to do so often lead to feelings of nausea and abdominal distension [33]. This phenomenon, referred to by various authors as "mild dehydration", "voluntary dehydration", "voluntary under-drinking", and "involuntary hypohydration", can lead to water depletion which may amount to one to two percent of the initial body weight [7, 18, 22, 33]. Dehydration due to voluntary under-drinking does not usually produce clinical manifestations. However, a clinically overt disorder can result from a sudden further demand placed on the body's water stores.

A connection between orthostatic intolerance and mild dehydration has been established [1, 6]. As would be expected, a markedly exaggerated orthostatic response is produced by a combination of dehydration, mild elevation in body core temperature, and bed rest, the latter supposedly producing the circulatory effects which can occur in the weightless environment (Chapter 10). Again the potentially disastrous effects of allowing such a combination of stresses to act on an astronaut, especially in a gravity environment during a space mission, are readily apparent.

Salt-Depletion Heat Exhaustion

This condition is due to the inadequate replacement of sodium chloride lost usually in prolonged sweating. It may occur even if fluid replacement is adequate.

Salt-depletion heat exhaustion is characterized mainly by fatigue. However, other signs and symptoms which can appear are dizziness, anorexia, nausea, vomiting, headache, mental confusion, muscle cramps,

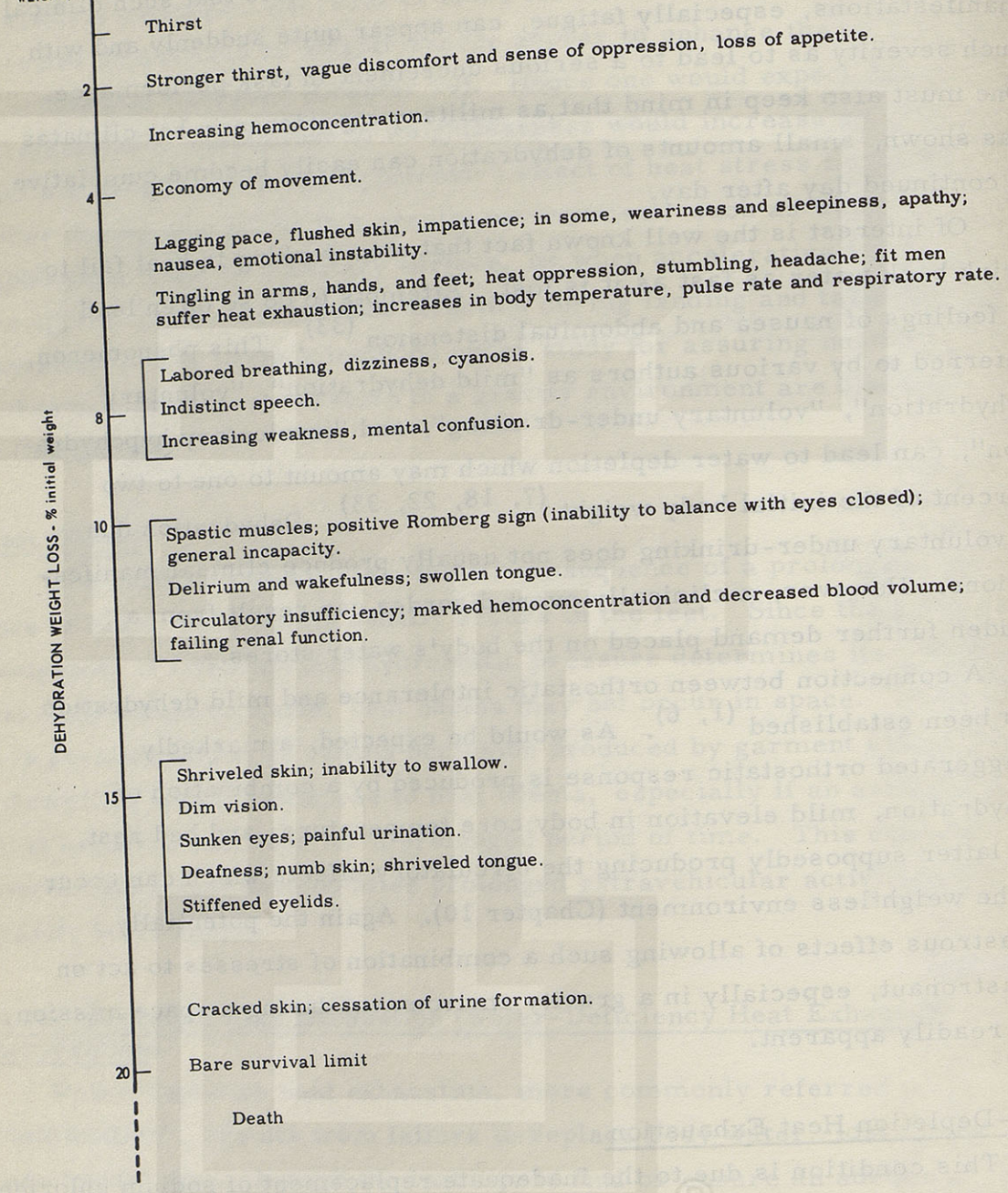

Figure 6.1 Dehydration.
(After Webb [33]).

constipation or diarrhea. Severe cases can progress into "shock", coma and death. The urine in all but the late stages of this syndrome is of reasonable volume, but contains negligible amounts of sodium chloride.

The plasma sodium concentration is decreased.

In contrast to water-depletion heat exhaustion, this syndrome characteristically tends to begin slowly, producing milder, more chronic symptoms [24]. Recognition of salt-depletion heat exhaustion is usually difficult, and hence its treatment tends to be delayed.

Water and salt-depletion heat exhaustion usually co-exist, the one or other possibly predominating, but both requiring treatment [24]. Moreover, by specifically treating the one disorder, it is possible to make the other manifest clinically. From the above considerations, an astronaut with a presumably adequate dietary sodium intake will more likely experience primarily water-depletion heat exhaustion.

Heat Cramps

Heat cramps are painful spasms of voluntary muscles. They are usually associated with hard physical work in a hot environment. The causative factor appears to be intracellular overhydration [24]. This can apparently result from either primary salt depletion or the replacement of sweat losses with unsalted water. The cramps may occur during or after exposure to a heavy work load. There are no prodromal symptoms. A typical cramp lasts about 30 seconds and then relaxes spontaneously. It is noted that the pain and muscular spasm of a heat cramp could conceivably be severe enough to incapacitate an astronaut temporarily.

Prickly Heat (Heat Rash, Miliaria)

This well known skin condition appears to result mainly from prolonged wetting of skin by sweat, as in a hot humid environment. It is apparently due to blockage of sweat gland ducts by keratin debris and edematous epithelium [24]. Associated symptoms can be annoying or be severe enough to disable the afflicted individual.

Prickly heat characteristically commences as many small discrete red papules on a mildly erythematous skin. These papules may develop into tiny vesicles which contain a clear or milky fluid, each surrounded by an erythematous area. In long-standing cases, the vesicles might become secondarily infected, forming pustules [19]. Hence, untreated

prickly heat can progress into an infected eczematous skin reaction.

Prickly heat is particularly prone to develop in skin creases where sweat collects and is poorly evaporated (e.g., axillae, front of elbows, groins, back of knees), or in areas where clothing exerts pressure, prevents adequate sweat evaporation, or chafes the skin (e.g., waist, sternum, back, shoulders, neck). It produces a sensation which is usually described as an intense prickling or tingling that comes on in waves and is triggered by an increase in sweating, by a sudden movement or by contact with clothing [24]. Severe itching and burning sensations are also common. It is readily apparent that this condition could seriously impair an astronaut's performance by producing sleep loss or severe distraction during critical work periods. The question as to whether prickly heat could lower the threshold for symptoms from radiation to skin in space (Chapter 11) remains to be answered.

The occurrence of prickly heat will be highly unlikely in a comfortable "shirt-sleeves" spacecraft cabin environment. On the other hand, it might conceivably result from prolonged operations in an inadequately ventilated, excessively warm space suit.

Anhidrotic Heat Exhaustion

Anhidrotic heat exhaustion affects individuals who are usually expose for several months to a hot climate [24]. Hence this syndrome would be most unlikely to occur in space.

This condition is characterized by the appearance of numerous discrete vesicles, mainly in the skin of the trunk and proximal parts of the limbs, and by diminished or absent sweating (anhidrosis) in the areas covered by this rash. In anhidrotic heat exhaustion, there is not only a decrease in sweat delivery to the skin surface due to sweat gland blockage, but also a depression of sweat production. Vesicles in this condition are more deeply situated than, and may even co-exist with the vesicles of prickly heat [24]. There are usually no signs of dehydration, in spite of the fact that polyuria for an unknown reason occasionally occurs [24]. The concentration of sodium chloride in the sweat is usuall

elevated.

The major symptom accompanying anhidrotic heat exhaustion is marked fatigue [24]. Palpitation and a sensation of oppression on exposure to heat are also experienced. Mild to moderate hyperthermia (100 to 102° F) has been observed. These symptoms usually subside rapidly on ceasing work and on exposure to a cool environment. Recovery of sweating is slow and heat tolerance may remain below normal for some time. As a rule, heatstroke does not follow, but must be distinguished from anhidrotic heat exhaustion.

Heatstroke (Heat Apoplexy, Hyperthermia, Heat Hyperpyrexia)

Heatstroke is characterized by a total absence of sweating, a self-perpetuating hyperthermia of usually 106° F or higher, and a severe disturbance of consciousness and brain function. Without treatment, this condition usually progresses on to death.

Very little is known about heatstroke, for as one of the most urgent of all medical emergencies, its immediate treatment has taken priority over its clinical investigation. Since it is associated with a high mortality, even when adequate cooling of an individual is carried out, this serious heat disorder cannot be induced for experimental purposes in man.

Heatstroke is not the usual response of man to extreme heat stress. The more common consequences which have been described above are, in contrast, characterized by continued sweating at reduced rates and a moderate or no elevation of body temperature. In a space flight context, there conceivably may be a situation where collapse results from combined heat stress and circulatory insufficiency without a remarkable rise in body temperature [33]. In this situation, the astronaut might be unable to take some life-saving action, so that if the heat stress continues, serious or fatal heatstroke might develop.

The pathogenesis of heatstroke is unknown. The question as to how much the decline in sweating is peripheral or central in origin remains to be answered [27]. Of note is the fact that the cessation of sweating and hence of the most important mechanism of body heat dissipation is permanent

unless heroic measures are undertaken to lower the body temperature.

A prodromal period of up to 5 days may precede heatstroke. Symptoms such as headache, dizziness, weakness, restlessness, syncope, nausea, vomiting, tachycardia, a feeling of oppressive heat, muscle cramps and dyspnea may occur [24, 33]. The prodrome appears to belong to a category in which heat exhaustion with moderate hyperthermia is the underlying disorder. If this prodrome is recognized and adequately treated, heatstroke is prevented. More often, however, an individual has the prodromal period measured in minutes, especially if exposed temporarily to a severe heat load. In fact he can be essentially asymptomatic up to the moment he loses consciousness. Cessation of sweating involving the entire body, including the face and axillae, may be often noted immediately prior to the onset of heatstroke. Other signs and symptoms in this critical period are a flushed dry skin, an increase in the rate and depth of breathing, a growing restlessness, an inability to fix attention on any task, and frequently pallor around the eyes and lips [33].

The skin of an individual suffering from heatstroke is characteristically hot, dry, and flushed. On occasion it becomes cyanotic. The body temperature tends to be highest in those cases with the shortest prodromal period, thus indicating the potential seriousness of this condition and the need for heroic emergency medical measures. If the prodrome is prolonged, the temperature is usually less than 106° F. Central nervous signs and symptoms vary from mild confusion to delerium, convulsions, and coma. A direct relationship between the nervous manifestations and the degree and duration of hyperthermia is apparently always evident. Breathing is rapid and deep. Signs of "shock", such as pallor, cyanosis, hypotension, "thready" pulse and oliguria, are not seen until heatstroke is far advanced. This type of circulatory failure is considered to be predominantly peripheral in origin by Minard and Copman [27] and cardiac in origin (forward heart failure) by Gold [16]. In spite of opposing views, however, treatment should probably be intensively directed at both causes of failure as "shock" usually heralds a rapid death. Except in those cases which

are preceded by severe heat exhaustion, hemoconcentration and changes in blood electrolytes are usually not seen in heatstroke. The state of acid-base balance during heatstroke remains to be determined. For a more detailed discussion of the clinical and pathologic findings in heatstroke, reference is made to the studies of Malamud and co-workers [26] and the review of Gottschalk and Thomas [17]. Reference is also made to the Army experiences with heatstroke in World War II, summarized by Schickele [31].

An over-all mortality figure in the range of 15 to 25 percent in heatstroke would seem to be a reasonable estimate from past data [2, 23], although Leithead and Lind [24] give a figure of 20 to 50 percent (average 35 percent). The majority of individuals who survive heatstroke usually recover [27]. Their body temperature usually remains unstable from 3 to 21 days, so that a strong predisposition for recurrence of heatstroke or other heat disorders exists during this time. A small percentage of individuals are chronically disabled to some degree by neurological lesions which most commonly involve the cerebellum (e.g., ataxia or motor incoordination, and dysarthria). Mental disturbances may range from those detected only by a special examination, to a complete change in personality or actual dementia [23].

Heat Hyperpyrexia

Heat hyperpyrexia is a term used in the classification of heat disorders by Leithead and Lind [24] to refer to a condition which differs from heatstroke in that the individual is still conscious and rational, and sweating is still present. The rectal temperature is usually above 105° F, but tends to be lower than in heatstroke. According to this definition, heat hyperpyrexia could conceivably represent either a form of heat exhaustion with hyperthermia, the prodrome of heatstroke, or a condition of hyperthermia following severe exercise. It is, therefore, a vague term which if not defined more specifically, might best be discarded.

Acute Heat Fatigue

A decrement in the performance of skilled mental and physical tasks

tends to occur in unusually hot environments. The reason for this has not been given. It is not associated with any of the clinical manifestations listed above. The degree of impairment is influenced by such factors as motivation, type of task, degree of acclimatization to heat and physical condition. Many different kinds of performance can be affected, including those which depend principally on perceptual activities, on thought processes of differing complexity, and on sensorimotor coordinations of response mechanisms [24]. This problem is not considered to require treatment other than a reduction of environmental temperature to a tolerable level. For further detail on this problem, reference is made to Leithead and Lind [24].

Diagnosis

For the most part, the diagnosis of most heat disorders in space will be obvious from the history and physical examination of an affected astronaut. Special laboratory procedures such as determinations of serum and urine sodium concentrations, even if possible in space, should not be required unless the signs and symptoms force consideration of a differential diagnosis. Information concerning past fluid intake and urine output might prove valuable, particularly in the diagnosis of a disorder which begins slowly. Rectal temperature readings would be preferable, but oral readings might suffice. For features diagnostic of the various heat disorders, reference is made to the preceding brief discussions of those disorders and to the references cited.

Prevention

The question arises as to whether or not an astronaut should be acclimatized to heat in anticipation of a possible exposure to an excessive heat load in space. Of great value in assessing the feasibility of this measure are the numerous writings cited in the following brief discussion of this area.

Acclimatization to heat is a qualitative and loosely used term referring to a complex physiologic response to an increased heat load. This response improves thermoregulatory processes, so that the potential harmful

effects of a heat load on the body are minimized and hence optimum body functioning is maintained. In spite of intensive investigation, the basic mechanism underlying acclimatization to heat has not been defined. Numerous studies have shown that with repeated exposures to an increased heat load, the thermal threshold for sweating and the concentration of salt in the sweat progressively decrease, and the maximum sweat rate progressively increases [1, 4, 5, 11, 13, 14, 20, 25, 29, 34]. Concomitantly, the elevation of skin and rectal temperatures and the pulse rate during an exposure, and the expenditure of energy for a given work load become progressively less. Other physiologic parameters measured during the acclimatization process have been discussed by Leithead and Lind [24], Bass [3], Robinson [28], and Fox and co-workers [12, 15]. The end result of acclimatization to heat is the loss of the characteristic subjective discomfort, lassitude, and impaired ability to work which affect the exposed, unacclimatized individual. As well, acclimatization markedly reduces the incidence of heat disorders.

Evidence is conclusive that this acclimatization process with its many physiologic variables behaves in many ways like a single physiologic response. Robinson and co-workers [29] clearly demonstrated the effectiveness of combining hard work with heat exposure to produce rapid acclimatization. The following characteristics of heat acclimatization, as presented by Bass [3], have been supported by many investigators [4, 5, 11, 25, 28, 29, 34].

> Heat acclimatization begins with the first exposure to heat, progresses rapidly and is usually well developed in 5 to 9 days.
>
> It can be induced by short, intermittent work periods in the heat lasting at least two hours daily. The general pattern of acclimatization is the same for short, severe exertion as for moderate work of longer duration. Inactivity in the heat usually produces only slight acclimatization.
>
> Subjects in good physical condition usually acclimatize more rapidly and are usually capable of doing more work in the heat. Good physical condition, however, does not

in itself confer acclimatization.

The ability to perform "maximal" work in the heat is attained quickly by progressively increasing the work load within the capacity of the individual.

Acclimatization to severe conditions will facilitate performance at lesser conditions and provide "partial" acclimatization to more severe conditions.

Inadequate water and salt replacement can retard the acclimatization process.

Acclimatization to heat is well retained during periods of no exposure for about 2 weeks. Thereafter, it is lost at a rate which varies among individuals. The major portion is lost within 1 to 2 months. Maintenance of optimum physical condition promotes the best retention of acclimatization.

Is it practical to attempt prophylactic acclimatization of an astronaut to heat in order that he might better handle an unanticipated high heat load in space? Since the major portion of this acclimatization appears to be lost within 1 to 2 months, it would seem impractical to carry out this measure prior to a mission of this duration. On the other hand, it is conceivable that acclimatization to heat, and so the optimum use of sweating as a thermoregulatory response, could be maintained in space by subjecting an astronaut to repeated high work (exercise) loads in a warm environment such as an inadequately cooled space suit. This view has been supported by the reports of Blockley [7], Roth [30] and Webb [33]. If such training were carried out, an astronaut would be prepared to take full advantage of a gas ventilating system during an extravehicular mission. Other advantages to acclimatization to heat would include a lessening of the susceptibility to circulatory insufficiency in situations involving some degree of heat load [33]. It is of interest to note that Fox and co-workers [14], have reported success in acclimatizing individuals to heat by artificially elevating the body temperature. The role of physical condition in determining both the ability of an unacclimatized astronaut to handle a high heat load and the duration of retention of acclimatization must also be considered.

The requirement for acclimatization to heat will be greatly influenced by future evaluations of the risks of inadequacy or failure of temperature control systems under various conditions which might result in the exposure of an astronaut to a high heat load. Therefore, it appears that the practicability of acclimatization to heat will depend on a continued evaluation of risk. This will in turn depend for the most part on the reliability data from the future development and testing of temperature control systems, and on the type and duration of the mission.

Other preventive measures are readily apparent, for all must be taken to prevent heat disorders, whether on Earth or in space. The main measures include an adequate salt and water intake, and adequately functioning spacecraft cabin and space suit temperature control systems. Ideally, serious dehydration should be prevented by taking small amounts of water during the time the water loss is high. Drinking large amounts of water may produce diuresis with a net loss of body water [21]. As well, gastric distress and even vomiting - a very serious hazard in the weightless environment (Chapter 8) - may be provoked. If heatstroke is suffered by an astronaut, he should not perform activity which could result in a heat load being forced upon him for at least 2 to 3 weeks.

Finally, it should be remembered that singly or combined, a loss of acclimatization, a decrement in physical condition, and a decrease in circulating blood volume on return to a gravity environment or due to voluntary under-drinking in space are factors which could seriously increase the susceptibility of an astronaut to heat stress and should, therefore, always be brought into consideration when the setting of normal and emergency tolerance limits to heat loads in space.

Treatment

The treatment of heat disorders has been discussed in detail by Leithead and Lind [24], Minard and Copman [27], and others [8, 9, 32, 33]. With the exception of heatstroke, all heat disorders which could occur in space should be cured rapidly and completely if adequately treated.

Based on well established principles, treatment will usually include a period of rest in a cool environment and the replacement of depleted body salt and water. Rarely might it be necessary to use special measures to lower the body temperature or to treat "shock".

Heat syncope on Earth usually responds rapidly on exposing the afflicted individual to a cool environment. However, if heat syncope occurs in space it should be assumed that since there is no postural hypotensive effect in the weightless environment, the syncope has been contributed to by a decrease in blood volume due to one or more related or unrelated causes, such as voluntary under-drinking, excessive sweating, inactivity or weightlessness *per se*. This might mean that syncope in an astronaut exposed to a heat load should be considered a possibly serious "shock" state which should be treated intensively with intravenous fluids, a vasopressor and oxygen if the astronaut does not respond rapidly to a cool environment.

Water and salt-depletion heat exhaustion and heat cramps should all be treated in the same manner. As previously pointed out, both water and salt-depletion will probably co-exist, so that the specific treatment of the one disorder could make the other disorder manifest clinically. Therefore, assuming that the kidneys can selectively handle either excess water or sodium chloride, salted water should be administered for both water and salt-depletion heat exhaustion. Usually 0.1 to 0.2 percent salt in water given orally suffices. However, if an astronaut is vomiting or seriously depleted, isotonic saline should be given intravenously. Salt tablets of any form are not indicated, for they dissolve too slowly and are very prone to cause gastrointestinal upset. An afflicted astronaut should rest in a comfortable cool environment. Rarely, special cooling measures discussed below might be required.

Both prickly heat and anhidrotic heat exhaustion respond well to continuous exposure to a dry, cool environment. Dry non-irritant clothing must be worn. Washing with an antiseptic soap, such as hexachlorophene,

will help to prevent or control secondary skin infection. If well established, a skin infection might require treatment with a suitable local or systemic broad spectrum antibiotic.

Heatstroke is a medical emergency requiring immediate "heroic" treatment. The body core temperature of an afflicted astronaut must be decreased as quickly as possible to 102° F. An acute lowering of body temperature below 102° F can apparently lead to a cardiac arrhythmias, and should, therefore, be avoided [32]. The practicability of various body temperature-lowering methods for use in space should be investigated. Evaporative cooling, accomplished by passing dry air over moist clothing might be possible in the space cabin. More practical, however, might be the use of a space suit liquid cooling garment. In this case, the vasoconstrictive effect of cold, especially on skin vessels, will be an important factor in considering an optimum coolant temperature. It is also noted that the effect of surface cooling is usually markedly enhanced by vigorous skin massage. The administration of cold fluids orally should also be considered for cases which are able to ingest these fluids. At the present time, chlorpromazine is being administered intravenously to patients being cooled for heatstroke, apparently for its role in depressing the hypothalamic center for heat conservation, in promoting peripheral vasodilatation, in abolishing shivering due to cold, and in preventing convulsions, restlessness and other hyperirritable states [24].

For reasons already discussed, an astronaut suffering from heatstroke and associated "shock" should receive oxygen and a vasopressor drug, such as metaraminol, even though such a drug might reduce heat dissipation by producing peripheral vasoconstriction. From the work of Gold [16], administration of a rapid-acting cardiac glycoside intravenously may be valuable in hyperpyrexia or early heatstroke, even in the absence of frank "shock". Such a measure must be undertaken with extreme caution because of the possible presence of marked electrolyte abnormalities which are conducive to digitalis intoxication. Intravenous fluids should be administered with care to avoid precipitation

of acute pulmonary edema, but can be given more intensively if serious salt or water depletion has been evident prior to onset of the heatstroke. The fluid of choice is normal saline. An osmotic diuretic, such as mannitol, might be added to this regimen if the danger of renal damage from "shock" exists. Sedatives or narcotics should not be given in heatstroke. If the astronaut is comatose, attention must be given to maintaining a clear airway, and urethral catherization.

An astronaut with hyperpyrexia unassociated with other signs or symptoms should rest in a cool environment and be watched carefully. His fluid intake should be kept at an optimum level. A special cooling measure might be indicated if his body core temperature remains elevated or if signs and symptoms of other heat disorders appear.

1. Adolp
2. Austi
3. Bass
4. Bass
5. Bean
6. Beeth
7. Block
8. Busk
9. Darli
10. DiGio
11. Edhol
12. Fox,

REFERENCES

1. Adolph, E. F., cited by Webb, P., (see ref. 33).

2. Austin, M. G., Berry, J. W., Observations on One Hundred Cases of Heatstroke. J.A.M.A., 161:1525-1529, 1956.

3. Bass, D. E., Thermoregulatory and Circulatory Adjustments During Acclimatization to Heat in Man, in Temperature: Its Measurement and Control in Science and Industry, Vol. 3, Pt. 3, Biology and Medicine, J. D. Hardy, (ed.). New York, Reinhold Pub. Corp., 1963, pp. 299-305.

4. Bass, D. E., Kleeman, C. R., Quinn, M., et al, Mechanisms of Acclimatization to Heat in Man, Medicine, 34:323-380, 1955.

5. Bean, W. B., Eichna, L. W., Performance in Relation to Environmental Temperature. Fed. Proc., 2:144-158, 1943.

6. Beetham, W. P. Jr., Buskirk, E. R., Effects of Dehydration, Physical Conditioning and Heat Acclimatization on the Response to Passive Tilting. J. Appl. Physiol., 13:465-468, 1958.

7. Blockley, W. V., Human Sweat Response to Activity and Environment in the Compensable Zone of Thermal Stress: A Systemic Study. NASA-CR-65260, National Aeronautics and Space Administration, Washington, D. C., 1965.

8. Buskirk, E. R., Bass, D. E., Climate and Exercise. QREC-EP-61, Quartermaster Research and Engineering Command, Natick, Massachusetts, 1957.

9. Darling, R. C., Heat Exhaustion, Heatstroke and Heat Cramps, in A Textbook of Medicine, R. L. Cecil, R. F. Loeb, (eds.). Philadelphia, W. B. Saunders Co., 1955, 9th Ed., pp. 517-519.

10. DiGiovanni, C., Jr., Birkhead, N. C., Effect of Minimal Dehydration on Orthostatic Tolerance Following Short-term Bed Rest. Aerospace Med., 35:225-228, 1964.

11. Edholm, O. G., Fox, R. H., Adam, J. M., Goldsmith, R., Comparison of Artificial and Natural Acclimatization. Fed. Proc., 22:709-715, 1963.

12. Fox, R. H., Heat, in The Physiology of Human Survival, O. G. Edholm, A. L. Bacharach, (eds.). New York, Academic Press, 1965, pp. 53-79.

13. Fox, R. H., Goldsmith, R., Hampton, I. F. G., Lewis, H. E., The Nature of the Increase in Sweating Capacity Produced by Heat Acclimatization. J. Physiol., 171:368-376, 1964.

14. Fox, R. H., Goldsmith, R., Kidd, D. J., Lewis, H. E., Acclimatization to Heat in Man by Controlled Elevation of Body Temperature. J. Physiol., 166:530-547, 1963.

15. Fox, R. H., Goldsmith, R., Kidd, D. J., Lewis, H. E., Blood Flow and Other Thermoregulatory Changes with Acclimatization to Heat. J. Physiol., 166:548-562, 1963.

16. Gold, J., Development of Heat Pyrexia. J.A.M.A., 173:1175-1182, 1960.

17. Gottschalk, P. G., Thomas, J. E., Heat Stroke. Proc. Mayo Clin., 41:470-482, 1966.

18. Greenleaf, J. E., Involuntary Hypohydration in Man and Animals: A Review. NASA-SP-110, National Aeronautics and Space Administration, Washington, D. C., 1966.

19. Hall, A. L., Martin, R. J., Prolonged Exposure in the Navy Full Pressure Suit at Space Equivalent Altitude. Aerospace Med., 31:116-122, 1960.

20. Horvath, S. M. Shelley, W. B., Acclimatization to Extreme Heat and Its Effect on the Ability to Work in Less Severe Environments. Amer. J. Physiol., 146:336-343, 1946.

21. Kenney, R. A., The Effect of the Drinking Pattern on Water Economy in Hot Humid Environments. Brit. J. Industr. Med., 11:38-39, 1954.

22. Ladell, W. S. S., Water and Salt (Sodium Chloride) Intakes, in The Physiology of Human Survival, O. G. Edholm, A. L. Bacharach, (eds.). New York, Academic Press, 1965, pp. 235-299.

23. Lambert, A., Sunstroke as It Occurred in New York City During 1896. Medical News, 71:97, 1897.

24. Leithead, C. S., Lind, A. R., Heat Stress and Heat Disorders. Philadelphia, F. A. Davis Co., 1964.

25. Lind, A. R., Bass, D. E., Optimal Exposure Time for Development of Acclimatization to Heat. Fed. Proc., 22:704-708, 1963.

26. Malamud, N., Haymaker, W., Custer, R. P., Heat Stroke: A Clinico-Pathologic Study of 125 Fatal Cases. Milit. Surg.,

99:397-449, 1946.

27. Minard, D., Copman, L., Elevation of Body Temperature in Disease, in Temperature: Its Measurement and Control in Science and Industry, Vol. III, Pt. 3, Biology and Medicine, J. D. Hardy, (ed.). New York, Reinhold Pub. Corp., 1963, pp. 253-273.

28. Robinson, S., Circulatory Adjustments of Men in Hot Environments, in Temperature: Its Measurement and Control in Science and Industry, Vol. III, Pt. 3, Biology and Medicine, J. D. Hardy, (ed.). New York, Reinhold Pub. Corp., 1963, pp. 253-273.

29. Robinson, S., Turrell, E. S., Belding, H. S., Horvath, S. M., Rapid Acclimatization to Work in Hot Climates. Amer. J. Physiol., 140:168-176, 1943-44.

30. Roth, E. M., Bioenergetics of Space Suits for Lunar Exploration. NASA-SP-84, National Aeronautics and Space Administration, Washington, D. C., 1966.

31. Schickele, E., Environment and Fatal Heat Stroke. An Analysis of 157 Cases Occurring in the Army in the U. S. During World War II. Milit. Surg., 100:235-256, 1947.

32. Talbott, J. H., Disorders Due to High Environmental Temperature, in Principles of Internal Medicine, T. R. Harrison, (ed.). New York, McGraw-Hill Book Co., Inc., 1962, 4th Ed., pp. 833-835.

33. Webb, P., Human Water Exchange in Space Suits and Capsules. National Aeronautics and Space Administration, Washington, D. C., in press, 1967.

34. Wilkinson, R. T., Fox, R. H., Goldsmith, R., et al, Psychological and Physiological Responses to Raised Body Temperature. J. Appl. Physiol., 19:287-291, 1964.

CHAPTER 7

COLD INJURY AND HYPOTHERMIA

Recent discussions of space suit and spacecraft cabin thermal control have indicated that an astronaut's risk of exposure to an excessive heat loss will be much less than his risk of exposure to an excessive heat load (Chapter 6) during space operations [30, 44, 77]. It is even conceivable that potential medical problems from heat loss will be virtually eliminated in future space systems. For the present, however, these problems should be considered possible, especially if an extravehicular astronaut is rendered immobile for a period of time in a shaded space environment. In this situation, local or total body conductive heat loss might be increased by an abnormal amount of moisture in his space suit, by an increased thermal conductivity of his suit insulation due to compression against an external object and by wide-spread contact between his suit and a cold lunar, planetary or spacecraft surface. It is also remotely possible that continued operation of an astronaut's suit thermal control system during such an exposure could be a factor contributing to a medical heat loss problem.

It has been speculated that either artificially-induced hypothermia or more preferrably an induction into a state resembling hibernation might provide a means of protecting astronauts from various hazards during long space missions [17, 57]. However, the practicability of such a measure remains to be proven.

In this chapter, the pathophysiology, clinical manifestations, diagnosis, prevention, and treatment of cold injury, resulting from excessive local body heat loss, and hypothermia, resulting from excessive accidental total body heat loss, will be discussed briefly. For greater detail than that to be presented here, one can consult the many excellent reviews cited.

Cold Injury

Pathophysiology

Cold injury is tissue damage which can result from either the non-freezing or freezing of tissues. Since the extent and severity of the damage depend

upon a great number of factors, a critical exposure temperature for cold injury in humans cannot be clearly defined. The major factors which could contribute to this injury in the space situation are the exposure temperature, the duration of exposure and the amount of conductive heat loss contributed by moisture in the space suit or other failures of thermal protection by the suit. Other important factors will be discussed below. To give some idea as to what exposures could cause cold injury, it is noted that past experience, particularly in military operations, has shown that the feet are usually injured following their exposure in excess of 12 hours in water at temperatures below 50°F (immersion foot) or in excess of 24 hours in moisture near freezing (trench foot) [6, 26, 62]. Thus cold injury could occur below 10°C (50°F) if the duration of the exposure is sufficiently prolonged [61].

It is important to note that various tissues do not show the same degree of susceptibility to cold injury. Blood vessels, nerves and striated muscles are highly sensitive to cold [6]. Skin, fascia, connective tissue, bone and tendon are quite resistant [6]. Damage to deep structures, such as nerve and muscle, can therefore occur without the overlying skin being significantly damaged by cold.

The pathophysiology of cold injury remains uncertain [48, 65, 67]. One reason for this has been the paucity of tissue from humans available for study during the acute phases of this injury [66]. Most authorities believe that cold injury can be secondary to vascular changes in the tissue during cold exposure and rewarming, due to direct injury of the tissue by cold, or from some combination of these mechanisms [6, 8, 16, 26, 51, 52, 62, 63, 67, 89, 92]. Because the management of cold injury is directed at these possible mechanisms, they are discussed below in some detail. Although not definitely stated, these considerations apply in particular to cold injury of the limbs. For readily apparent reasons, the damage develops at first distally, then progresses proximally in the limb.

Cold-induced constriction of arterioles and small arteries can conceivably produce local hypoxic tissue damage. Further lowering of the local tissue temperature secondary to vasoconstriction sets up a vicious cycle which leads to further local hypoxia. The vasoconstriction can be not only due to

a normal local response to cold, but also to the centrally-induced, generalized peripheral vasoconstriction which occurs if the total body heat loss is sufficient to force the body to preserve its core temperature [42, 46]. Of great interest are the observations that vasoconstriction might not occur if the body does not have to conserve heat, and that constricted vessels in cold extremities can be reopened if the total body heat is maintained at a level bordering on positive heat balance [4, 75, 81, 84]. These findings point to the importance of maintaining adequate total body heat during exposure to both local and generalized heat loss.

Apparently to protect the vasoconstricted extremity from cold injury, the so-called hunting or Lewis phenomenon occurs [58]. This rather complex response to cold is a periodic vasodilatation which allows periodic surges of warm arterial blood to pass through the cooling tissues [16, 58]. It is usually triggered at tissue temperatures below 10°C (50°F) [40, 45]. The hunting phenomenon may do little to provide adequate heat and oxygen replacement to cooled peripheral tissues in man, however, for apparently the capillary flow in these tissues increases only slightly while most of the blood passes through arteriovenous anastomoses [39, 45]. Moreover, it has also been shown that this phenomenon can be prevented or reduced in magnitude by an excessive total body heat loss [12, 28], or by emotional states such as anxiety [2, 12]. Even in subjects who are generally warm, the transient vasoconstriction caused by deep respiration or startle is considerably prolonged when the hand or finger is exposed to cold [7]. Therefore the hunting phenomenon might at best be a poor and unpredictable protective mechanism. However, this discussion of the body's attempt to protect itself from cold injury does suggest that specific measures which increase both peripheral blood flow and tissue perfusion might offer some protection from cold injury.

The major vascular mechanism of cold injury appears to be the irreversible vascular occlusion and subsequent tissue hypoxia which follow the rewarming of frozen tissues or tissues exposed to non-freezing cold for long periods of time [6, 26, 51, 52, 53, 68]. From observations made in extensive animal experimentation, Kulka [51, 52, 53] described the sequence of cold-induced vascular changes as: arterial and arteriolar con-

striction, excessive venular-capillary dilatation, increased endothelial leakage, erythrostasis, arteriovenous shunting, segmental vascular necrosis and massive thrombosis. He noted that neural, humoral or hemic factors may all contribute to the production of the three basic functional defects of vasoconstriction, venular dilatation and endothelial leakage [51]. Mundth [67, 68] has also presented evidence which indicates that the primary pathologic process in response to freezing injury appears to be an alteration in the intravascular cellular stability with the formation of platelet and erythrocyte aggregates. It has also been noted that the tissue damage can be enhanced further by vasoconstriction proximal to the injured area, mechanical irritation and bacterial infection [26, 52]. As will be discussed, various measures which are directed at improving local tissue perfusion, and inhibiting intravascular cellular aggregation and clotting have had a beneficial effect on tissue survival and function following cold injury.

Although freezing can cause tissue damage by mechanically disrupting cellular structure, especially in highly specialized tissues, it is a well known fact that certain tissues can survive unquestionable freezing [52, 63]. On the other hand, death of other tissues has occurred in spite of there being no histological evidence of disruption [62]. The reason for this has been postulated in reviews by Meryman [61, 62, 63]. He stated that during freezing, intracellular dehydration occurs. This dehydration results from extracellular ice crystal formation. The remaining, unfrozen extracellular fluid is rendered hyperosmotic with respect to the intracellular fluid, so that water is drawn osmotically from the cells. The high concentrations of electrolytes and other cell constituents then causes cumulative injury to the cell through biochemical means, such as denaturation from electrolyte concentration and unnatural chemical bonding [63]. Meryman also noted that rapid freezing is tolerated better than slow freezing [61, 62]. However, he quoted reports indicating that the successful survival of rapidly frozen tissues depends primarily on rates of freezing and subsequent rewarming which cannot be attained in the clinical situation.

It is possible that a prolonged exposure of certain tissues to low non-freezing temperatures could cause an irreversible imbalance in the function

of metabolic enzyme systems [48, 77]. However, this view is not definitely stated by other authors [6, 26, 89].

Outside of the conclusion that cold or frozen tissue should be rewarmed as quickly as possible, no specific beneficial measures appear to be indicated by the above considerations of the mechanisms of direct injury by cold. Therefore the prognosis apparently cannot be improved if the damage has been caused by the direct effect of cold. Notably, this contrasts to the significant improvement derived from measures which are directed at the vascular mechanisms of cold injury.

Clinical Manifestations

Cold injury usually occurs quite insidiously, so that warning symptoms are often insufficient to prevent tissue damage. The only warning symptoms may be paresthesias followed by anesthesia of the exposed part. In cases of hand exposure, manual dexterity will, of course, be impaired. The skin is usually erythematous at first, but then becomes pale or waxy-white in appearance. Frozen tissue is described as "dead white". It is hard and may even be brittle. It is completely lacking in sensation and movement.

In the past, cold injury has been classified clinically under one of four categories — chilblains, immersion foot, trench foot, and frostbite. Although this more operational classification could apply to cold injuries in space, it is generally believed that such injuries are best classified simply as two types — freezing or non-freezing. Even this classification could be considered inappropriate, for a local cold exposure in space would undoubtedly produce a graded injury, characterized by a possible freezing injury of the most exposed part and lesser degrees of non-freezing injury progressing centrally from this part. Fortunately, however, tissue damage and its management are very similar for both freezing and non-freezing injury, the only variable being severity of the damage.

Most authors describe cold injuries as falling into one of four degrees of severity. Since it takes several days for the degree of freezing and non-freezing tissue damage to become fully manifest, this classification is of little value from therapeutic and prognostic standpoints in the immediate

period after a cold exposure [6, 26, 48, 65]. Mills has pointed out that a cold injury in its early stages may be classified often as no more than superficial or deep [64]. However, the broader classification summarized below from many authors [6, 11, 20, 26, 48, 70, 74, 92], is useful for a detailed description of the clinical manifestations and the course of cold injury as related to its severity.

First Degree - hyperemia and edema. During rewarming, the skin initially becomes mottled and cyanotic, then red, hot, and dry. This hyperemia blanches poorly on pressure, with capillary refilling being very sluggish or absent. At first there is frequently an intense burning or itching sensation; later there is a deep-seated ache. In milder cases, these symptoms may cause intense discomfort for several hours, and then gradually disappear without serious sequelae. In more severe cases, they are not only more severe and prolonged, lasting for periods up to several days, but deep aching pain, paresthesias, cyanosis, hyperhidrosis and coldness of the injured part may appear 2 to 3 weeks after injury and persist for many months. Edema usually begins within 3 hours after rewarming and usually disappears within 10 days if the patient is at rest. Desquamation of the superficial layers of the skin begins 5 to 10 days and may continue for several weeks.

Second Degree - vesicle formation. The signs and symptoms of first degree cold injury are also present. However, the edema is usually not marked and disappears within 3 to 5 days after rewarming. Light touch and position sense are usually absent. A throbbing or aching pain is usually experienced from 3 to 20 days after injury. Blisters and, in more severe cases, huge blebs may appear within 6 to 12 hours after rewarming. These vesicles, which usually form on the dorsum of the fingers, hand and great toes, and on the heel, are often deep in the epidermis. However, they do remain superficial to the germinative layer, so that the epidermis is regenerated. The vesicles may contain blood as well as fluid transudate. They dry, forming black eschars within 10 to 24 days after rewarming. Hyperhidrosis may occur as well at this time. The eschar gradually separates, leaving a thin, soft, poorly keratinized skin which is easily traumatized.

Third Degree - necrosis of the skin and subcutaneous tissue. This cold injury involves the full thickness of the skin and often extends into the subcutaneous tissue. Vesicles may appear at the periphery of the area of third degree injury. Edema of the involved part is extensive,

usually disappearing with 6 days. This injury is associated with burning, aching, throbbing or shooting pains which begin in the second week and persist for about 5 weeks. The skin over the area of a third degree injury usually dries to a black, hard eschar, which eventually separates from poorly vascularized underlying granulation tissue. Epithelialization of this area is gradual, healing often taking 2 to 3 months. Hyperhidrosis and cyanosis of the involved part may appear between the fourth and tenth week after injury and persist for months, resulting in a prolonged uncomfortable convalescence. It should be noted that trauma due either to injury other than cold or to superimposed infection may complicate this degree of cold injury and result in a more extensive tissue loss.

Fourth Degree - destruction of the entire injured part, including bone, with resulting loss of the part. Upon rewarming, the skin becomes mottled and cyanotic. Edema begins rapidly, starting within an hour and reaching a maximum within 6 to 12 hours. Bleb formation is common. In most fourth degree cold injuries, the extent of injury becomes apparent only as the edema resolves, the eschar formation or gangrene frequently not being evident until 2 to 3 weeks after injury. In severe injuries, the affected tissue will progress rapidly to dry gangrene and mummification. Demarkation between living and dead tissue becomes fully apparent in about one month, and extends down to bone in 2 months or more after injury.

Finally it should be noted that following any degree of cold injury, an astronaut could become sensitized to some degree to a further cold (65, 66). With a mild injury, the involved part might be sensitized to cold for days or weeks and with a severe injury, this sensitization might be permanent (26). For such cases, even a minor exposure to cold may be followed by an exaggerated and prolonged reactive vasodilatation with associated redness, edema and tingling pain. Edema of a urticarial type and even systemic reactions are also possible (91).

Diagnosis

The diagnosis of cold injury in space should be obvious on clinical observation, with no special diagnostic procedures being required. It is again pointed out that cold injury often requires several days to become fully manifest, so that an early prediction of the extent and severity of a cold

injury will be impossible.

Prevention

Emphasis is placed on the importance of recognizing and adequately correcting for certain physiological and space suit and spacecraft cabin design factors which will undoubtedly influence the risk of exposure of the astronaut to an excessive heat loss and subsequent cold injury during space missions. As mentioned previously, these factors would apply particularly to operations in the space suit in a shaded space environment.

The distal parts of an astronaut's extremities, especially the fingers, will be highly susceptible to cold injury, due not only to their large surface area per volume of tissue and their usual marked vasoconstrictive response to cold, but also the fact that, for mobility, only minimal suit insulative material will surround these parts. Moisture in the suit and direct contact of the surface of the suit with other materials in a shaded space environment could lead to an excessive conductive heat loss, particularly from a minimally insulated distal extremity. When designing and fitting space suits, consideration must be given to avoiding constrictions and tightness which in any way might jeopardize the blood flow to an extremity, and thus increase the susceptibility of the extremity to cold injury. The "coolant" of suit liquid cooling systems could pass through hand and foot areas last, so providing a "fail safe" effect.

As mentioned previously, the maintenance of adequate total body heat during a localized or extensive heat loss from the space suit might serve to protect an astronaut from cold injury by preventing the localized vasoconstriction or the centrally-induced, generalized peripheral vasoconstriction in response to cold. Thus if an astronaut is subjected to an excessive heat loss through one or more areas of his suit, he might attain some protection from cold injury by having the amount of heat removed from his suit by the life support system reduced, even to the point of allowing him to go into slightly positive heat balance. Increased body heat production through physical activity would play a similar role. However, it must be remembered that anxiety and other possible factors (e.g., hypocapnia) might tend to prevent this protective effect [75].

The importance of continuous physical activity for providing sufficient metabolic heat to maintain thermal balance in the space suit under all circumstances is readily apparent. The suggestion that ingestion of food of a high specific dynamic action prior to a possible exposure to an excessive heat loss might have some protective value, by reason of its tendency to increase the basal heat production of the body, has not been supported in recent experiments [49, 75].

It has been suggested that agents which prevent or abolish a cold-induced vasoconstriction might be useful in protecting an exposed part from cold injury [75]. However, no topical vasodilators appear to exist which can be used to give a graded response, or which will not be absorbed and hence result in a whole-body effect. Systemic administration of such agents will probably always be contraindicated unless their action is highly specific and the cold exposure anticipated will be of a short duration.

The marked influence of systemic hypoxia on the extent and severity of tissue damage by cold is well known [20, 55]. In space, this hypoxia would be most likely caused by a reduction of the ambient oxygen tension. On the other hand, an elevated partial pressure of oxygen tends to produce a peripheral vasoconstriction which can contribute to cold injury [29]. It is apparent, therefore, that the vascular effects of oxygen at the partial pressures to be used in the space suit should be investigated.

The view is generally held that prolonged exposure to weightlessness will produce both a decrease in the total blood volume and a decrease in capacity of the vessels in the lower extremities to maintain their tone when an astronaut stands upright in a gravity environment. If these effects are not prevented or corrected before an astronaut walks on a lunar or planetary surface, a potential or manifest state of orthostatic hypotension might result, depending on the ability of his body to compensate for his inadequate circulating blood volume. This compensation would occur mainly by peripheral vasoconstriction, which could lead to the astronaut being more susceptible to cold injury of the feet. It also considered possible that this susceptibility might be enhanced by the use of elastic garments to prevent orthostasis.

All environmental conditions being equal, the Negro appears to be about six times more vulnerable to cold injury than the Caucasian [26]. It appears

that a physiologic basis does exist for this difference [60, 76]. As well, the geographic origin of man seems to be a significant factor among Caucasian personnel in the incidence of cold injury, for origin from the warmer climates of the United States has been shown to predispose to cold injury [16, 66, 70]. However, whether these factors would be significant enough to influence selection of astronauts is debatable. Finally, it will be necessary to rule out the presence of cold agglutinins in astronaut candidates.

It is pointed out again that following any degree of cold injury, an astronaut could become sensitized to some degree to cold. With milder injuries, the involved part might be sensitized to cold for days or weeks, and with more severe injuries, this sensitization might be permanent.

As will be discussed under "hypothermia", the possible protective effect of cold acclimatization, even if it exists, remains debatable.

Treatment

The treatment of cold injury remains controversial, due mainly to the lack of knowledge of the mechanisms of cold injury [6, 55, 65, 70]. Since more definitive forms of therapy will not be accomplished in the space environment, the more conservative methods for the treatment of cold injuries in space will have to suffice. It is noted that all cold injuries receive basically the same treatment from the beginning, modifications being carried out as indicated by the degree of injury.

Initially, the injured part should be completely uncovered and all items of clothing or equipment which might in any way restrict blood flow to the part removed. Rewarming of the cold-injured part to body temperature should be accomplished as quickly as possible by exposing the part to temperatures recommended above 32°C (89.6°F) but not above 42°C (107.6°F) by most authors [6, 16, 33, 34, 55, 65, 72]. Methods which maximize heat transfer by conduction are preferred. Even though a water bath will not be practical in space, surrounding the injured part with flexible plastic containers, such as a balloon splint, containing warm fluid might be a useful substitute. Moist warm towels might also be used. It is pointed out that good conductive heat transfer can be obtained by placing the injury in contact with warm areas, such as the axilla, perineal area, and trunk, of either an

injured or uninjured astronaut's body. As will be discussed, rewarming of an astronaut suffering from generalized hypothermia should be done gradually, so that the above methods of rewarming will apply only to cold injured areas. Massage of the rewarming part is contraindicated because of the possibility of causing further trauma to the injured tissue [34, 65, 70, 89]. The use of ultrasound to rewarm cold-injured tissues is not recommended, as there is evidence of it having deleterious effects in deep tissue injuries [65].

The major aims of treatment after rewarming should be the prevention of further trauma to and possible infection of damaged tissues, and the maintenance of an optimum range of movement in the damaged part [19, 55]. It is again emphasized that the degree and extent of cold injury may become fully evident only after several days. Hence a more serious injury than that observed initially should always be anticipated.

The damaged part should be gently washed with a mild, antiseptic soap (e.g., hexachlorophene soap) [65]. Whereas lesions without vesicles are usually left exposed under sterile conditions on Earth, all cold injuries in space should be dressed in order to provide optimum protection from further trauma and infectious organisms. Dressings should be loose and dry, and cotton pledgets should be placed between digits to avoid maceration [50, 65]. Debridement of vesicles should not be undertaken initia unless they are disrupted [6, 26, 33, 54, 89]. Petrolatum dressings as indicated in burn therapy should never be applied [6, 65, 92].

Antibiotics are usually given to cases of cold injury only if there is obvious deep infection [55, 65, 70]. However, in the space situation, consideration might be given to prophylactic antibiotic administration, especially to possible third and fourth degree cold injuries, in order to maximize the protection of the damaged tissue from invasion by pathogenic organisms. Such therapy should be continued until a clean demarkation is evident.

Dressings should be changed daily. At this time, wet dead tissue from ruptured vesicles might be removed, infected vesicles opened and, if indicated, constricting eschars bivalved [6, 33]. Optimum cleanliness must be maintained. If in any way contaminated, the injured area should be gently washed with antiseptic soap and dried. As soon as the acute in-

flammation has subsided, active physiotherapy should be commenced [6, 55, 92]. The performance of digital exercises of each joint of every involved digit throughout the waking hours and Buerger's exercises at least four times daily have been recommended [65]. It should be kept in mind that all parts of an injured extremity should be exercised.

All eschars should be allowed to separate rather than being removed surgically [55]. In fourth degree injuries, so-called physiological amputation will occur, usually in 2 months or more after injury. If adequate care is taken to keep the injured part dry and free from infection, the possibility of wet gangrene and the requirement for surgical amputation will be remote. Circumferential eschars, which tend to constrict and so restrict blood supply, should be bivalved if possible [6, 33, 55].

Although pain is usually not a serious problem in cold injury, a non-narcotic analgesic or tranquilizing drug might be indicated in the period after thawing [6, 48, 65]. A tetanus toxoid booster prior to missions in space should eliminate the need for such an injection following cold injury. A cold-injured astronaut should receive a vitamin supplemented diet which is high in calories and protein content.

Various measures directed at improving local tissue perfusion and inhibiting intravascular cellular aggragation and clotting have been studied for their possible beneficial effect on tissue survival and function following cold injury. Meryman pointed out that it would not be fair to presume that none of these measures have been clinically successful, since the evaluation of therapeutic procedures in clinical frostbite is hampered by the lack of criteria for determining the severity of injury prior to the initiation of therapy. However, the vasodilator drugs have generally not been proven effective either experimentally or clinically [6, 26]. This might in part be due either to a negation of the possible increase in blood flow through the dilated vessels at the site of injury by the systemic hypotension associated with use of these drugs, or to delays in attempting to forestall circulatory obstruction immediately after thawing before such obstruction develops.

Regional sympathectomy has been somewhat successful in animal experi-

ments, reducing both edema and the amount of tissue loss [25, 37]. As a therapeutic measure in human cases, it has been highly effective in reducing the number of severity of sequelae, such as coolness, hyperhidrosis, pallor, vasospastic complaints, and ulcers, which follow cold injury [78, 79]. The inherent difficulties in assessing the effectiveness of sympathectomy on the extent of tissue loss in human cases are readily apparent. Surgical sympathectomy is a highly specialized, major procedure, the performance of which would be precluded by the space situation. However, success in the treatment of sequelae of cold injury by sympathectomy would suggest that the sympatholytic drugs and, in certain cases, regional sympathetic nerve block with a local anesthetic might also be effective in the treatment of these sequelae.

Low molecular-weight dextran has been administered to cold injury cases because it has been shown to be a specific agent for the inhibition of intravascular cellular aggregation and the improvement of small vessel blood flow in injured tissue [67]. The beneficial results obtained with this agent in animal experiments do not appear to be attributable to the expansion of plasma volume and hemodilution which it also produces [5, 67, 68, 69]. The actual clinical effectiveness of this drug remains to be established, however [26, 33, 69, 71, 80].

Heparin, used to prevent microvascular clotting, has had success in animal experiments [33, 73]. However, its effectiveness in human cold injury cases has not been proven [6, 55, 92].

If vasodilating, anti-sludging, or anti-coagulant agents are in fact proven clinically useful, in the treatment of cold injury, it is readily apparent that they must be administered as soon as possible after and perhaps before starting the rewarming of the injured area, and for many hours to several days thereafter. Unfortunately, the early administration of such agents to cold injury cases has up to this time been difficult and most often impossible to accomplish. Therefore the results of well controlled animal experiments may well have to be relied on in anticipating their clinical effectiveness for some time to come.

Steroids, administered in attempts to limit the inflammation associated with cold injury, and flavenoids, taken for the reduction of capillary perme-

ability and fragility in cold injured tissue have not been beneficial in the treatment of cold injury [90].

Hypothermia

Pathophysiology and Clinical Manifestations

Hypothermia, which has been discussed in several excellent reviews, has been defined as a state of body temperature which is below normal in a homeothermic organism [9, 13, 18, 27, 54, 56, 82, 83, 85]. Little [59] attempted to make this definition more meaningful by stating terms which could be used to characterize the depth and duration of the hypothermia under consideration. The depth of hypothermia was categorized in terms of body core temperature, as light (37° to 32°C; or 98.6° to 89.6°F), intermediate or moderate (32° to 26°C; or 89.6° to 78.8°F), deep (26° to 20°C; or 78.8° to 68°F), and profound (under 20°C, or 68°F); and the duration of hypothermia as acute (few hours), and chronic or prolonged (many hours, days, or weeks). This classification has a greater application to considerations of hypothermia used as a therapeutic tool than to considerations of hypothermia acquired accidentally. However, each depth of hypothermia categorized above appears to correlate well with the clinical picture an astronaut might present if rendered hypothermic to a particular level of body core temperature. The clinical features of these various depths of hypothermia are:

> Initial Response to Cold. The initial response to cold mimics intense stimulation of the sympathetic nervous system, being characterized by intense shivering, marked peripheral vasoconstriction, elevation of systemic arterial pressure and significant increases in oxygen consumption, respiratory rate, and cardiac output (59). This stress response may actually produce a slight rise in temperature, and so delay the onset of hypothermia which will eventually result if physiological compensatory mechanisms are inadequate (9).
>
> Light Hypothermia (37° to 32°C; or 98.6° to 89.6°F). This depth of hypothermia is characterized by a sensation of severe cold and intense shivering which may be painful, especially around the neck. The toes and fingers become increasingly painful, then numb. Respiration is increased in rate and depth from the onset of hypothermia but subsequently decreases, especially below 34.5°C (94.1°F), in a manner that can lead to respiratory acidosis

in spite of an overall normal arteriovenous oxygen difference being maintained (83, 87). It is also pointed out that as the body temperature decreases, the solubility of carbon dioxide in body fluids increases and the oxygen carrying capacity of the blood decreases. An increase in metabolic rate occurs during a normal response to cold, persisting until the core temperature has fallen to approximately 35°C (95°F), and thereafter declines to reach basal values or lower in the intermediate or moderate hypothermia range (15, 27). As the temperature falls, the heart rate decreases. During this period, the blood pressure falls, but only gradually (15).

Intermediate or Moderate Hypothermia (32° to 26°C; or 89.6° to 78.8°F). At this depth of hypothermia, the individual becomes increasingly somnolent and resistant to pain, and finally loses consciousness (3, 32). Shivering ceases between 33°C (91.4°F) and 30°C (86°F), but muscular rigidity may persist to 27°C (80.6°F) (15). Respiration will continue to decrease, becoming irregular about 30°C (86°F) and finally cease about 28°C (82.4°F) (15). Cardiac arrhythmias (nodal rhythm, auricular fibrillation, ventricular extrasystoles, etc.) appear at core temperatures below 30°C (86°F) (15). Ventricular fibrillation becomes an increasing hazard at temperatures below 28°C (82.4°F) (87). Hypothermia in this range might occasionally aggravate epilepsy and certain other types of seizures (59).

Deep Hypothermia (26° to 20°C; or 78.8° to 68°F). Death usually occurs about 25°C (77°F), from either ventricular fibrillation or cardiac asystole (3, 15). However, the lethal temperature might be quite variable as demonstrated by a case in which a woman survived a fall in core temperature to 18°C (64.4°F) or even lower (15, 57).

Profound Hypothermia (under 20°C; or 68°F). Survival of accidental hypothermia to this level is considered highly unlikely.

The general effect of hypothermia is currently thought to be entirely depressive, even though there is an increasing tendency of the heart to become more sensitive to the development of arrhythmias and the central nervous system to become more excitable as the core temperature of the body falls. Accordingly, the slowdown of body functions do not appear to parallel each other. Hence a potentially dangerous physiochemical state can result (57). The physiologic changes that occur in response to hypothermia are

complex and not well understood. Yet they may be tolerated for some period of time without harm. For example, Talbott [85, 86] and Dill and Forbes [27] treated patients suffering from psychoses by slowly cooling them to a rectal temperature of about 26.5°C (79.7°F). The patients were maintained at this temperature level for periods of up to 24 hours and then slowly rewarmed. There were two deaths from cardiac failure during the hypothermic phase in the series of 20 cases, with no after-effects being noted in the survivors.

The most serious complication of hypothermia has been ventricular fibrillation, which occurs particularly at temperatures below 28°C (82.4°F). Unfortunately, there appears to be no proven method of reversing this arrhythmia in an individual who is in the hypothermic state. Moreover, it is highly unlikely that the standard methods of defibrillation, which are in themselves often only momentarily effective, could be undertaken in the space situation.

Lewis [54] has cited work which has shown that an impressive irreversible cardiac failure can develop in cases of prolonged hypothermia. This fatal event appeared particularly during rewarming. Conflicting evidence has been presented on the important question of the occurrence of other hypothermic organ damage [59].

The most common complication which might occur on rewarming a hypothermic astronaut is so-called rewarming shock [31]. This syndrome consists of the development of hypotension and acute circulatory collapse, which is characterized by tachycardia, diminished cardiac output and inadequate respiration [12]. It appears to be due to acidosis which is predominately metabolic in origin although, as previously mentioned, carbon dioxide accumulation due to cold-induced respiratory depression and increased solubility of this gas in cooled body fluids also occurs and might contribute to some degree to the acidosis [59]. Shivering and rapid warmth-induced increases of blood flow through the vascular beds of cold muscle masses during rewarming can result in marked increases of circulating acid metabolites, and so produce or aggravate rewarming shock. Undoubtedly other factors can also be implicated in the etiology of rewarming shock. A

marked warmth-induced peripheral vasodilatation might itself be conducive to shock or seriously aggravate the tendency to shock produced by metabolic acidosis. As well, the loss of circulating plasma volume, which occurs during prolonged hypothermia, might be inadequately restored if rewarming is accomplished rapidly [15, 85, 86, 88]. There is also the possibility that cardiac inadequacy, caused by a reduction of muscular glycogen or myocardial damage from prolonged hypothermia, might contribute to rewarming shock [15].

Another significant complication of rewarming has been discussed by Burton and Edholm [15]. It has been noted that rapid increases in blood flow through cooled parts of the body can result in a large volume of cooled venous blood returning to the heart. For example, Behnke and Yaglou [10] recorded sharp falls of gastric, oral and rectal temperatures initially on rewarming their subjects. Burton and Edholm [15] thus suggested that the resulting drop in cardiac temperature might produce cardiac arrest or ventricular fibrillation, particularly under conditions of rapid rewarming.

Diagnosis

The level of the core temperature of a hypothermic astronaut should be determined as soon as possible in order to decide on the potential seriousness of the situation and thus the therapeutic approach to be followed. For example, shivering can occur over a wide range of temperatures (37° to 30°C; or 98.6° to 89.6°F), so as a clinical finding it alone could indicate either a mild response to cold or a serious clinical situation. On the other hand, an astronaut could be stuporous or unconscious, not shivering, and yet hypothermic (core temperature less than 30°C, or 89.6°F). The level of core temperature might conceivably also be necessary to establish the diagnosis of hypothermia as distinct from other causes of stupor or unconsciousness. If ever possible in space, determination of blood pH could serve as a valuable adjunct in deciding on specific therapy of a hypothermic astronaut.

Prevention

The question arises as to whether or not acclimatization of man to a cold

environment is possible and if so, whether or not such a long-lasting adjustment of physiological functions should be induced in an astronaut if unusually high risks of excessive local or total body heat losses are anticipated during operations in space. Although it has been well established that true physiologic acclimatization to heat occurs (Chapter 6), Davis [21] has pointed out that there is a significant group of investigators who have found that there is no defined evidence of cold acclimatization in man. On the other hand, various recorded changes in the reaction of the peripheral blood circulation to cold and in the cold-induced increase in metabolism after repeated or prolonged cold exposure have been interpreted as evidence of acclimatization to cold in man.

In his excellent review and from his studies in this area, Hellström [46] pointed out that much evidence can be accumulated to show that cold-induced vasodilatation is more marked and comes on more rapidly in individuals who are chronically exposed to cold in their occupations, as compared to those who work in a warm environment. These workers also demonstrated a higher pain threshold and better manual functioning on cold exposure, and a lowered response to the cold pressor test as compared to those who work in a warm environment. He found no convincing evidence of a seasonal variation in these parameters studied in students. Daily exposure of one hand to cold water (temperature initially 3°C, rising to 12°C during 30 minutes) for 11 to 15 consecutive working days in the early summer in a thermally "neutral" environment did not appear to alter hand blood circulation or the deteriorating effect of cold on hand function. Such was also the case when the same local cold exposure was applied 6 days a week for 3 weeks during the winter to individuals who sat naked at 15.5°C ambient air temperature for 70 minutes. However, a reduction of cold-induced pain in the exposed hand and a decrease in the cold pressor response took place in both experiments.

Davis [21, 22, 23, 24] has managed to produce a significant elevation of the shivering threshold of individuals exposed, nude, 8 hours a day for 31 days to an ambient air temperature of 11.8°C. This was also found to result from seasonal or climatic temperature decreases. He concluded that the elevation of the shivering threshold appears to define the occurrence

of cold acclimatization in man with some precision. Using this criterion, Davis demonstrated that the seasonal cold acclimatization in man was not retained over the summer whereas the acclimatization following the chronic nude cold exposure was retained through at least one summer season. Heat acclimatization in these studies did not affect artificially or naturally induced cold acclimatization. This finding, in the light of the demonstration by others that heat acclimatization is unaffected per se by cold exposure, indicates both acclimatizations can co-exist in an individual [36, 47, 83]. Studying other parameters, Davis found that the initial cold-induced heat production in unacclimatized subjects was consistently higher (value of 64 percent above basal) in those studied in the summer as compared to those studied in the winter season (value of 30 to 40 percent above basal). After the chronic nude cold exposure, this response stabilized around 30 to 40 percent in both groups. Lastly, he found that the body core temperature of the chronic exposure group decreased significantly on cold exposure.

Numerous other studies described in the literature point as well to the fact that most past work on acclimatization to cold in man has been concentrated on efforts to establish criteria for it, prove its very existence in various groups of cold-exposed subjects and evaluate the degree of cold exposure necessary to produce changes of physiological reactions which deserve interpretation as evidence of acclimatization to cold. It is apparent that the possible degree of cold acclimatization which can take place in man has not been startling -- a sharp contrast to the rather overwhelming evidence that true physiologic acclimatization to cold exists in other non-hibernating homeotherms [43]. Moreover, it does not appear to have been proven that cold acclimatization can actually offer man significant protection from cold injury or accidental hypothermia. Thus, at the present time the conclusion can be drawn that even if cold acclimatization could confer some protection in an astronaut, the practicability of inducing it might be outweighed by the exposure temperature and duration which would be required for its induction. As well, possible loss of cold acclimatization over early months of a prolonged mission in space would also

suggest impracticability.

Treatment

In order to minimize the risk of the complications of hypothermia discussed previously, an astronaut's normal body temperature should be restored as slowly as possible. By allowing the peripheral tissues to rewarm slowly, the acid metabolites and carbon dioxide which have accumulated in these tissues will be slowly washed out into the systemic circulation. Thus adequate time will be allowed for the breakdown and buffering of these metabolites, so preventing severe metabolic acidosis and possible rewarming shock. Moreover, a marked warmth-induced peripheral vasodilatation might itself be conducive to shock or seriously aggravate the tendency to shock produced by metabolic acidosis. It is also possible for the volume of plasma lost during a prolonged period of hypothermia to be inadequately restored if rewarming is accomplished rapidly [15]. Lastly, slow rewarming decreases the risk of a further drop in cardiac temperature, and so possible fatal cardiac arrhythmias, by keeping the flow of cold venous blood from the cold peripheral tissues to the heart to a minimum.

To accomplish slow rewarming, the entire body surface of a hypothermic astronaut should be exposed to normal environmental temperatures (about 23°C; or 72°F). Accordingly, his body will be allowed to rewarm by metabolic activity alone. As noted elsewhere in this chapter, a local cold injury should, however, be rewarmed as quickly as possible. Under certain circumstances, a hypothermic astronaut might have to be rewarmed while in a space suit. Optimum temperature control settings which will allow a slow rewarming of his body will have to be determined, depending on whether a gas or fluid system is used for temperature control in the suit.

Whether a drug such as chlorpromazine should be administered to minimize shivering during the rewarming process remains controversial [69]. This measure could keep the acid metabolites contributed by muscular activity to a minimum, so reducing the tendency to rewarming shock due to metabolic acidosis. As well, the metabolic heat output by muscular activity could be minimized, so allowing a slow rewarming of the body. However,

since drugs such as chlorpromazine are also vasodilatory, their use might be contraindicated.

If rewarming "shock" occurs, intensive treatment of this serious event should be commenced immediately, with appropriate measures being selected as sound clinical judgment dictates. A solution of glucose, saline, and bicarbonate in water should be administered intravenously. Oxygen should be given. An appropriate vasopressor, such as metaraminol, might be indicated. If the possibility of cardiac damage from the hypothermia exists, a cardiac glycoside, such as digoxin, might be given intravenously. Possible external sources producing excessive body heating should be removed.

1. Adam
2. Adam
3. Alexa
4. Ander
5. Ander
6. Artz,
7. Bader
8. Beaco
9. Behnk
10. Blair,
11. Blair,
12. Blaisd

REFERENCES

1. Adams, J. M., Goldsmith, R., Cold Climates, in Exploration Medicine, O. G. Edholm, A. L. Bacharach, (eds.). Baltimore, Williams and Wilkins Co., 1965, p. 245.

2. Adams, T., Smith, R. E., Effect of Chronic Local Cold Exposure on Finger Temperature Responses. J. Appl. Physiol., 17: 317-322, 1962.

3. Alexander, L., Treatment of Shock from Prolonged Exposure to Cold, Especially in Water. Rept. No. 250, Department of Commerce, Office of the Publication Board, Washington, D. C., 1946.

4. Andersen, K. L., Hart, J. S., Hammel, H. T., Sabean, H. B., Metabolic and Thermal Response of Eskimos During Muscular Exertion in the Cold. J. Appl. Physiol., 18:613-618, 1963.

5. Anderson, R. G., Hardenbergh, E., Frostbite Treatment in the Mouse with Low Molecular Weight Dextran. J. Surg. Res., 5:256-261, 1965.

6. Artz, C. P., Thermal and Radiation Injuries, in Christopher's Textbook of Surgery, L. Davis, (ed.). Philadelphia, W. B. Saunders Co., 1964, 8th Ed., pp. 160-190.

7. Bader, M. E., Mead, J., Effect of Local Cooling in Finger Blood Flow in Individuals Exposed to Warm Ambient Temperature. J. Appl. Physiol., 3:508-512, 1951.

8. Beaconsfield, P., Afflictions of the Extremities Resulting from Increased Vasomotor Activity. Surg. Clin. N. Amer., 40: 25-44, 1960.

9. Behnke, A. R., Yaglou, C. P., Physiological Responses of Men to Chilling in Ice Water and to Slow and Fast Rewarming. J. Appl. Physiol., 3:591-602, 1951.

10. Blair, E., Montgomery, A. V., Swan, H., Posthypothermic Circulatory Failure: Physiologic Observations on Circulation. Circulation, 13:909-915, 1956.

11. Blair, J. R., The Treatment of Frostbite, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp.321-337.

12. Blaisdell, R. K., Effect of Body Thermal State on Cold-Induced Cyclic Vasodilatation in the Finger. Environmental Protection Section Rept. No. 177, Quartermaster Climatic Research Lab., Natick, Massachusetts, 1951.

13. Brauer, R. W., Behnke, A. R., Hypothermia, in Principles of Internal Medicine, T. R. Harrison, R. D. Adams, (eds.). New York, McGraw-Hill Book Co., Inc., 1962, 4th Ed., pp. 835-841.

14. Burton, A. C., Bazett, H. C., A Study of the Average Temperature of the Tissues, of the Exchanges of Heat and Vasomotor Responses in Man by Means of a Bath Calorimeter. Amer. J. Physiol., 117:36-54, 1936.

15. Burton, A. C., Edholm, O. G., Man in a Cold Environment. London, Edward Arnold, Ltd., 1955, pp. 220-222.

16. Carlson, L. D., Thrush, H. L., Protection of the Extremities in Extreme Cold: A Selected, Annotated Bibliography. AAL-TR-59-19, Arctic Aeromedical Lab., Ladd AFB, Alaska, 1960.

17. Cockett, T. K., Beehler, C. C., Protective Effects of Hypothermia in Exploration of Space. J. A. M. A., 182:977-979, 1962.

18. Cooper, K. E., Ross, D. N., Hypothermia in Surgical Practice. Philadelphia, F. A. Davis Co., 1960.

19. Crismon, J. M., Fuhrman, F. A., Studies on Gangrene Following Cold Injury. VIII. The Use of Casts and Pressure Dressings in the Treatment of Severe Frostbite. J. Clin. Invest., 26:486-496, 1947.

20. Davis, L., Scarff, J. E., Rogers, N., Dickinson, M., High Altitude Frostbite. Surg. Gynec. Obstet., 77:561-575, 1943.

21. Davis, T. R. A., Acclimatization to Cold in Man, in Temperature; Its Measurement and Control in Science and Industry, J. D. Hardy, (ed.). New York, Reinhold Pub. Corp., 1963, Vol. III, Pt. 3, pp. 443-452.

22. Davis, T. R., Chamber Cold Acclimatization in Man. J. Appl. Physiol., 16:1011-1015, 1961.

23. Davis, T. R., Experimental Cold Acclimatization in Man. U. S. Army Med. Res. Lab., 457:1-8, 1960.

24. Davis, T. R., Joy, R. J., Natural and Artificial Cold Acclimatizati in Man. U. S. Army Med. Res. Lab., 474:62-84, 1961.

25. De Jong, P., Golding, M. R., Sawyer, P. N., Wesolowski, S. A., Recent Observations in the Therapy of Frostbite. Surg. Forum, 12:444-445, 1961.

26. Departments of the Army, the Navy, and the Air Force, Cold Injury. TB-MED-81 (NAVMED 5052-29; AFP 161-1-11). Washington, D. C., 1964.

27. Dill, D. B., Forbes, W. H., Respiratory and Metabolic Effects of Hypothermia. Amer. J. Physiol., 132:685-689, 1941.

28. Edwards, M., Burton, A. C., Correlation of Heat Output and Blood Flow in the Finger, Especially in Cold-Induced Vasodilatation. J. Appl. Physiol., 15:201-208, 1960.

29. Eggers, G. W. N., Jr., Paley, H. W., Leonard, J. J., Warren, J. V., Hemodynamic Responses to Oxygen Breathing in Man. J. Appl. Physiol., 17:75-79, 1962.

30. Erb, R. B., Thermal Balance and Heat Protection, in Manned Spacecraft: Engineering Design and Operation, P. E. Purser, M. A. Faget, N. F. Smith, (eds.). New York, Fairchild Pub., Inc., 1964, pp. 89-104.

31. Fairley, H. B., Hypothermia for Adult Cardiovascular Surgery: Technique of Anaesthesia. Canad. Anaesth. Soc. J., 4: 96-104, 1957.

32. Fay, T., Smith, G. W., Observations on Reflex Responses During Prolonged Periods of Human Refrigeration. Arch. Neurol. Psychiat., 45:215-222, 1941.

33. Flatt, A. E., Frostbite of the Extremities - A Review of Current Therapy. J. Iowa Med. Soc., 52:53-55, 1962.

34. Fuhrman, F. A., Fuhrman, G. J., The Treatment of Experimental Frostbite by Rapid Thawing. Medicine, 36:465-487, 1957.

35. Gildenberg, P. L., Hardenbergh, E., The Effect of Immediate Sympathectomy on Tissue Survival Following Experimental Frostbite. Ann. Surg., 160:160-168, 1964.

36. Glaser, E. M., Acclimatization to Heat and Cold. J. Physiol., 110: 330-337, 1949.

37. Golding, M. R., Mendoza, M. F., Hennigar, G. R., et al, On Settling the Controversy on the Benefit of Sympathectomy for Frostbite. Surgery, 56:221-231, 1964.

38. Gordon, A., Personal Communication. Lovelace Clinic, Albuquerque, New Mexico, 1965.

39. Grant, R. T., Bland, E. F., Observations on the Arteriovenous Anastomoses in Human Skin and in the Bird's Foot with Special Reference to the Reaction to Cold. Heart, 15:385-407, 1931.

40. Greenfield, A. D. M., Shepherd, J. T., Whelan, R. F., The Part Played by the Nervous System in the Response to Cold of the Circulation Through the Finger Tip. Clin. Sci., 10: 347-360, 1951.

41. Grosse-Brockhoff, F., Pathologic Physiology and Therapy of Hypothermia, in German Aviation Medicine in World War II, U. S. Government Printing Office, Washington, D. C., 1950, Vol. II, pp. 828-842.

42. Hardy, J. D., Dubois, E. F., Differences Between Men and Women in Their Response to Heat and Cold. Proc. Nat. Acad. Sci., 26:389-398, 1940.

43. Hart, J. S., Physiological Responses to Cold in Nonhibernating Homeotherms, in Temperature: Its Measurement and Control in Science and Industry, J. D. Hardy, (ed.). New York, Reinhold Pub. Corp., 1963, Vol. III, Pt. 3, pp. 373-406.

44. Hays, E. L., Space Suits, in Manned Spacecraft: Engineering Design and Operation, P. E. Purser, M. A. Faget, N. F. Smith, (eds.). New York, Fairchild Pub., Inc., 1964, pp. 161-168.

45. Hegnauer, A. H., Angelakos, E., Hand and Finger Blood Flow Rates Under Different Temperature Conditions. WADC-TR-53-501, Wright Air Development Center, Wright-Patterson AFB, Ohio 1953.

46. Hellström, B., Local Effects of Acclimatization to Cold in Man. The Institute of Work Physiology, Oslo, Norway, 1959.

47. Henschel, A., Taylor, H. L., Keys, A., Persistence of Heat Acclimatization in Man. Amer. J. Physiol., 140:321-325, 1943.

48. Hermann, G., Schechter, D. C., Owens, J. C., Starzl, T. E., The Problem of Frostbite in Civilian Medical Practice. Surg. Clin. N. Amer., 43:519-536, 1963.

49. Horvath, S. M., Adaptation of Man to Cold Environment. University of California, Annual Progress Report, 1963-1964.

50. Johnston, J. P., Frostbitten Ears. Henry Ford Hosp. Med. Bull., 11:453, 1963.

51. Kulka, J. P., Experimental Injuries Produced by Prolonged Exposure to Cold Air, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 13-2

52. Kulka, J. P., Roos, T. B., Dammin, G. J., Blair, J. R., Physiopathology of Cold Injury: Cutaneous Circulation in the Feet of Rabbits Following Prolonged Exposure to Sub-freezing Air. AMRL-326, U. S. Army Med. Res. Lab., Fort Knox, Kentucky, 1957.

53. Kulka, J. P., Cold Injury of the Skin. Arch. Environ. Health, 11: 484-497, 1965.

54. Lane, F. H., Bollerud, J., Evaluation of Methods for the Treatment of Frostbite. Proj. No. 21-01-012, Arctic Aeromedical Lab., Ladd AFB, Alaska, 1951.

55. Lapp, N. L., Juergens, J. L., Frostbite. Mayo Clin. Proc., 40: 932-948, 1965.

56. Laufman, H., Profound Accidental Hypothermia. J.A.M.A., 147: 1201-1212, 1951.

57. Lewis, F. J., Hypothermia. International Abstr. Surg., 113:307-336, 1961.

58. Lewis, T., The Blood Vessels of the Human Skin and Their Responses. London, Shaw and Sons, 1927, pp. 139-150.

59. Little, D. M., Jr., Hypothermia. Anesthesiology, 20:842-877, 1959.

60. Meehan, J. P., Jr., Individual and Racial Variations in a Vascular Response to a Cold Stimulus. Milit. Med., 127:247-252, 1962.

61. Meryman, H. T., The Mechanism of Local Cold Injury. Naval Medical Research Institute, Bethesda, Maryland, Project NM 000 018.01.07, 1953, Vol. XI, pp. 741-766.

62. Meryman, H. T., Tissue Freezing and Local Cold Injury. Physiol. Rev., 37:233-251, 1957.

63. Meryman, H. T., Mechanism of Freezing Injury in Clinical Frostbite, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 1-7.

64. Miller, D., Bjornson, D. R., An Investigation of Cold Injured Soldiers in Alaska. Milit. Med., 127:247-252, 1962.

65. Mills, W. J., Jr., Clinical Aspects of Frostbite Injury, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 149-196.

66. Mills, W. J., Jr., Whaley, R., Frostbite: A Method of Management, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 127-141.

67. Mundth, E. D., Studies on the Pathogenesis of Cold Injury: Microcirculatory Changes in Tissue Injured by Freezing, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 51-59.

68. Mundth, E. D., Low Molecular Weight Dextran: A New Agent in the Treatment of Experimental Frostbite, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 269-275.

69. Mundth, E. D., Long, D. M., Brown, R. B., Treatment of Experimental Frostbite with Low Molecular Weight Dextran. J. Trauma, 4:246-257, 1964.

70. Orr, K. D., Fainer, D. C., Cold Injuries in Korea During Winter of 1950-51. Medicine, 31:177-220, 1952.

71. Penn, I., Schwartz, S. I., Evaluation of Low Molecular Weight Dextran in the Treatment of Frostbite. J. Trauma, 4:784-790, 1964.

72. Pichotka, J., Lewis, R. B., Effect of Rapid and Prolonged Rewarming on the Extent of Local Cold Injury. Proj. No. 21-23-006, Rept. No. 7, U. S. Air Force Sch. Aviation Med., Randolph Fiel Texas, 1951.

73. Pichotka, J., Lewis, R. B., The Use of Heparin in the Treatment of Experimental Frostbite. Proj. No. 21-02-079, Rept. No. 1, U.S. Air Force Sch. Aviation Med., Randolph Field, Texas,

74. Pichotka, J., Lewis, R. B., Freytag, E., Sequence of Increasing Local Cold Injury. Proj. No. 21-23-006, Rept. No. 6, U.S. Air Force Sch. Aviation Med., Randolph Field, Texas, 19

75. Rapaport, S. I., Fetcher, E. S., Shaub, H. G., Hall, J. F., Control of Blood Flow to the Extremities at Low Ambient Temperatures. J. Appl. Physiol., 2:61-71, 1949.

76. Rennie, D. W., Adams, T., Comparative Thermoregulatory Response of Negroes and White Persons to Acute Cold Stress. J. Appl. Physiol., 11:201-204, 1957.

77. Roth, E. M., Bioenergetic Considerations in the Design of Space Suits for Lunar Exploration. NASA-SP-84, National Aeronautic

and Space Administration, Washington, D. C., 1966.

78. Shumacker, H. B., Jr., Sympathectomy in the Treatment of Frostbite, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 293-309.

79. Shumacker, H. B., Jr., Kilman, J. W., Sympathectomy in the Treatment of Frostbite. Arch. Surg., 89:575-584, 1964.

80. Simeone, F. A., Experiences with Conservative Management of Cold Injury Among Civilians, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 207-223.

81. Spealman, C. R., Effect of Ambient Air Temperature and of Hand Temperature on Blood Flow in Hands. Amer. J. Physiol., 145: 218-222, 1945.

82. Smith, R. M., Stetson, J. B., Therapeutic Hypothermia. New Eng. J. Med., 265:1097-1103, 1147-1151, 1961.

83. Stein, H. M., Eliot, J. W., Bader, R. A., Physiological Reactions to Cold and Their Effects on the Retention of Acclimatization to Heat. J. Appl. Physiol., 1:575-585, 1949.

84. Stromme, S., Andersen, K. L., Elsner, R. W., Metabolic and Thermal Responses to Muscular Exertion in the Cold. J. Appl. Physiol., 18:756-763, 1963.

85. Talbott, J. H., Physiology of Hypothermia. New Eng. J. Med., 224:281, 1941.

86. Talbott, J. H., Consolazio, W. V., Pecora, L. J., Hypothermia. Arch. Intern. Med., 68:1120, 1941.

87. Vandam, L. D., Burnap, T. K., Hypothermia. New Eng. J. Med., 261:546-553; 595-603, 1959.

88. Virtue, R. W., Hypothermic Anesthesia. Springfield, Charles C. Thomas, 1955, 1st Ed.

89. Washburn, B., Frostbite: What It is - How to Prevent It - Emergency Treatment. New Eng. J. Med., 266:974-989, 1962.

90. Webster, D. R., The Effects of Drugs in the Therapy of Frostbite, in Proceedings Symposia on Arctic Medicine and Biology. IV. Frostbite, E. Viereck, (ed.). Arctic Aeromedical Lab., Fort Wainwright, Alaska, 1964, pp. 257-268.

91. Wilkins, R. W., Peripheral Vascular Diseases Due to Exposure to Cold, in Textbook of Medicine, R. L. Cecil, R. F. Loeb, (eds.) Philadelphia, W. B. Saunders Co., 1965, pp. 1390-1392.

92. Yarington, C. T. Jr., Bales, G. A., The Local Cold Injury: With Special Reference to Frostbite of the Ears. Milit. Med., 128:1024-1026, 1963.

CHAPTER 8

MEDICAL PROBLEMS DUE TO PARTICLE AND DROPLET CONTAMINATION OF THE SPACECRAFT CABIN ATMOSPHERE

Introduction

Particles and droplets of all sizes tend to remain suspended in the weightless environment. Various forms of particulate and liquid matter can, therefore, present much greater hazards if introduced into a confined atmosphere in space than if introduced into a confined atmosphere on Earth. These contaminants might not only give rise to certain medical problems in space, but also might produce temporary or permanent malfunctioning of spacecraft components which are vital to the safety of the mission.

By recognizing all possible sources of particles and droplets which might contaminate the spacecraft cabin atmosphere, various preventive and control measures can be taken to eliminate or minimize both potential and real particle and droplet hazards in space. As well, an astronaut might take specific measures to protect himself in a "high risk" situation. However, even though these measures might seemingly eliminate the likelihood of medical problems in space from contaminant-astronaut contact, it still must be assumed that such problems might be the result of an unforeseen accident or failure of the environmental control system to remove rapidly enough larger particles and droplets of debris which will inevitably be introduced into the spacecraft cabin atmosphere. Therefore the various clinical problems which might arise if the astronaut should be exposed to particle and droplet contamination of the spacecraft cabin atmosphere should be predicted and their management in space considered.

Sources

A simple classification of the major possible sources of particle and droplet contamination of the spacecraft cabin atmosphere is presented in Table 8.1. These sources fall under one of two categories - exogenous

sources, or sources existing outside of the spacecraft in space, and endogenous sources, or sources existing within the spacecraft itself.

EXOGENOUS
- Meteoroid
- Extravehicular

ENDOGENOUS
- Construction
- Maintenance and Repair
  - Preflight
  - Inflight
- Operation
- Food - Water - Waste
- Astronaut
- Experiment

Table 8.1 Sources of Particle and Droplet Contamination

The major exogenous sources are meteoroids and other extravehicular sources. Meteoroids which completely penetrate the wall of the spacecraft will lead to free-floating particles of meteoroid and wall. Further particle and even droplet contamination can result if structures within the cabin are disrupted by fragments of meteoroid and wall or by the blast wave produced by the "explosive oxidation" of vaporized meteoroid and wall materials. Fumes and smoke can be produced by the "explosive oxidation" and possibly by fires caused by the ignition of combustible materials by molten and hot fragments of meteoroid and wall. Fragments may also disrupt electrical circuits and structures which contain flammable liquids and gases to produce fires. A meteoroid which does not completely penetrate the spacecraft wall might still result in particle contamination of the spacecraft cabin atmosphere by producing fragmentation, or spallation of the inner surface of the cabin wall.

Other extravehicular sources, primarily of particle contamination, are

extraterrestrial dust and possibly particles of organic matter. Such particles could adhere to the space suit or to other equipment during extravehicular operations on lunar or planetary surfaces. Samples taken from extraterrestrial environments are also potentially contaminating, especially if they are in the form of small particles or in a liquid state, and are to be analysed on board the spacecraft.

It is thought that almost all particles and droplets which can contaminate the spacecraft cabin atmosphere will originate from endogenous sources, or sources existing within the spacecraft cabin itself. Metal particles and dust may remain within the spacecraft following its construction and subsequent checkout. During preflight and inflight maintenance procedures, it might be possible, for example, to release non-chemical particles such as metal, glass, and plastic through breakage, chipping, or dislodgement; to release chemical particles such as lithium hydroxide or superoxides from the environmental control system, or chemical droplets from biochemical or other analytical systems; and to release microbiologically-contaminated water from the waste disposal system. Also during the normal operation of the spacecraft, particles and droplets might be introduced into the spacecraft cabin atmosphere through dislodgement, chipping, and breakage.

Food, water, and waste sources of particle and droplet contamination are apparent. It is noted that solid foods which tend to crumble when handled could be a likely source of particle contamination.

An astronaut could well be the greatest source of particle and droplet contamination of the spacecraft cabin atmosphere. Hair and desquamated epithelium, especially as "dandruff", is shed continuously from the body surface. Talking, coughing, and sneezing will eject droplets of saliva and respiratory tract mucus into the atmosphere. Lint can be released from the astronaut's clothing, Velcro fasteners, and towels. Droplets of urine and wash water, and fecal particles might be accidentally released into the atmosphere. Vomiting will be an extremely serious potential contamination hazard.

Finally, it should be noted that in-space experiments which utilize

chemicals, or fragmentable materials or apparatus might create significant potential particle and droplet hazards, especially if chemicals in biochemical or other analytical systems are to be replaced or if such systems are to be serviced in space.

Preventive, Control and Protective Measures

A number of obvious preventive, control and protective measures may be taken to eliminate or minimize potential or existing particle and droplet hazards in space. Various preventive measures are: the selection and design of systems which present minimum potential particle and droplet hazards, especially if serviced in space; the exclusion or shielding of potentially contaminating systems and subsystems from the rest of the spacecraft cabin environment; the use of materials which are non-combustible, lint-free, and do not splinter, flake or shatter; the preparation of foods which do not crumble or powder; the use of contamination "proofed and proven" devices for shaving, haircutting, teethcleaning, washing, urination and defecation; the use of "paper strip" techniques whenever possible for biochemical analyses; and the removal of all metal and other particles created during the manufacture and servicing of the spacecraft before flight. Some control measures are: the compartmentalization of the spacecraft interior, thus separating or being able to separate living, and various "high risk" areas from each other; the provision of a regulatable efficient air ventilating-filtering system and "vacuum cleaners" which can reach anywhere in the spacecraft; the capability of venting a contaminated compartment in space; and procedures for "decontaminating" astronauts and equipment after extravehicular operations on lunar and planetary surfaces. Various protective measures are: the placing of suitable protective equipment such as masks, eye shields, and total body garments throughout the spacecraft, readily available for use; the wearing of protective equipment in a "high risk" situation; keeping the number of astronauts exposed to a "high risk" situation, such as while servicing the environmental control system, to a minimum; and the placing of adequate shielding around instru-

ments which can be affected by particle and droplet contaminants.

Predicted Medical Problems

The medical problems which can result if suspended particles or droplets come into contact with an astronaut will be determined by their physical, chemical, and microbiological properties. Taking into consideration the properties which the various possible particle and droplet contaminants of the spacecraft cabin atmosphere might have, the major medical problem areas appear to be; eye problems due to non-chemical particles* and chemical particles and droplets; skin burns due to chemical particles and droplets; and medical problems due to the inhalation of non-chemical, chemical, and microbiologically-contaminated particles, and chemical, and microbiologically-contaminated droplets. A brief discussion of various possible eye problems from particles and droplets, and clinical problems due to particle and droplet inhalation into the respiratory passages follows. Chemical skin burns are discussed in Chapter 13.

Eye Problems

The potential hazard to an astronaut's eyes of an atmospheric particle or droplet contaminant will be determined mainly by the physical and chemical characteristics, and the velocities of the particles or droplets. Non-chemical particles, referred to here as "foreign bodies", can irritate and injure eye tissues through a physical, or mechanical effect. Chemical particles cannot only act as foreign bodies but also, through a chemical effect, irritate and burn eye tissues. Chemical droplets can irritate and possibly burn.

As particles and droplets are accelerated by circulating air, they will become more hazardous to the eyes, for their impact frequency will increase and the "blink" reflex, which prevents approaching particles and droplets from impinging on the eyes, will become less effective. It is also thought possible that some particles and droplets might acquire a static

* In subsequent discussions, the terms "non-chemical particle" and "foreign body" are used interchangeably.

electrical charge and so might be attracted to the eye if in close proximity to it.

A brief discussion of the clinical features and the principles of treatment in space of possible eye problems caused by foreign bodies and chemicals follows. For more detailed coverage of this area, reference is made to the writings of Duke-Elder [12], Adler [1], Roper-Hall [46], Grant [19], Kuhn [34], Ryan [48, 49, 50], Zimmerman [60, 61, 62], and others [2, 53]. A diagram of the sagittal section of the human eye is provided (Figure 8.1) to point out anatomical features of the eye which will be mentioned in the following discussion.

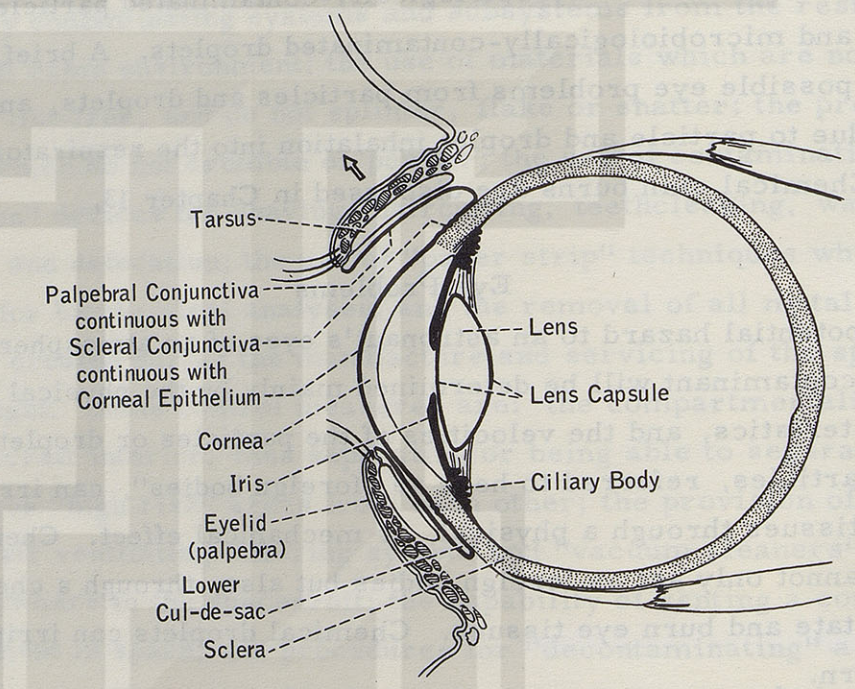

Figure 8.1 Sagittal Section of Human Eye.

Foreign Bodies

Hairs, fibres, desquamated epithelium and small food and metallic particles should comprise most of the potential foreign body hazard to the eyes in space. Although the risk of meteoroid penetration of a spacecraft cabin is extremely low (Chapter 12), it should be pointed out that fragments of meteoroid and spacecraft wall from penetration will present a particularly

great hazard to the eyes because of their great number, high velocities, high temperatures, and rough or sharp shapes.

All eye problems caused by foreign bodies are usually accompanied by pain, lacrimation, and blepharospasm. It should be pointed out that in an emergency situation, temporary relief of these symptoms can be obtained by instilling a non-allergenic topical anesthetic such as 0.5 percent "Ophthaine" in the affected eye. However, one must assume the risks associated with leaving a foreign body either trapped under an eyelid or embedded in the cornea.

The trapping of foreign bodies under the eyelids will probably be the cause of most of the eye problems which occur in space. Most foreign bodies should only produce irritation. However, some with sharp edges or corners could actually injure the cornea or conjunctiva.

Fortunately, the majority of foreign bodies which get under the eyelids, especially the lower one, are either coated with mucus and automatically worked out by tearing and lid and eye movement, or removed by the well known method of overlapping the eyelids. On the other hand, it is possible that a trained astronaut might have to evert an eyelid to search for and remove a foreign body. Before undertaking this measure, pain and blepharospasm should be relieved by instilling a topical anesthetic. A foreign body under an eyelid can be removed with a cotton-tipped applicator moistened with saline, with cilia forceps or by one of the irrigation methods to be discussed under chemical eye problems. Although foreign bodies under the eyelids are usually removed by one of the above means, an occasional particle, especially if metallic or glass, can become embedded in either the palpebral or scleral conjunctiva. In this case, it is necessary to use a needle or eye spud for removal. Finally, special note should be made always to examine the lacrimal punctae when searching for foreign bodies in the eye in space, for it is considered possible that the risk of a short hair or fibre entering the eye and then being washed into and becoming firmly fixed in a punctum might be much higher in space than on Earth.

Such foreign bodies are easily removed with suitable forceps.

Any foreign body which becomes embedded in an astronaut's cornea will probably be a small single metal particle. Multiple foreign bodies could become embedded at the time of a meteoroid penetration, however.

The cornea should always be examined if no foreign body is found on searching under the eyelids, or if many foreign bodies could have entered the eye. Detection of a small embedded foreign body can usually only be accomplished with good illumination and magnification. Since the cornea is extremely sensitive, it is always necessary to instill a topical anesthetic before attempting to remove a foreign body embedded in it. A needle or eye spud should be used for removal, and the subsequent management of this injury accomplished in the manner outlined below for non-penetrating corneal injuries.

A ring of rust or debris may occasionally remain in the cornea after removal of a foreign body. This is most likely to occur if easily oxidizable metals, such as iron or copper are left embedded for a period of time. Unless superficial and easily removable in space, rust and debris should be allowed to remain in the cornea.

A foreign body embedded in the sclera is managed in the same way as one in the cornea. However, a scleral foreign body is usually more difficult to remove because of overlying conjunctiva and hemorrhage, neither of which are a problem in corneal foreign bodies.

The majority of non-penetrating injuries inflicted on the eyes by foreign bodies involve the cornea. Non-penetrating injuries of the sclera are managed similarly to those of the cornea. Conjunctival injuries are best left untreated.

An abrasion or wound of the corneal epithelium can result from a foreign body striking but not embedding in the cornea, or by a foreign body which is under the lid and is rubbing on the cornea. The wound remaining after an embedded corneal foreign body is removed is essentially similar to an abrasion. Fortunately this injury usually heals within 24 hours unless it becomes infected.

A rough or sharp foreign body which strikes the cornea at a high velocity or is trapped under a lid and rubs against the cornea could produce a laceration which is deeper than the corneal epithelium. Healing of this wound leads to scar formation and possibly a permanent visual defect, depending on the position, size, and density of the scar.

The diagnosis and determination of the extent of a non-penetrating corneal injury should be made first by staining the cornea with fluorescein. Use of a sterile paper impregnated with fluorescein (e.g., "Fluor-I-Strip" applicators) would be more practical in the weightless space environment than fluorescein solution. Then a bacteriostatic ointment, such as 10 percent sulfacetamide ointment, should be placed in the eye and a light, dry patch applied over closed lids. In 24 hours, the cornea should be stained and re-examined, and if healing is not complete but is progressing satisfactorily, the same treatment should be repeated. Also on this occasion, 5 percent homatropine might be instilled in the eye as a preventive measure for posterior synechiae and for the relief of pain due to inflammation of the iris.

If a non-penetrating injury of the cornea should become infected, a bactericidal ointment, such as chloramphenicol or "Neosporin" ointment, should be placed in the eye every three hours. As well, 1 percent atropine should be instilled one to three times daily. If possible in space, the frequent application of heat to the affected eye is also indicated.

A foreign body could strike the cornea or sclera of an astronaut's eye with sufficient velocity, as might be attained from a meteoroid penetration or explosion, to pierce these structures and enter the globe. The severity of penetrating injuries of the eye depends upon such factors as the size, temperature and inertness of the foreign body, and the tissues which are damaged during penetration. Some foreign bodies, such as plastics, sand, and glass, are quite inert. Corrosion-resistant nickel-base berrylium and aluminum alloys, and steel alloys containing chromium, vanadium, cobalt, nickel, titanium and boron incite little or no reaction with ocular tissues, usually becoming encapsulated over a period of time. On the other hand, corrosive alloys and various pure metals, such as copper, iron, zinc, and aluminum, react to a certain degree with ocular tissues, producing an

inflammatory reaction and ultimately visual impairment and perhaps even destruction of the involved eye.

Part of the iris prolapsed through a penetrating eye wound would not only be difficult to replace but also invite infection into the eye. Whenever the lens capsule is damaged, a traumatic cataract forms, leading to an impairment of vision. Such a cataractous lens can swell and, by blocking the angle of the anterior chamber of the eye, can cause secondary glaucoma.

An inflammatory process involving the uveal tract (iridocyclitis) commonly occurs following a penetrating injury of the eye. It is characterized by deep-seated pain, photophobia, miosis and blurred vision. If the injury involves the region of the ciliary body, sympathetic ophthalmia, or a similar inflammatory process in the other eye may rarely occur, usually 2 weeks to 2 months after the injury. This extremely serious eye condition can progress on to complete loss of vision unless the injured eye is ennucleated as soon as symptoms appear in the normal eye. No other treatment is definitely effective. Some cases have been controlled with rigorous local and systemic corticosteroid therapy (1, 59).

Because the skill and special instruments of the ophthalmic surgeon are required for the removal of an intraocular foreign body and for other emergency surgical procedures on the eye, it is doubtful if such procedures, except perhaps for ennucleation will ever be carried out in space (52). Thus the risk of permanent blindness occurring from penetrating injuries will be somewhat higher in space than on Earth. It is thought that maximum possible supportive therapy may be adequate in most instances, however.

If a penetrating injury of an astronaut's eye is suspected, his visual acuity should be determined. Then his lids, sclera and cornea should be inspected for a small cut where a foreign body might have penetrated. This wound might be detected only by staining with fluorescein. It should be remembered that an eye suspected of having a penetrating injury should never be palpated and, of course, the astronaut should be warned to avoid rubbing his injured eye. Blood might be present in the anterior chamber of the eye, and the iris might be torn and the pupil irregular. Flattening

of the anterior chamber is an important sign of perforation. If x-ray facilities are ever placed on board spacecraft, every suspected case of foreign body penetration should be x-rayed.

Foreign bodies trapped under the eyelids, or embedded in the cornea or sclera should be removed. If part of the iris is prolapsed and cannot be replaced in the eye, it should best be excised with sterile scissors. Since it is thought that most penetrating foreign bodies in space will be reasonably sterile when they enter the eye, a local bacteriostatic agent might not be necessary [55]. One must keep in mind that such an agent in ointment form could itself be a dangerous foreign body if it enters the interior of the eye through the wound. However, if single or multiple foreign bodies have been removed, or other non-penetrating injuries are present, it might be wise to instill an aqueous bacteriostatic agent frequently in the eye. Prophylactic systemic antibiotic therapy is usually not indicated in such cases.

One percent atropine should be instilled every 8 to 12 hours in an eye penetrated by a foreign body, until healing appears complete and all signs and symptoms of inflammation have subsided. Both eyes should be patched except in critical operational situations when the best vision possible is required for a period of time. Except for eye examination, a local anesthetic should not be repeatedly instilled in an injured eye for the relief of pain. An analgesic or sedative will have to suffice.

An intraocular infection can result from the entry of bacteria through a penetrating wound, either at the time of or after penetration. As well as the treatment outlined above, local heat should be applied. Penicillin or a sulfonamide may be administered orally or by injection, but these drugs are frequently ineffective since they pass across the blood-aqueous barrier poorly [1, 55]. On the other hand, some success has been reported with chloramphenicol [54].

The drug of choice in the treatment of secondary glaucoma has been a carbonic anhydrase inhibitor, such as acetazolamide. Of interest is the success reported with intravenous dehydrating agents [10, 18, 23, 58, 59]. The possible potential usefulness of them in space has been discussed in Chapters 1, 2, 4, and 14. These agents are apparently effective in the

treatment of acute glaucoma of both the primary and secondary types, and may also aid in the absorption of blood out of the anterior chamber. Mannitol has been the preferred dehydrating agent. A carbonic anhydrase inhibi drug can be used in conjunction with a dehydrating agent. In some instances, especially where the glaucoma is primarily due to hemorrhage, the frequent instillation of a miotic drug, such as 1/2 to 4 percent pilocarpine, to maintain continuous pupillary constriction may be indicated. On the other hand, it may be advisable to instill instead a cycloplegic drug, such as 1 percent atropine, if severe inflammation supervenes. The selection of such drugs requires sound clinical judgment based on extensive ophthalmologic experience. Hence consultation with an Earth-based ophthalmologist will be a must if such a situation should develop in space.

Chemicals

The severity of any chemical injury of the eyes will depend on various factors, such as the type, concentration and physical nature of the chemical, and the duration that the eyes are exposed to the chemical. It should be remembered that solid reactive chemical particles can produce mechanical injuries of the eyes as well as severe local burns.

Alkaline chemicals are a much greater threat to the eyes than any other chemical [48]. The greatest degree of damage apparently occurs between pH 11 and 12 [48]. Alkalis penetrate the eye tissues rapidly, producing deep burns and all of the possible complications of severe eye burns discussed below. On the other hand, serious injuries from acids rarely occur above pH 2.5 and are often limited to the epithelium [48]. Accordingly, serious complications are less likely to occur following mild exposures to acids than to alkalis. Eye injuries caused by other classes of chemicals have been discussed by Ryan [48, 49, 50] and Grant [19].

Every effort must be directed at minimizing the use of hazardous chemicals in space and at maximizing the safety factors if such chemicals are required. The probability of carbon dioxide absorbents, such as lithium hydroxide and sodium superoxide, becoming a threat to the eyes might be greatly increased if environmental control systems require servicing in

space. These absorbents are alkalis which, as mentioned above, are extremely damaging to the eyes. As well, they tend to change from pellet to powder form as they are utilized. It is noted again that most analytical systems will employ hazardous chemicals which could be spilled at the time of replacing spent chemicals or servicing a system, or during analytical procedures.

Various degrees of injury, from a temporary mild inflammation to a severe burn of the extraocular tissues could be possible if a hazardous chemical should come into contact with an astronaut's eyes in space. A mild injury is accompanied by lacrimation, an itching or burning sensation, and blepharospasm. A severe burn is accompanied by lacrimation, burning pain, blepharospasm, and congestion, edema and possibly immediate necrosis of extraocular tissues.

Perforation of the globe is possible with deep burns. Injured eye tissues are very susceptible to infection, which would enhance the degree of damage and delay healing. Other serious early complications which may follow a seemingly mild chemical burn are iridocyclitis and secondary glaucoma.

A burn involving the subepithelial tissue of the cornea will heal by scar tissue formation and ingrowth of vascular tissue, leading to some degree of impaired vision. A severe burn of the palpebral conjuntiva can be followed by marked contraction of this tissue, resulting in inversion of the lid (entropion). A severe conjunctival burn can also lead to the formation of adhesions between the eyelids and the globe (symblepharon). Scarring of the outer surface of the lids can result in lid eversion (ectropion).

If a harmful chemical should come into contact with the eyes of an astronaut in space, his eyes should be irrigated as soon as possible with copious amounts of water or, if as readily available, isotonic saline or other more physiologic solution. Special buffering agents available for the irrigation of eye injuries, which could be produced by specific chemicals carried on board the spacecraft, might be applicable in the space situation. Irrigation is usually continued for at least 20 to 30 minutes for alkalis or other

severely damaging chemicals. For more innocuous chemicals, as little as 10 minutes irrigation may suffice.

Irrigation of an eye will be difficult in the weightless environment. However, no adequate procedure can be substituted for irrigation. It is suggested that with water-absorbing material around the eye, a suction vent near the eye, and the water or saline directed in a suitable stream at the eye, irrigation of the eye should be accomplished in space without creating a droplet hazard. An eye cup with water circulating through it might be another method of irrigation to be considered. In order to relieve pain and blepharospasm, and so facilitate irrigation under the lids, a local anesthetic can be rapidly instilled in the eye just prior to or after having started irrigation. The lids should be held open during the irrigation, so that the solution reaches all parts of the conjunctiva and cornea. In order to be assured that all chemical, particularly if in solid form, has been removed from the eye, each eyelid should be completely everted and the posterior surface of the cul-de-sac irrigated. Solid particles can also be removed from the eye with a moist cotton-tipped applicator or suitable forceps.

After irrigation, the cornea and conjunctiva should be stained with fluorescein and carefully examined, under magnification if possible, in order to determine the severity of injury and, if applicable, detect any small chemical particles which still remain in the eye. The importance of examining the under-surfaces of the lids and cul-de-sacs cannot be overemphasized.

All chemical burns of the surface of the eye should be treated with an ointment or water-soluble preparation which includes both a bactericidal agent and a cortisone derivative (e.g., "Neodeltacortef", "Neodecadron"). Authorities agree that the beneficial effect of a cortisone derivative, especially in minimizing the inflammatory reaction, and corneal scarring and vascularization, far outweighs the potential risk of this agent causing aggravation of a possible ocular viral disease. The ointment preparation and a mydriatic drug, such as 5 percent homatropine or 1 percent atropine, should be placed in the eye every 8 to 12 hours if a patch is to be applied. If the injury is mild or if the eye must be left open, a water-

soluble preparation would be preferred, instilled in the eye at least every one to 2 hours. A topical mydriatic drug is a necessity for all corneal injuries of any significant degree, for it will do much to prevent extension of corneal inflammation to the iris and ciliary body, and to prevent severe ache from iris and ciliary muscle spasm.

A dry patch should be applied to most mild and all severe chemical burns. The patch immobilizes the lids in a closed position, which tends to exclude contamination and minimize mechanical trauma. The repeated use of local anesthetics in the eye is contraindicated, for such agents can delay healing and may even increase damage. If possible in space, the local application of cold may help to prevent or reduce congestion, edema, and pain. An analgesic drug should be given as required.

One of the most common complications of chemical burns of the eye is the adherence of the palpebral to the scleral conjunctiva if they are badly damaged. The topical ointments mentioned above may prevent this adherence to some degree. However, it may be necessary to break down adherent points under local anesthesia daily with a suitable instrument such as a smooth glass rod.

The secondary glaucoma which sometimes develops after chemical burns, especially from alkaline agents, is usually very difficult to control. Foremost in the treatment of this kind of glaucoma is the administration of an oral carbonic anhydrase inhibiting drug, such as acetazolamide. A topical cycloplegic, such as 1 percent atropine, also can be used, but it seldom is effective enough to control severe glaucoma by itself. Use of miotics seems unattractive because of the possibility of increasing discomfort and allowing posterior synechiae to form [19].

Definitive treatment of complications such as corneal scarring and vascularization, conjunctival scarring and symblepharon, entropion and ectropion of the lids, and secondary glaucoma which has not responded to drug therapy, demand the skill and instruments of the ophthalmic surgeon. Hence it is doubtful if such treatment will ever be possible in space.

Predictions

Busby and Mercer have predicted what the characteristics of particle and droplet inhalation into and deposition in the respiratory tract will be in the weightless environment [8]. The medical implications to be drawn from this study, which is summarized below, serve as a basis for discussing various respiratory problems which are considered most likely to occur in space.

The first question which arose was whether or not suspended particles or droplets of sizes up to that which can enter the nasal passages or mouth can be inhaled if they come into contact with the inspiratory air stream. Air flow and particle or droplet size were related in the equation:

$$u = v\left(1 - e^{-\frac{3.42 \times 10^5 t}{d_a^2}}\right)$$

which gives the velocity, u, which a particle or droplet of aerodynamic diameter*, d_a microns, might have, t seconds after it is introduced into air flowing at velocity, v. This relationship is illustrated graphically in Figure 8.2, which shows the times required for particles or droplets of various aerodynamic diameters to reach one-half of an air velocity. From this relationship it was predicted that particles and droplets of sizes having an aerodynamic diameter less than a few hundred microns, if in the inspiratory air stream, will approach the velocity of the inspiratory air stream rapidly that for all practical purposes, the concentration and distribution of such particles and droplets which enter the nose or mouth during a normal

* "Aerodynamic diameter" of a given particle or droplet means the diameter of a sphere of unit density having the same settling velocity as the particle or droplet at room temperature and pressure.

inspiration will not be significantly different from that in the spacecraft cabin atmosphere.

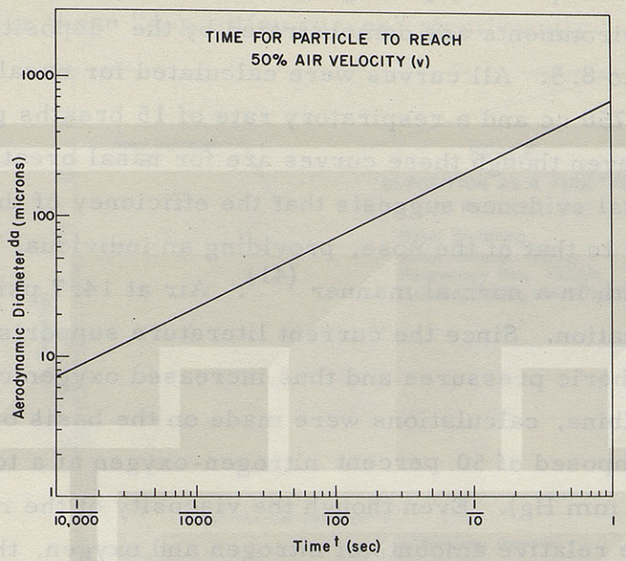

Figure 8.2 Time for Particles or Droplets of Various Aerodynamic Diameters to Reach 50% of Air Velocity (v).

(After Busby and Mercer [8])

Since gravity is a factor in determining the particle and droplet deposition in the respiratory passages, the other question which had to be answered was what the characteristics of particle and droplet deposition in the respiratory passages might be in the weightless environment. Mercer [40] had modified and extended the method first employed by Findeisen [15] to calculate values for the deposition of various aerodynamic diameter particles or droplets in the respiratory passages in the Earth (unit gravity) environment, and had shown that these values compared quite favorably with available experimental data. To consider the analogous situation that would exist in the space (weightless) environment, it was only necessary to discount in such calculations that contribution made to deposition by sedimentation, which is due to gravity.

The characteristics of aerodynamic diameter particle or droplet deposition in the respiratory passages in the Earth (unit gravity) and space (weightless) environments are demonstrated by the "deposition curves" in Figures 8.3 to 8.5. All curves were calculated for nasal breathing, a tidal volume of 750 cc and a respiratory rate of 15 breaths per minute. It is noted that even though these curves are for nasal breathing, available experimental evidence suggests that the efficiency of the mouth as a filter is similar to that of the nose, providing an individual breathes through his mouth in a normal manner [41]. Air at 14.7 psia is breathed in the Earth situation. Since the current literature supports the use of reduced atmospheric pressures and thus increased oxygen concentrations in spacecraft cabins, calculations were made on the basis of an inhaled gas mixture composed of 50 percent nitrogen-oxygen at a total pressure of 7.0 psia (362 mm Hg). Even though the viscosity of the respired gas is altered by the relative amounts of nitrogen and oxygen, the effect of this change on the "deposition curves" appears to be negligible [41].

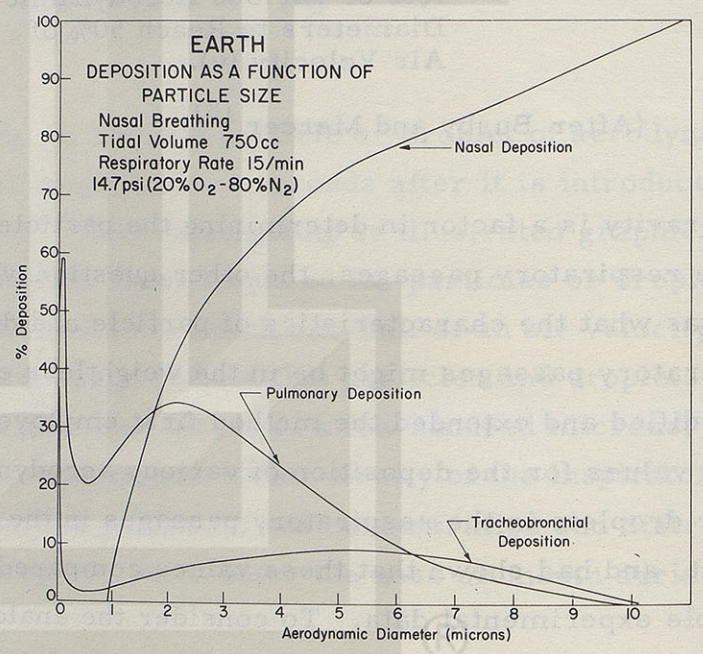

Figure 8.3 Deposition as a Function of Particle or Droplet Size in the Earth (Unit Gravity) Environment.

(After Busby and Mercer [8]).

As well, it is believed that the substitution of helium or another inert gas for nitrogen would alter viscosity by only a few per cent, and hence should not alter these "deposition curves" significantly.

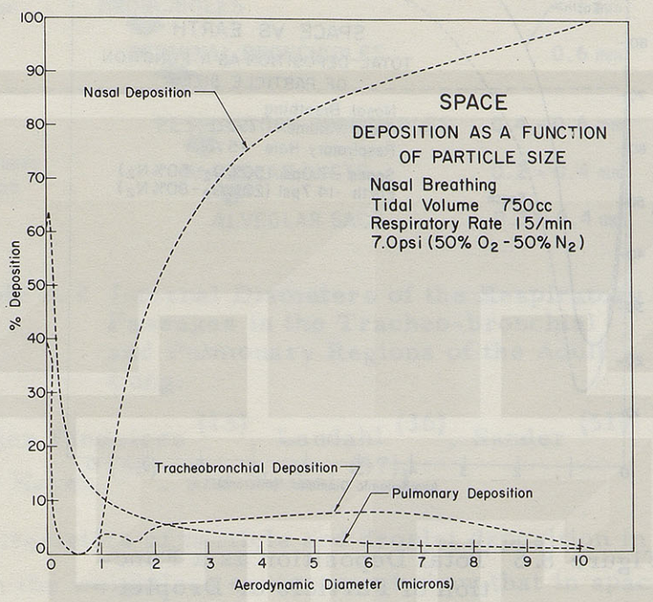

Figure 8.4 Deposition as a Function of Particle or Droplet Size in the Space (Weightless) Environment.

(After Busby and Mercer [8]).

For considerations of the pattern of deposition, the respiratory tract was divided into nasal (or nasopharyngeal), tracheobronchial and pulmonary regions. The subregions of the airways and their dimensions are shown in Table 8.2. The tracheobronchial region includes all the ciliated airways (including the larynx), which are assumed to terminate at the distal ends of the terminal bronchioles. The pulmonary region includes the distal respiratory passages such as the respiratory bronchioles, and alveolar ducts and sacs. It is also pointed out that in the discussion which follows, the term "upper respiratory passages" refers to the nasal (or oral) regions of the respiratory passages, and the term "lower respiratory passages" refers to the tracheobronchial and pulmonary regions.

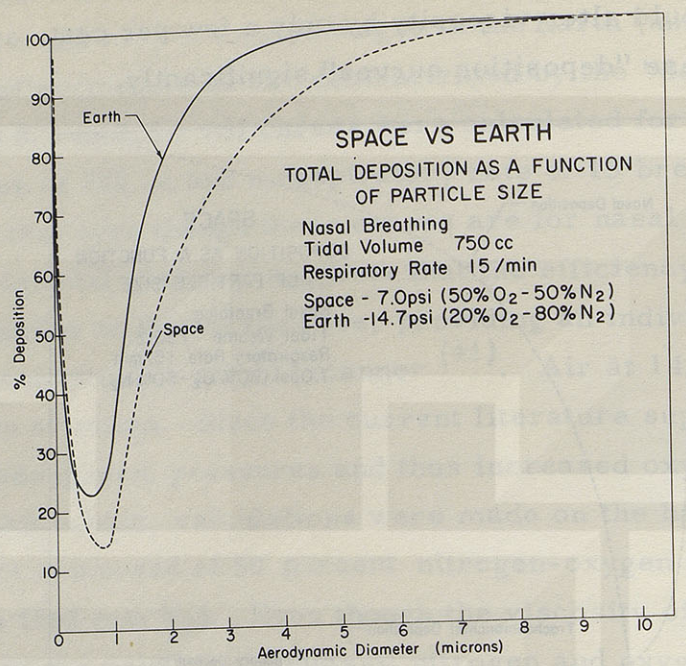

Figure 8.5 Total Deposition as a Function of Particle or Droplet Size in the Earth (Unit Gravity) and Space (Weightless) Environment.

(After Busby and Mercer [8]).

A number of medical implications can be drawn from these predictions of the characteristics of particle and droplet inhalation into and deposition in the respiratory passages in the weightless environment. It is assumed here that all particles and droplets will tend to follow the same predicted pattern of inhalation into and deposition in the respiratory passages that would be expected to standard "aerodynamic diameter" particles.

The tendency for particles and droplets to remain suspended in the weightless environment and the predicted characteristics of particle and droplet inhalation into the respiratory passages in the weightless environment imply that the amount of particle or droplet contaminant which an exposed astronaut might inhale could be markedly increased, possibly by several orders of magnitude, over the amount that can be inhaled if the same contaminant is introduced in a similar situation into a unit gravity environment. The

	TRACHEA (transverse 25% greater than saggital)	13 - 22 mm
Tracheo-bronchial Region	BRONCHI	main - 7.5 - 12.5mm
	BRONCHIOLES	< 1 mm
	TERMINAL BRONCHIOLES	0.6 mm
Pulmonary Region	RESPIRATORY BRONCHIOLES	0.4 - 0.6 mm
	ALVEOLAR DUCTS	0.2 - 0.4 mm
	ALVEOLAR SACS	0.3 - 0.4 mm

Table 8.2 Internal Diameters of the Respiratory Passages in the Tracheo-bronchial and Pulmonary Regions of the Adult Lung.

(After Findeisen [15], Landahl [36], Sander [51], von Hayek [56], and Weibel [57]).

predicted characteristics of particle and droplet deposition in the respiratory passages in the weightless environment show that in space, as on Earth, the nose or mouth should continue to operate as highly efficient filters, protecting the lower respiratory passages from all particles and droplets above about 10 microns in diameter. Fortunately, this size is considerably less than that of particles and droplets of most of the aforementioned contaminants which might be introduced into the spacecraft cabin atmosphere. In this respect, it should be pointed out that the use of powdered chemicals of particle sizes greater than 10 microns in space would be an important safety measure.

It must still be considered possible, however, for an astronaut to be exposed to particles (e.g., aggregates of smoke and fume particles) and droplets (e.g., liquid ejected as a fine spray) less than about 10 microns in diameter. The "deposition curves" predict that fewer inhaled particles and droplets between about 0.5 and about 10 microns in diameter will be deposited in the lower respiratory passages, especially in the pulmonary region, in the weightless as compared to the unit gravity environment. This implies that weightlessness might offer some protection to an astronaut from

certain contaminants which, if inhaled in a similar concentration in a unit gravity environment, would be irritating to or damage alveoli and respiratory bronchioles, or produce systemic toxic effects by being absorbed. It is of interest to note that weightlessness exerts its greatest protective effect in the pulmonary or non-ciliated region of the respiratory passages -- a region where deposited contaminants are not moved out of the respiratory passages by ciliary action. This predicted decrease of particle and droplet deposition in the pulmonary region in the weightless as compared to the unit gravity environment implies that the concentration of particles and droplets one micron in diameter inhaled into the respiratory passages in the weightless environment could be approximately doubled before the percent deposition of such contaminants in the pulmonary region in this environment would be equivalent to their percent deposition in the unit gravity environment. Similarly, the inhaled concentration of particles, and droplets could be increased by approximately 6 times for particles and droplets 2 microns in diameter, 7 times for those 3, 4, and 5 microns in diameter, 6 times for those 6 microns in diameter, 5 times for those 7 and 8 microns in diameter, and 3 times for those 9 microns in diameter. However, even though it is predicted that the pulmonary deposition of inhaled particles and droplets between about 0.5 and about 10 microns in diameter will be significantly reduced in the weightless environment, one must remember that such contaminating particles or droplets could still be suspended in a concentration which would be harmful.

Since the weightless environment does not alter the high percent deposition of particles and droplets below about 0.5 microns in diameter in the lower respiratory passages, the consequences of inhaling such contaminants will not be different in the weightless as compared to the unit gravity environment. Contaminants of this size are most likely to be in the form of fumes or smoke. Since particles or droplets below 0.9 microns in diameter will apparently not be deposited in the nasal (or oral) regions of the respiratory passages, their inhalation should not produce clinical problems in the upper respiratory passages. On the other hand, because of the very high percent deposition of particles and droplets below about 0.5 microns in diameter, tracheobronchial and pulmonary tissues could be severely irritated

or damaged.

From the equation which illustrated the relationship between air flow and particle size, Busby and Mercer concluded that the concentration and distribution of particles and droplets of diameters up to a few hundred microns which will enter the nose or mouth in the inspiratory air stream will not be significantly different from that in the spacecraft cabin atmosphere [8]. Whether or not particles or droplets larger than a few hundred microns in diameter (e.g., several hundred microns to 1 cm) can be inhaled will depend less on particle and droplet size, and more and more on such important factors as particle or droplet shape and density, their spatial relationship to the inspiratory air stream and mouth and nasal openings, their velocities and directions of movement relative to an astronaut, the velocity-time profiles of the inspiratory and expiratory air streams, and the duration of the pause between inspiration and expiration. Taking all of these factors into consideration, it is predicted that various particles, especially those of low density particles, and droplets of possibly up to 1 cm in diameter, could be inhaled in the weightless environment. Accordingly, it is thought that as compared to on Earth, an astronaut in space might run a somewhat higher risk not only of inhaling large particles and droplets into his nose and mouth, but also of aspirating large particles and droplets into his lower respiratory tract. For aspiration to occur, it must be assumed that normal mechanisms, such as coughing, swallowing and reflex glottic closure, which exclude large particles impacting in the oropharynx from the larynx might not always be effective, especially if an astronaut should inhale several large particles or droplets at one time or if his exposure to and inhalation of the contaminant occurs unexpectedly. An inspiratory gasp, which produces high air velocities, might occur from an astronaut being "startled" or "stimulated" by an inhaled contaminant and could, therefore, increase the risk of the contaminant being aspirated. Because a much larger particle or droplet can enter and pass through the mouth than the nasal passages, aspiration is much more likely to occur if an astronaut is

breathing through his mouth.

Acute Chemical Inflammation of the Upper Respiratory Tract

The inhalation into the nose of a particulate chemical, such as lithium hydroxide or a superoxide used in environmental systems, or a liquid chemical, such as an acid or alkaline reagent used in an analytical system, could lead to a severe non-specific inflammation of the sensitive lining of the nose and pharynx, or so-called acute chemical rhino-pharyngitis. Considered much less likely to occur following inhalation of a chemical, severe chemical inflammation of the lining of the mouth is managed in a similar fashion to that of the nose.

The initial response to a chemical deposited in the nose is vasoconstriction. This is accompanied by symptoms ranging from an itching-burning sensation to severe pain. Within minutes, however, vasodilatation occurs. The hyperemic nasal mucosa rapidly becomes edematous and secretes a watery fluid. This response can manifest clinically as a feeling of fullness or tightness in the nose and sinus regions, nasal obstruction, a profuse watery discharge, a "sore throat", lacrimation and continued sneezing. The lining of the nose and pharynx can undergo some degree of localized or diffuse, immediate or delayed necrosis, particularly if larger chemical droplets or particles are inhaled. In this case, the nasal discharge is in the form of an exudate, which is opaque and viscous. It can be blood-streaked and contain pieces of necrotic intranasal tissue. Frank nasal and pharyngeal bleeding may occur up to several days after the incident.

The most common sequela of acute chemical rhino-pharyngitis is secondary infection of the damaged nasal and pharyngeal lining. The nasal discharge becomes purulent and remains so until the continuity of the ciliated epithelium is restored. Severe infections are usually accompanied by fever and general malaise. The remote possibility of secondary bacterial invaders producing disorders of serious consequence, such as sinusitis, otitis media, mastoiditis, meningitis, osteomyelitis, and brain abcess, should be kept in mind.

The treatment of acute chemical rhino-pharyngitis has been suggested by Fischer [16] and Kilgore [33]. As soon as possible after inhaling a

chemical into his nose, an afflicted astronaut should use any method possible to irrigate his nose and pharynx. Water or, if available, isotonic saline or any other isotonic solution should be flushed in and out of his nose and gargled. Irrigation should be continued for several minutes or until the initial irritation has subsided. It might be carried out for many minutes if he inhales large particles which could be impacted in his nose.

It is debatable as to whether or not to instill immediately a potent, rapid-acting, topical vasoconstrictor, such as 1/1000 epinephrine, in a chemically-inflamed nose. On the one hand, such an agent would, by shrinking the nasal lining, allow better nasal irrigation and possibly less absorption of a toxic chemical into the body. On the other hand, one must keep in mind the damage which would be incurred by a chemical while waiting for a vasoconstrictor to take effect. Accordingly, it is thought that vasoconstriction should be attempted after some irrigation has been carried out.

As will be pointed out in the discussion of acute chemical inflammation of the lower respiratory tract, steroid drugs appear to have an excellent anti-inflammatory action on the respiratory tract mucosa. Therefore, it is suggested that suitable steroid preparations be administered as indicated both intravenously (e.g., hydrocortisone sodium succinate) as soon as possible after an astronaut inhales a chemical agent, and instilled in his nose (e.g., 1 percent hydrocortisone acetate) after irrigation. An oral steroid (e.g., methylprednisolone) might be given for several days to serious cases.

Control of nasal bleeding secondary to chemical damage can usually be accomplished without any special treatment or with the very simplest of measures. Since bleeding is most likely to occur from the anterior part of the nasal septum, a cotton pledget should be placed in the front of the nasal cavity and pressure applied to the nose to compress it against the septum. Soaking the pledget with a vasoconstrictor, such as 1/1000 epinephrine, or the local application of a hemostatic agent, such as "oxycel", "gelfoam" or topical thrombin might be required to arrest bleeding. Finally, nasal packing is a specialized procedure which is rarely required for persistent nasal bleeding [6].

If the lining of the nose has been extensively denuded by a chemical, the raw surfaces should be covered with petrolatum gauze to prevent the formation of adhesions. This dressing should be changed every 2 to 3 days until the areas are re-epithelialized. A suitable broad spectrum antibiotic should be administered by the oral or intramuscular route if infection of damaged nasal or pharyngeal tissues occurs. Finally, it should be noted that an analgesic or sedative drug might be required by a serious case of acute chemical rhino-pharyngitis.

Intranasal Foreign Body

An astronaut could inhale a non-chemical particle which, because of its size and shape, might become impacted in the nasal cavity rather than being expelled by sneezing or escaping in secretions. Food, metal and plastic particles are examples of such possible foreign bodies.

A small smooth foreign body in the nasal cavity could give little or no discomfort (29). As a result, its presence might remain undetected until ulceration of the nasal mucosa occurs from mechanical and possibly some chemical irritation. The clinical manifestations of mucosal involvement may appear from days to weeks after the foreign body enters the nose. They are characterized at first by a unilateral serous discharge, then an odorous, purulent discharge. Blood streaking of the discharge or frank bleeding could occur.

No foreign body should be allowed to remain in an astronaut's nasal cavity, for it could produce necrosis and secondary infection of nasal tissue or be aspirated into his lower respiratory tract (6). With good illumination and a nasal speculum, either the foreign body itself or an accumulation of secretion at its site of location will be seen. Better visualization and possibly facilitated removal of the foreign body might be accomplished by shrinking the nasal mucosa with a topical vasoconstrictor, such as 1/1000 epinephrine (29). The majority of foreign bodies in the nasal cavity should be located in the anterior part of the nasal cavity or in the inferior meatus along the floor of the nose. If ever possible in space, an x-ray of the nasal passages for the location of a foreign body might on occasion prove useful.

An intranasal foreign body can be removed using an open-ended suction tip or cotton-tipped applicator, a blunt bent probe and a suitable forcep, such as an alligator forcep. Care must be taken to avoid pushing, or having an astronaut inadvertently suck a foreign body into his pharynx, from which the foreign body might be aspirated. Measures which might be taken to control secondary bleeding are discussed above. A suitable broad spectrum antibiotic should be administered as indicated for infection.

Aspirated Foreign Body

The aspiration of a non-chemical particle into the lower respiratory tract in space can lead to a number of serious clinical problems which have been discussed so well in the vast literature on this area. Particular reference is made to the excellent reviews of Jackson and Jackson [28, 29, 30], Hollinger [24, 25, 26, 27] and other authors [3, 7, 9, 13, 14, 17, 38, 39, 42, 43, 45] for greater detail than that to be presented below.

Generally speaking, both the clinical manifestations produced by an aspirated foreign body and the times of appearance of these manifestations are highly variable, depending in most cases on the site where the foreign body lodges, the degrees of primary obstruction and irritation that it produces, and the length of time that it remains in the lower respiratory tract. These factors are determined in readily apparent ways by the size, shape, and chemical activity of the foreign body. It is also possible that an aspirated foreign body in space could be microbiologically contaminated, and thus serve as a nidus for infection.

In the light of the above considerations, it is understandable how a non-irritating, non-obstructing foreign body such as a smooth particle of an inert metal, glass, or plastic can remain lodged for months to years in the lower respiratory tract without giving rise to clinical manifestations [5, 21, 44]. In the majority of instances, however, the consequences of obstruction of the laryngeal, tracheal, or bronchial passages by a foreign body ensue. Signs and symptoms may appear immediately if obstruction of a passage is complete. They may present after a quiescent period of days to weeks during which, through mechanical and chemical irritation, the foreign body causes

localized mucosal swelling that perfects the occlusion of the passage. Characteristically,the delayed periods are shortest in cases of aspirated vegetal foreign bodies, for all vegetal substances irritate the respiratory tract mucosa by chemical action, producing a violent laryngotracheobronchitis and obstructive swelling (14). On the other hand, clinical manifestations from aspirated metallic foreign bodies often take many weeks to many months to appear, even if these foreign bodies are initially rough and obstructive or become so by corrosion, or produce some chemical irritation through corrosion.

A foreign body in the larynx of an astronaut will produce paroxysms of violent coughing, gagging, choking and wheezing. An obstructing foreign body may cause immediate death unless coughed out. Lodgment of a non-obstructing foreign body can produce any one or more of the following signs and symptoms: hoarseness, croupy cough, stridor, wheezing, dyspnea, pain, aphonia, hemoptysis, and a subjective feeling of the presence of the foreign body in the larynx. Often a small non-obstructing foreign body may become asymptomatic for a period of time. Any foreign body remaining in the larynx is potentially dangerous, however, for secondary inflammation can produce fatal edema of the larynx, and secondary infection can destroy laryngeal tissues and lead to grave consequences by spreading out into the tissues of the neck and down into the mediastinum.

The presence of a foreign body in an astronaut's larynx is in most cases apparent from his history alone. Confusing the diagnosis, however, might be laryngeal symptoms persisting from trauma caused by a foreign body that has passed on into deeper respiratory and food passages, or by one that has been coughed out. Therefore, indirect laryngoscopy and rarely, if possible on board the spacecraft, an x-ray are required for confirmation. Since direct laryngoscopy requires special skills and instrumen and often general anesthesia, this procedure is not considered possible in space in the foreseeable future. It should be remembered that a foreign body which is not found in the larynx could be resting temporarily in deeper respiratory passages without producing symptoms.

A non-obstructing foreign body in the larynx is usually coughed out

within minutes. The simplest maneuver, such as a slap on the back during an expulsory effort, may sometimes assist to dislodge a foreign body [38]. If an astronaut's larynx is obstructed or suffocation is threatening, an immediate tracheostomy must be performed. It is pointed out that if this surgical procedure cannot be performed immediately, life-sustaining ventilation of the lungs can be achieved temporarily by inserting a large-bore needle (e.g., 16 gauge needle) through the cricothyroid membrane. If efforts at expelling a foreign body are unsuccessful, it should be withdrawn as soon as possible with suitable forceps and indirect laryngoscopy. This procedure is rendered comparatively easy if a suitable topical anesthetic, such as 10 percent cocaine or 2 percent xylocaine, is applied to the laryngeal mucous membrane, epiglottis and base of the tongue prior to attempting removal. It is possible that disimpaction and possibly removal of a foreign body might be carried out by way of a tracheal wound previously made for the relief of airway obstruction. Extreme care must be taken to prevent a foreign body in the larynx from being dislodged during removal and entering the deeper respiratory passages. Other possible measures in the treatment of a foreign body in the larynx in space are supportive. A broad spectrum antibiotic may be indicated if infection ensues. If the foreign body cannot be removed in space, a more permanent tracheostomy might be required until direct laryngoscopic removal can be performed on Earth. Measures might be needed for post-hypoxic cerebral edema resulting from the temporary asphyxia (Chapter 1).

Usually a foreign body in the trachea initially produced paroxysms of coughing as well as one or more of the following manifestations: a chronic cough, hoarseness, dyspnea, cyanosis, and a slapping feeling on inspiration and expiration. A large foreign body may completely obstruct the trachea and, in spite of possible immediate attempts to remove the foreign body through a tracheostomy wound, may cause death in a few minutes. A foreign body remaining in the trachea is potentially dangerous. Irritative inflammation, especially from vegetal foreign bodies, can result in fatal obstructive swelling or severe laryngotracheobronchitis. Secondary infection may produce a fatal mediastinitis or pneumonitis.

If elicited, a history of initial choking, gagging, and wheezing will be helpful in the diagnosis of a foreign body in the trachea. The pathognomonic signs of a foreign body in the trachea are an "audible slap" heard at the mouth and a "palpable thud" felt over the larynx, created as the foreign body is trapped at the larynx by the vocal cords during a cough or forced expiration (28, 29, 30). A wheeze is usually heard when the foreign body lodges somewhere in the trachea and becomes stationary. If ever possible on board the spacecraft, an x-ray might make or confirm the diagnosis.

A non-obstructing foreign body in the trachea is often coughed out within minutes. This might even be more the case in the absence of gravity which tends to pull a foreign body back down into the trachea. The removal of a tracheal foreign body should be attempted immediately through a tracheostomy wound if it is obstructing or threatening suffocation. Bronchoscopic removal is a highly skilled procedure which will probably not be performed in space in the foreseeable future. Removal of a tracheal foreign body might be attempted through a tracheostomy wound if expulsory efforts fail and if it is thought that disastrous sequelae could occur prior to returning to Earth. Otherwise, only supportive forms of therapy, such as a broad spectrum antibiotic for infection and an antitussive agent for chronic cough, might be given. Measures might also be required for post-hypoxic cerebral edema resulting from temporary asphyxia (Chapter 1).

The initial symptoms produced by a foreign body in a bronchus are coughing, asthmatoid wheeze and others mentioned above. At once or after a symptomless interval, a productive cough, blood-streaked sputum, metallic taste, odor of the foreign body, fever, and malaise may be present due to decomposition of the foreign body and the pathologic sequelae it produces. As was pointed out above, non-obstructing relatively inert foreign bodies can be asymptomatic for weeks, months, or even years. On the other hand, obstruction of a bronchus is followed by atelectasis of the portion of the lung supplied by the bronchus, after which suppurative manifestations such as lung abcess, empyema, bronchiectasis, and pneumonia might ensue. Such sequelae can also result from prolonged partial obstruction

from swelling of the mucous membrane or growth of granulation tissue at the site of the foreign body [42]. It is pointed out again that vegetal foreign bodies are markedly irritating by chemical action. They produce a violent laryngotracheobronchitis with signs and symptoms of toxemia, cough, dyspnea, cyanosis, and irregular fever. Finally, a sharp foreign body or one that produces an obstructive emphysema can cause a disruption of pulmonary structure, with complications such as a sudden pneumothorax, mediastinal emphysema extending often into the neck, or acute mediastinitis being possible [17, 39].

The diagnosis of a foreign body in a bronchus of an astronaut will in most cases be made from the initial symptoms and the physical findings to be outlined below. Occasionally, however, the diagnosis might only be based on a high index of suspicion and a careful history, for manifestations produced by the foreign body may not appear until long after an episode of choking or coughing, at which time the possibility of a foreign body passing into a bronchus was not considered. If ever possible in space, an x-ray would be valuable not only in making or confirming the initial diagnosis but also for diagnosing sequelae and the response of these sequelae to therapy. The physical signs will vary with the conditions present in different cases and at different times in the same case. Secretions, both normal and pathologic, may shift from one location to another. The foreign body may change position, admitting more, less, or no air into a lung or lung segment. It may shift to a new location in the same lung or even in the other lung. The signs of diagnostic importance are chiefly those of partial or complete bronchial obstruction. They are classically described as follows [29, 30, 42]:

> If obstruction is partial, there is usually a persistent sonorous rhoncus, more conspicuous during expiration. In cases with equal air entry and air exit past the site of the obstruction, a rhoncus and occasionally a small patch of rales over the position of the foreign body may be the only signs. In cases with inadequate air entry but adequate air exit, partial collapse of the lung occurs, associated with dullness, diminished breath sounds and rales. In cases with adequate air entry but inadequate air exit, obstructive emphysema is produced, with hyper-resonance and diminished breath sounds being noted over the involved lung.