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Cold injury

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COLD INJURY

A Review of Recent Literature

by

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I. INTRODUCTION

Frequently I have been asked why I chose the subject - cold injury - as a topic for my senior thesis. My colleagues who pose the question express surprise that this injury could be sufficiently interesting to warrant the effort required for the preparation of a thesis. Although the problems of cold injury have received little attention in our medical school curriculum, my interest has been stimulated by the avocation, mountaineering.

While one is employed during the summer in the high country of the front range of the Rocky Mountains, the natural beauty of alpine life subtly stimulates a desire to climb to the summit of surrounding snowcapped peaks. As one ascends an increasing number of these peaks, it becomes necessary to master the techniques of rock climbing and of manuevering on snow and glaciers. In this setting, inevitably, mountaineers are born.

Part of the appeal of mountaineering lies in overcoming the hazards imposed by Nature on one's climb to the summit. Of these, unexpected variations in climatic conditions pose a major threat to survival. Above the tree line, about 11,000 feet in the Colorado Rockies, near freezing or subfreezing temperatures predominate

year 'round. The possibility of cold injury looms as a major concern to a climber.

A thorough understanding of cold injury--its cause, pathogenesis, and relation to other metabolic factors--is necessary in order to provide maximal protection against the consequences of local and systemic cooling. With this conviction, and a desire to practice in a mountain community, the subject of cold injury evolves as an area of personal and future professional interest.

II. CLASSIFICATION AND CLINICAL PICTURE

Cold injury is a collective term applied to trauma resulting from exposure to cold with similar clinical and pathologic manifestations.[13] The failure of treatment regimes to minimize the extent of damage resulting from cold injury can be related to misunderstanding or miscomprehension of the pathophysiology produced by the injury.

Names have been assigned to varieties of cold injury based retrospectively on the circumstances of the injury. Terminology employed reflects variations in the length of exposure and in the cooling environment.

Acute Pernio. Acute pernio, or acute chilblain is, in northern temperate climates, one of the most commonly encountered of the cold injuries. Women are more prone than men due to exposure of the legs by knee-length skirts. In windy, subzero temperatures, red-blue inflammatory areas appear on one or both legs causing mild discomfort at the time of exposure. When rewarmed, an intense burning or itching sensation may persist for several hours, and usually regresses completely.

Chronic Pernio. Chronic pernio (chilblain) is a rare and confusing disease which can mimic several other more common diseases. Women are more commonly afflicted

than men, and complain of ulcerating, reddened, recurrent lesions on the anterior and posterior surfaces of their legs. The lesions initially appear with the onset of cold weather, and usually clear during the warmer months.[26]

At first, reddened areas appear on the skin with metamorphosis into painful superficial blisters. Ulcers result with little or no drainage. Brownish pigmentation frequently remains after a healing process of three to five weeks. In prolonged cases the lesions may not clear in the summer, and chronic leg ulcers persist.[26]

Immersion Foot. Exposure to cold water for days or weeks at air temperatures above freezing, results in "immersion foot."[41] Cessation of exposure results in a prehyperemic stage with anesthesia during rewarming, followed by extreme edema.[14] Anhydrosis and hyperemia follow in several hours, and paresthesias develop as anesthesia disappears. This stage may last from hours to days, and is succeeded by hypersensitivity to cold.

Freezing temperatures are not required in order to produce gangrenous changes, if exposure has been sufficiently prolonged.[39] Necrotic tissue is eventually shed revealing highly sensitive, hyperemic, cutaneous tissue underlying. Muscle wasting has also been noted.

Trenchfoot. Exposure to moisture at or near the

freezing point for a period of one to many days results in "trenchfoot," a term coined in World War I years when this injury was frequent among soldiers encamped in trenches and foxholes for days or weeks.[26] The injury is associated with immobility, dependency, and wet-cold exposure. As in immersion foot, a prehyperemic stage with edema, anesthesia, and anhydrosis are characteristic following cessation of exposure. Paresthesias and prolonged cold sensitivity result, with superficial gangrene a frequent complication.[41]

Many authorities do not distinguish between immersion foot and trench foot, and clinical distinction cannot be made. The injuries differ only in conditions of exposure.

Frostbite. Frostbite involves actual solidification of exposed tissue that has been chilled below its freezing point.[12] Superficial frostbite renders the part white with exterior solidification. Tissue below skin surface remains soft and compressible. After rewarming, the tissue becomes hyperemic and edematous with purple to blue discoloration. Anesthesia subsides and burning paresthesias develop with blister formation in outer skin layers within 24 hours. The blisters become hard and black, subsiding in about two weeks. Paresthesias may persist for several weeks, and as

swelling subsides, the involved skin peels away. Underlying areas remain red, tender, and very sensitive to even mildly cold temperatures.

Deep frostbite involves not only skin and subcutaneous tissue, but also may freeze underlying muscle, nerves, blood vessels, and bone in severe cases. The deepest injury is accompanied by the formation of large blisters which take several days to weeks to develop. Initially the affected part is waxy white, solid, and with a consistency of wood or metal. Bluish discoloration and immobility of the digits during the first few days are associated with aching, burning pain which persists for weeks. The blisters blacken, dry, and slough, often as a complete cast of the involved part. Swelling persists for a month or more.

Frequently permanent deep tissue loss ensues, and is heralded by characteristic skin changes. The skin takes on a dirty gray color, remains cold, and does not become red and blistered. Mummification ensues with a transitional zone of hyperemia demarcating dead and adjacent swollen, but healthy tissue. Autoamputation of dead tissue will result in time with a maximum of healthy tissue being spared unless infection complicates the injury.[12]

III. HEAT EXCHANGE AND COLD INJURY

Body temperature is the metabolic resultant of heat production and heat loss. When physiologic balance exists, core temperature is maintained at 37.5°C. In the extremities, a relatively large skin surface area and a generous vascular bed near the skin surface favor heat loss in excess of the amount conveyed peripherally by the blood flow and produced by local tissue metabolism. Differences in core and peripheral temperatures increase progressively upon exposure to cold. Cold injury is therefore likely to occur under conditions favoring heat loss from the skin of the extremities, and/or inhibition of heat production within the body. Susceptibility to cold injury varies with individuals. Acclimatization and training can modify the individual susceptibility, and alterations in peripheral blood flow play a role in acclimatization to cold.[14, 26, 41]

Examples of variations in susceptibility to cold can be drawn from contemporary scenes. Alcoholics are relatively frequent victims because of extended inadvertent exposure to cold while inebriated.[12] Cold injury plagues winter military campaigns in frigid climates. Air crews exposed to freezing temperatures at high altitudes in noninsulated planes have suffered permanent

frostbite injury.[41] On the other hand, natives of cold, rugged climates, such as Eskimos and Tibetans, seem to become acclimated to cold. They tolerate cold much more readily than outsiders. Balti porters have walked barefoot through Himalayan snow for hours, at altitudes of 13,000 - 16,000 feet without visible injury or discomfort. Many experts insist that this "resistance" is the result of experience, and even though the porters do not feel cold as readily as others, their tissues will freeze, as others do, in similar contact and exposure situations.[41]

Heat is dissipated from the body surface by means of convection, conduction, and radiation. The integrity of the skin and the rich subepidermal capillary bed is vital to heat removal in order to sustain caloric balance. Any alteration in blood flow decreasing perfusion of the peripheral capillary bed will upset caloric balance in favor of heat loss and increase the probability that exposure to cold will produce injury. Thus, a number of common denominators abetting the possibility of cold injury can be identified.

A diminished blood flow results from both a decreased effective blood volume, as in shock, and a reduction in circulation time, as in heart failure. Fatigue and malnutrition decrease general caloric production capacity to

dangerous levels. Hypoxia, resulting from either cardiopulmonary disease or increased metabolic demands at high altitude, produces general symptoms of body fatigue and cerebral impairment. Prolonged hypoxia results in malaise, anorexia and poor dietary intake, a relative anemia, and a marked increase in ventilatory exchange leading to further heat loss.[6, 41]

For years it was assumed that serious cases of frostbite at high altitudes were the result of changes in blood composition secondary to a reduction in atmospheric pressure. Repeated studies indicate that this assumption is not valid. Increased red cell concentration--secondary polycythemia--following lengthy stays at high altitudes does not increase blood viscosity, nor does it slow capillary circulation.[41] There has been no correlation between levels of cold agglutinins in the blood and individual susceptibility to cold injury.[21]

Environmental temperature and length of exposure are the primary factors resulting in cold injury. Other factors influencing surface heat loss can be cited, all of which hasten cooling by accelerating body heat dissipation. Inadequate clothing does not provide the insulating layers of warm air at body surface necessary for protection. Constrictive clothing, particularly gloves and footwear, diminish circulation. High winds rapidly disperse body

heat by convection. Contact with efficient conductors of heat--cold water and cold metal--results in rapid heat loss. Mountaineers have incriminated metal crampons as a necessary evil. They provide sure footing on snow and ice, but greatly increase heat loss from the feet.[38] Many persons have inadvertantly laid wet hands on metal in freezing temperatures only to have them stick immediately --actually frozen to the metal surface. Too hasty removal without rewarming results in painful separation of one's self from frozen skin.

IV. PATHOGENESIS OF NONFREEZING COLD INJURY

The extent of tissue injury as a result of exposure to a cold environment is the product of exposure time and the temperature attained in the tissues.[20] When tissue injury occurs, there are no histologic differences that distinguish the source of the injury.[3, 21, 32] However the mechanisms of injury in freezing and nonfreezing exposure are sufficiently dissimilar to warrant discussion.

The primary factor in nonfreezing cold injury is pathologic alteration of the peripheral circulation to the involved tissues. Normal peripheral circulatory flow is dynamically changing in response to fluctuating tissue demands. Peripheral arterioles and venules are sheathed by involuntary muscle, and are interconnected by means of precapillary "shunts." In these arteriovenous anastomoses, a muscular sheath exists but is quite thin. Capillaries have no muscular layer. They consist of a single layer of flat endothelial cells, this lining containing minute pores through which O_2, CO_2, and metabolites may pass. Arteriolar muscle fibers are innervated by the adrenergic system and respond to stimulation by contracting, thus narrowing arteriolar caliber and decreasing peripheral flow.

Peripheral flow through capillary beds is regulated by precapillary sphincters, consisting of a minute ring of muscle cells at the capillary origins which expand and contract rhythmically according to tissue demands. Consequently, peripheral blood flow to a given area is changing constantly. Only segments of this vast network are open at any one time.

This complex system is controlled by the nervous system, by endocrine gland hormones, and by chemical substances liberated from the peripheral tissues served by the vascular bed. The adrenergic nervous system directly controls arteriolar caliber. Corticosteroids are essential for the maintenance of vascular tone and integrity. Epinephrine produced by the adrenal medulla and norepinephrine produced by nerve endings are potent constrictors of all vessels but the coronaries. Acetylcholine produces relaxation of vascular muscle fibers.[42]

Peripheral tissues could be capable of regulating their own blood supply by employing the principle of the "feedback mechanism." As metabolic rates increase, products of cellular metabolism, which have not been specifically identified, accumulate near precapillary sphincters and decrease the capacity of this muscle to respond to stimuli and maintain their tone. As the sphincter relaxes, blood flows through the capillaries.

The mechanism becomes self limiting as nutritional requirements are met, and regulating substances are decreased in concentration. Sphincter muscle regains its tone and flow diminishes.[35, 42]

Such a vasoactive substance, produced by peripheral tissues has been identified. Bradykinin, a polypeptide, is believed to function as a regulator of local blood flow, and because it is rapidly inactivated by blood and lymph, its activity is largely restricted to the tissues in which it is formed. The highest concentrations of bradykinin are found in glandular tissue which may be able to control their own blood supply independently of the nervous system. Bradykinin has five principal pharmacologic activities which include slow stimulation of smooth muscle, vasodilation, increase of capillary permeability, stimulation of leukocyte migration, and pain production.[27]

Physiologic effects of uncomplicated cold have been extensively reviewed by Montgomery.[28] These effects can be separated into two broad categories: the reduction of circulation due to cold, and biochemical effects of cold per se.

The first local response to cold is vasoconstriction. Lewis divides this response into three overlapping steps: a direct reaction of superficial vessels to cold,

transient vasoconstriction secondary to reflex action, and a central reaction to cooled venous blood resulting in generalized vasoconstriction.[24] Experimental studies in cooled human extremities indicate that a marked reduction in blood flow occurs promptly following cold exposure. Arms of human volunteers were immersed in water at 55°F for two hours, and blood flow was noted to have been reduced to about 3% of control levels.[1]

Reduction of blood supply also results in reduction of heat conveyed to the extremity. As temperature falls, further vasoconstriction ensues and the cycle results in the dominance of direct constricting action of cold upon vessels. A reduction in circulation with cooling leads to the development of stasis and subsequent increase in blood viscosity due to pooling, increased vascular permeability and loss of intravascular fluid.[26]

The question of total circulatory cessation at temperatures above the actual point of freezing has not been resolved. Lewis has cited a "hunting" response of the peripheral vasculature as evidence against total circulatory arrest.[23] He describes a cyclic opening and closing of peripheral vessels with subsequent transient rise in temperature. Greene has shown that this response is primarily the result of opening of arteriovenous anastomoses, which serves to provide heat, not nutrition,

to the tissues.[11] Meryman considers this response to be a compromise in the physiology of body heat conservation at the expense of an extremity; the compromise being promptly abandoned at the point that body heat conservation is seriously threatened.[26] The "hunting" response is discarded, and prolonged vasoconstriction is manifest at the expense of the affected limb.

Although cooled tissues require less oxygen, the profound reduction in peripheral blood flow is considered by many authorities to be sufficient to produce ischemia and cell death.[12, 26] Such a mechanism could explain gangrene in nonfreezing cold injury, and would provide an important stage in frostbite pathology at colder temperatures.

Biochemical effects of nonfreezing cold must be considered. There is an interdependence between the effects of circulatory reduction and the alteration of biochemical processes due to cold. By diminishing blood flow to an extremity cold reduces metabolic rates, the influx of metabolic precursors, and the rate at which metabolites are returned centrally to be excreted by the various routes available. Does metabolic need exceed supply in nonfreezing cold injury? Anoxia does result in severe nerve and muscle damage, but the death of nerve fibers due to cold may in itself be at least partly

responsible for muscle degeneration. Whether tissue necrosis is a direct result of cold without ice crystal formation is still controversial. Lower temperatures hasten the rate of injury development. Tissue loss from exposure to temperatures above freezing usually results only after a prolonged exposure of several days. If tissue actually freezes, an hour or less of exposure time may be sufficient to produce severe and extensive necrosis.[26] Vasoconstriction and a reduction of tissue perfusion, decreased metabolic supply, accumulation of metabolites, and oxygen deficit, must all be considered. Whatever the mechanism, cold injury without ice crystal formation is the result of a gradual accumulation of tissue damage, progressing slowly toward irreversibility.[28, 39]

V. PATHOGENESIS OF FREEZING INJURY

As a result of prolonged exposure at temperatures below freezing, in the cyclical manner described above, vasoconstriction results in a drop in peripheral temperature to the point that tissues begin to freeze. The consequence of freezing is cell injury or death. The mechanism of cell death is controversial. Clarification of this mechanism remains the most important factor in determining proper and effective therapeutic measures.

Two schools of thought exist concerning the mechanism of frostbite. One, represented by Lewis[19] and Meryman,[25, 26] considers frostbite to be essentially a thermal injury and believes that the extent of tissue damage has been determined before treatment is undertaken; subsequent treatment accomplishes little in reducing the degree of damage. Others, representing the majority, believe that cold-induced disturbance in the peripheral circulation is in itself the major factor in producing injury. They consider post-freezing measures aimed at prompt restoration of circulation of importance in limiting and even reversing the extent of tissue loss.[8, 9, 17, 32, 36, 41]

During actual freezing, tissue becomes opaque, as determined by transillumination studies.[7] Freezing is a

physical phenomenon in which all available water is removed from solution and relocated as inert ice crystals.[25] At high rates of freezing, crystals form at random throughout the tissue, within and outside of cells. Rapid freezing can only be produced experimentally. At slower rates of freezing ice crystals form exclusively in the extracellular spaces. This phenomenon takes place in frostbite.

Freezing and intercellular ice crystal formation produce important metabolic changes other than vascular disturbances. Meryman is a reviewer.[25, 26] As ice crystals form outside and between cells during slow freezing a hypertonic solution is created around the crystal. Intracellular water is drawn forth to the extracellular space and contributes to growth in crystal size. The process utilizes all water not bound to other molecules, resulting in a highly concentrated intracellular solute, surrounded by ice crystals larger than the original cells.

It was formerly believed that ice crystal formation took place intracellularly and led to cell death by mechanical rupture of cell membranes. Meryman has pointed out that despite distortion of cellular architecture by ice crystal formation, the water is released during thawing, is reimbibed by the cells which reassume their

configuration and appear histologically normal. Even experimental intracellular ice crystal formation is not noted for rupturing cell membranes or changing cell configuration. Ice crystal formation is not in itself an invariably lethal factor.

Potential biochemical alterations due to the profound solute concentration of electrolytes, sugars, proteins, enzymes, and substrates resulting from ice crystal formation are manifold. High salt concentration, being an unphysiologic state, has not frequently been the subject of in vivo biochemical studies. Alterations in pH, and the concept of pH itself in a state in which no free water is available, need further investigation. Proteins are likely salted out and precipitated at high solute concentrations, although salts themselves have not been demonstrated in crystal form by X-ray analysis.

A marked increase in enzyme or enzyme substrate concentration would certainly have a telling effect on the efficiency of their catalytic activity. Decreased temperature itself would tend to markedly affect reaction times in tissues. Freezing may result in pathologic accumulation of intermediates in vital oxidation-reduction reactions. Thus the concept of dehydration and solute concentration is a factor in freezing injury as it is in burns.

Whatever mechanisms are involved in the process of biochemical alteration secondary to freezing injury, they proceed according to a time temperature relationship. At very low temperatures the injury accumulates slowly. The rate of injury increases as temperature increases to reach a maximum near the freezing point. It is at this point evidently, that due to alteration in circulation and biochemical processes, metabolic demand exceeds supply to the greatest extent.

Postulated mechanisms of slow freezing injury can thus be summarized: Extracellular ice crystals displace and dehydrate soft tissue cells and while some tissues may be injured by this process alone, most cells collapse, only to reexpand with thawing by reimbibing lost water. Removal of intracellular water results in high electrolyte concentrations which produces a cumulative cellular injury. As temperature falls, more water is withdrawn from cells, increasing the potential of cell death. Further temperature drop below -15°C. produces no significant rise in solute concentration for at that temperature all water not molecularly bound has been withdrawn, and the rate of biochemical reactions has been maximally diminished.[26]

The mechanical and biochemical events attending freezing are reflected in the observed changes of

frostbitten tissue. The tissue appears normal for a short period after thawing. Then edema develops; ecchymosis appears as a result of rupture of small vessels, particularly venules.[3] Increased interstitial fluid may compress vessels, intensifying the damage.

Using microangiographic techniques on frozen rabbit ears it has been demonstrated that changes in small blood vessels may progress for weeks.[3] At the junction of frozen and uninvolved tissue there is an immediate, intense, arterial vasoconstriction. In a few hours an increase in vascularity occurs in a narrow, hyperemic, transitional zone between healthy and injured tissue. Capillaries dilate and blood flow accelerates. Soon stasis renders capillaries nonfunctional, flow rate is reduced, and intravascular sludging occurs as red blood cells agglutinate.[2, 3, 12, 16, 21] Many small areas of stenosis and occlusion appear within two to three days in the previously frozen area, and tubular filling defects, considered to be thrombi, are noted in both arteries and veins. Within ten days these thrombi either regress or persist as permanent occlusions.

Both arteries and veins disappear from frozen areas during the following weeks. To a degree this loss of vessels is compensated for by an increase in transitional zone blood supply, and new vessels are thought

to proliferate into formerly frozen areas.[3, 16] But these new vessels undergo involution within three months, and if the injured area does not undergo necrosis, a distorted, reduced, vascular pattern persists. Freezing and thawing produce a type of local arteritis and after the acute process has subsided, arteries and arterioles develop fibroblastic proliferation of the intima with permanent narrowing of the lumen.[2, 34] Fibrous replacement of degenerated smooth muscle in vascular walls with contracture further decreases the diameter of vessel openings.[5]

Tissue types vary greatly in their susceptibility to tissue injury. Nerves and skeletal muscle are highly sensitive. Skin, fascia, and connective tissues are highly resistant. In the sense that blood vessel injury leads to increased permeability following freezing they are quite susceptible to injury. However they are fairly resistant to actual cold-induced necrosis.

Gangrenous changes have been noted in muscle without necrosis of overlying skin.[18] Actual solidification is not a prerequisite for tissue death; severe chilling can produce similar damage. And freezing of tissue with ice crystal formation does not necessarily result in gangrene.[21]

Gangrenous changes in skin are seen first in

superficial epithelial layers, resulting is desquamation with survival of deeper layers. Atrophy, hyperkeratosis, and flattened papillae are produced following the initial injury. Increasing the intensity of the cold or prolonging exposure time is followed by a deeper tissue necrosis.[4]

Freezing produces immediate functional disturbances in nerve tissue manifested by sensory loss, muscle weakness, or paralysis. The nerve fibers become edematous with degeneration of myelin sheaths and patchy degeneration of axis cylinders. The rapidity of onset of functional loss is evidently due to the direct effects of cold. If these disturbances were secondary to vascular changes, onset would be delayed and progress more slowly.[40]

The least severe freezing injury involving muscle tissue is atrophy. Fibers are noted to diminish in size but maintain their form. If cold is more intense, necrosis of muscle develops, and fibers are replaced by dense scar tissue. The most severe injury to muscle is actual coagulation necrosis, or acute cell death. The fibers become swollen and homogenous with loss of cross striations. This process can occur experimentally in 15 minutes, and does not support the theory of vascular induced gangrene. Tourniquet induced ischemia takes as

long as three to four days to produce similar changes.[22]

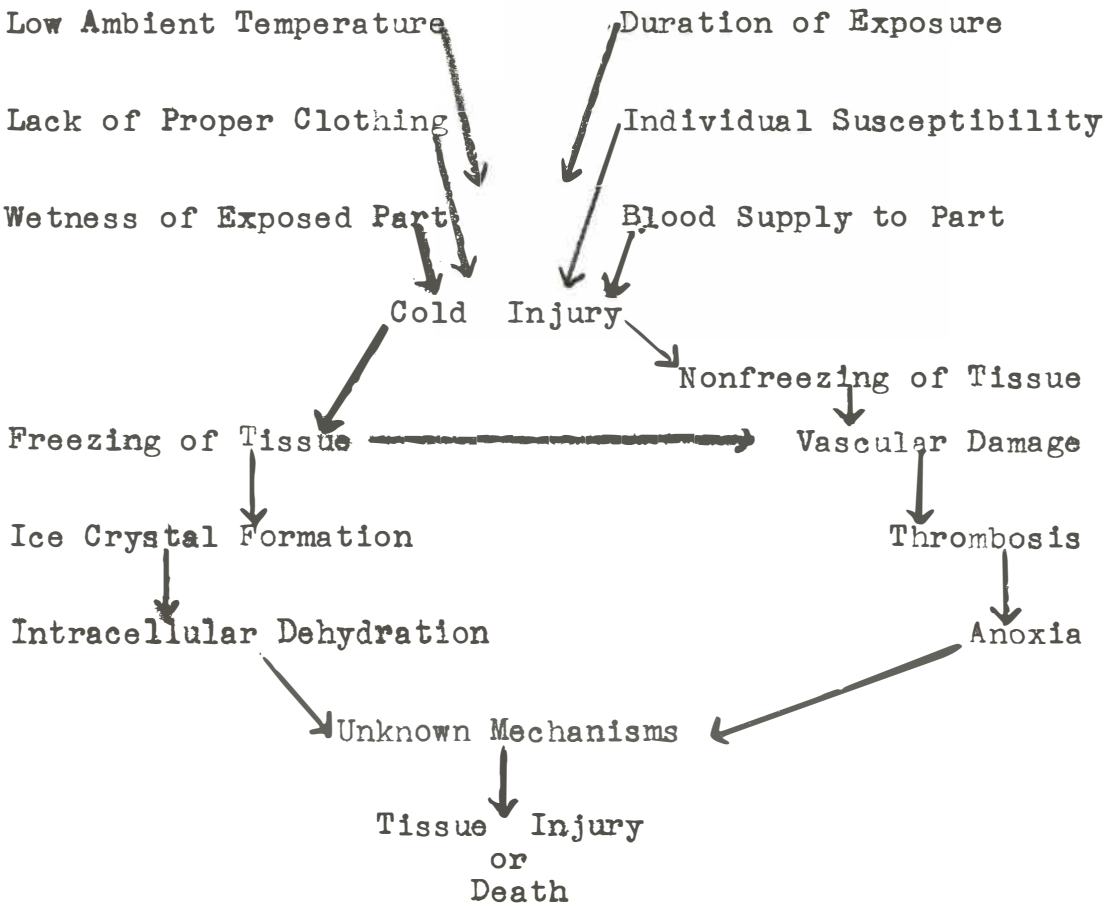
Bone marrow is quite cold sensitive for constituent cells disappear rapidly and are replaced by a gelatinous material which in turn becomes denser connective tissue. The bony cortex is more resistant to cold injury than bone marrow but freezing can produce atrophy, demineralization, and porosity. Joint cartilage has been affected to the extent that ankylosis develops. Tendon is quite resistant, and in general all connective tissues proliferate and recover relatively rapidly.[4]

Rapid freezing produced experimentally must be distinguished from slow, clinical freezing because the former results in the formation of intracellular ice crystals. Survival after rapid freezing has been considered by some authors to be an academic question because of the difference in ice crystal distribution which is dissimilar to all clinical freezing.[20, 25, 26] They consider clinical results obtained from rapid freezing experiments, with particular reference to treatment, not applicable to conventional freezing. This problem must be resolved by further investigation and possibly the reproduction of slow freezing injury for treatment evaluation.

Neither peripheral circulatory alterations nor unobservable biochemical alterations can be singled out

as the more important or dominant factor in the production of cold injury. Both phenomenon occur, are closely associated, and are in a very complex fashion interdependent. To resolve the mysteries of each is a desirable goal for the future as a guide to effective prevention and therapy. To debate relative importance is futile except as a stimilus to further investigation.

The pathophysiology of frostbite can be graphically illustrated in abbreviated form by a diagram modified from Hermann, et al.[12]



VI. TREATMENT AND PREVENTION OF COLD INJURY

The basic aim of treatment in clinical cold injury is minimizing tissue injury or death. The blood supply of the affected part must be restored, and vascular damage with further thrombosis and anoxia prevented. Ice crystal formation with resultant intracellular dehydration must be reversed promptly to protect the vitality of cells. Infection, a frequent complication, must be prevented. With these basic objectives in mind, treatment regimes have been improved in the past decade.

For many years it was believed that rewarming of the frozen extremity should be accomplished slowly. Cold water baths, walking and exercising, massaging and beating the injured part, or rubbing the part with snow and ice, were all variants of the slow rewarming approach. Despite public and professional acceptance, a disappointingly poor salvage of injured tissue resulted from these measures. During this era, rapid rewarming was viewed as detrimental, contributing only to greater pain and edema.[39, 41]

In general, contemporary treatment can be divided into measures related to local care of damaged tissue, and measures designed to diminish the secondary effects of vascular injury. The value of rapid and thorough

rewarming, at a location where the patient can remain warm, comfortable, and rest continuously during recovery, has emerged as the most important factor in limiting the effect of freezing soft tissue.[7, 8, 12, 32, 34, 41] Distinguishing freezing from nonfreezing cold injury is not clinically possible unless the part remains frozen. Usually the physician encounters the injured after partial rewarming has taken place. Since clinical appraisal is inaccurate in estimating the type and degree of damage, all cold injuries should be treated similarly.[41]

Details of the rapid rewarming process are explicit. Two basic regimes should be simultaneously carried out; one for exposure, the other for frostbite. While the entire body is being actively rewarmed by means of hot liquids and prewarmed coverings, a large vessel of water should be warmed to 108 to 112°F.(42 - 48°C). All clothing should be removed from the limb and the injured part immersed in the water bath. Water temperature should be maintained at 110± 2°F. and should not be allowed to exceed 112°F. so that a burn injury is not superimposed. Maximum benefits result after twenty minutes. Rapid rewarming reduces the total time of cold exposure. Tissue not rapidly rewarmed remains frigid for many hours, in spite of surface thawing.[12, 26, 41] The process is frequently quite painful so that analgesia

and sedation are necessary during rewarming.

Ultimate success in frostbite treatment depends largely on two factors: careful local care during and after rewarming, and prevention of infection.[12, 14, 41] Injured parts should be thoroughly cleansed at the completion of rewarming with a mild nonalcoholic antiseptic or mild soap. Alcohol promotes further injury by fixing injured tissues, cools by rapid evaporation, and is painful when applied. Rubbing or scrubbing is contraindicated.

The injured part may be exposed to the air as long as the environment is kept warm. If it must be covered, dry, soft, loose dressings should be provided. Greasy, oily dressings should be avoided because they macerate tissue. Soft cotton between toes and fingers will prevent friction and contact maceration. A small frame or cradle will elevate the bedclothes from injured feet. Blisters should not be pricked or opened, for intact skin provides a natural barrier to infection. Benefits in the form of increased tissue preservation and cleanliness have been derived from daily, gentle, whirlpool baths at body temperature in water containing 2 - 3% hexachlorophene solution. General supportive measures should include a high protein, vitamin rich diet and abstinence from smoking. Tetanus immunigation is

recommended, and specific antibiotic therapy should be directed at any subsequent infection.[41]

Specific attempts at restoring circulation and diminishing secondary vascular damage have been utilized with varying degrees of success. The value of regional sympathectomy has been enthusiastically supported by some authors as an effective means of improving circulation when performed within the first 24 hours following injury.[9, 10, 36] They report amelioration of pain and diminution of edema, earlier and more distal demarcation of injured tissue, more rapid epithelialization, and a favorable rate of healing. They also cite regional sympathectomy as an effective means of minimizing vasospastic hypersensitivity to cold.

Others have had less satisfying results with regional sympathectomy and believe that this procedure cannot alter the progression of irreversible injury. For the acute vasoconstriction that occurs at the time of cooling regresses promptly with thawing and is followed by vasomotor dilation with hyperemia at the marginal zone. The cold injury has likely effected a perivascular sympathectomy because of the sensitivity of nerves to cold. Surgical sympathectomy may offer little augmentation of blood supply.[12] Most others agree that if regional sympathectomy is considered, permanent surgical

methods are more advantageous than repeated temporary nerve blocks.

Numerous reports have contrasted the value and lack of effect of intra-arterial vasodilators. They cannot be expected to produce greater vasodilation than that resulting from the inherent process of recovery.[12] Intra-arterial sympatholytic drugs such as Priscoline have been noted to provide relief of causalgic pain.[12, 26]

Prominent features of the frostbite injury are progression of vascular changes long after the acute injury. The changes include sludging of blood and the formation of agglutinative thrombi. Anticoagulants have been evaluated as adjuncts to therapy in cold injury, and heparin has received the greatest trial. Results have been equivocal.[12, 15, 26, 31, 33]

The most recent experimental attempts at restoring circulation in cold injury have involved low molecular weight dextran which is believed to decrease blood viscosity and reduce cellular aggregation. Although intravenous low molecular weight dextran therapy was associated with increased edema of the extremities and more rapid thawing, it did not consistently reduce the amount of skin loss sustained in experimental freezing injury of dog and rabbit extemities.[29,31] Fibrinolysins have not been evaluated as yet, because a satisfactorily

stable preparation has not been prepared.

Physiotherapy should be attempted only by the patient himself. Voluntary, careful movement of the joints at regular intervals is an important part of current treatment. Active exercise helps maintain flexibility of muscles, tendons, and ligaments but must be undertaken very carefully. It is not unusual to see good motion and eventually good function of blackened fingers and toes. Static immobilization favors fibrosis and stiffening.[12, 41]

Tissue should not be excised, for a blackened and apparently hopelessly traumatized extremity may be eventually preserved with only superficial skin slough. As long as there is movement in the involved area, salvage is possible. Nature usually effects its own removal by autoamputation. Even minor surgical procedures expose damaged tissue to infection.

As treatment progresses, patients should be warned in advance of the dramatic changes in appearance they will observe. Without forewarning the patient may be demoralized by witnessing the development of huge blisters, dusky discoloration, and grisly necrosis of fingers and toes. He should be reminded that usually the worst looking hands and feet will shed their shriveled black shells revealing healthy pink skin underneath, with

treatment and adequate time. Patience is vital.

Cold injury can precipitate a long term illness and uncomforable sequelae with a degree of disability related to the severity of the original injury. A sympathovascular syndrome manifest by causalgic pain, hyperhidrosis, coldness of extremities, and stiff joints is the most common. Discomfort is greater in cold weather, and although regional sympathectomy has been cited for relieving discomfort to a degree, only adequate protection of cold-injured parts and prevention of further cold exposure offer significant relief.

With this understanding of the progress and sequelae of cold injury, preventive measures can be outlined. Foremost is the avoidance of exposure. Overall physical well-being, insulated clothing, and intelligent field operations are the best insurance against cold injury among military men and winter sportsmen. Exhaustion, hunger, illness, injury, and hypoxia enhance the danger of sustaining cold injury. One must dress to maintain general body warmth with particular attention to the face, head, and neck, which are often neglected. Adequate amounts of nourishing, appetizing food should be provided to aid in production of maximum body heat. Cold weather diets should emphasize fats. All constrictive clothing on extremities are to be avoided. In

order that dampness due to perspiration be minimized, adequately ventilated clothing should be worn with prompt change of wet garments.

Of utmost importance is the recognition of the sensations of being cold. Loss of sensation in extremities following prolonged cold exposure is a definite danger sign and should prompt one to seek warmth and shelter as rapidly as possible.

VII. SUMMARY

That cold injury is a serious illness with potentially dangerous consequences has been discussed. Therapeutic attempts in the past have been haphazard, poorly documented, and not based on an understanding of the pathophysiology of the injury. Current, more successful methods of treatment have been emphasized. Other adjunctive measures have been less successful and remain controversial, but the problem is being approached rationally by focusing on the biochemical and vascular changes attending cold injury. Prevention cannot be overemphasized. As a result of present day interest in cold injury more effective means of treatment will be discovered, making the winter and high altitude environments less hazardous for the military, the adventurer, and the sportsman.

BIBLIOGRAPHY

1. Bancroft, H. and O.G. Edholm: The Effect of Temperature on Blood Flow and Deep Temperature in the Human Forearm. J. Physiol. 102:5, 1943.

2. Bellman, S. and R.J. Adams: Vascular Reactions After Experimental Cold Injury: A Microangiographic Study On Rabbit Ears. Angiology. 7:339, 1956.

3. Bellman, S. and J.O. Strombeck: Transformation of the Vascular System in Cold-Injured Tissue of the Rabbit's Ear. Angiology. 11:108, 1960.

4. Brownrigg, G.M.: Frostbite - Classification and Treatment. Am. J. Surg. 67:370, 1945.

Crismon, J.M. and F.A. Fuhrman: Studies on Gangrene Following Cold Injury: VI. Capillary Blood Flow After Cold Injury and the Effect of Rapid Rewarming and Sympathetic Block. J. Clin. Invest. 26:468, 1947.

6. Davis, L., J.E. Scarff, N. Rogers and M. Dickinson: High Altitude Frostbite. Surg. Gynec. Obst. 90:430, 1950.

7. Fuhrman, F.A. and J.M. Cusmon: Studies on Gangrene Following Cold Injury: Treatment of Cold Injury by Immediate Rapid Rewarming. J. Clin. Invest. 26:476, 1947.

8. Fuhrman, F.A. and G.J. Fuhrman: Treatment of Experimental Frostbite by Rapid Thawing. Medicine. 36:465, 1957.

9. Gildenberg, P.L. and E. Hardenbergh: The Effect of Immediate Sympathectomy on Tissue Survival Following Experimental Frostbite. Ann. Surg. 160:160-167, 1947.

10. Golding, M.R., P. deJong, P.N. Sawyer, G.R. Hennigar and S.A. Wesolowski: Protection From Early and late Sequelae of Frostbite by Regional Sympathectomy; Mechanism of "Cold Sensitivity" Following Frostbite. Surg. 53:303-308, 1963.

11. Greene, R.: The Hunting Response. Lancet. 243: 695, 1942.

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

13. Kavanaugh, G.J.: Cold Injuries in Civilian Practice. Heart Bull. 13:16-18, 1964.

Kleitsch, W.P. and E.K. Connors: Cold Injury of the Extremities. Postgrad. Med. 16:192-200, 1954.

15. Kreyberg, L.: Development of Acute Tissue Damage Due to Cold. Physiol. Rev. 29:156, 1949.

16. Kulka, P.J.: Vasomotor Microcirculatory Insufficiency and Observations on Nonfreezing Cold Injury of the Mouse Ear. Angiology. 12:491, 1961.

17. Lange, K. and L.G. Boyd: The Functional Pathology of Experimental Frostbite and the Prevention of Subsequent Gangrene. Surg. Gynec. Obst. 80: 346-350, 1945.

18. Lewis, R.B.: Pathogenesis of Muscle Necrosis Due to Local Cold Injury. Am. J. M. Sc. 222:300, 1951.

19. _____: The Wellcome Prize Essay for 1951: Local Cold Injury; Frostbite. Milit. Surgeon. 110:25, 1952.

20. _____: Local Cold Injury. Am. J. Phys. Med. 34:538, 1955.

21. _____: Local Cold Injury. Christopher's Textbook of Surgery. Saunders Co. 198-204, 1960.

22. _____and P.W. Moen: Further Studies on the Pathogenesis of Cold Induced Muscle Necrosis. Surg. Gynec. Obst. 95:543, 1952.

23. Lewis, T.: The Hunting Response to Prolonged Cold. Heart. 15:177, 1929.

The Triple Response to Cold. British M. J. 2:795, 1941.

Meryman, H.T.: Mechanics of Freezing in Living Cells and Tissues. Science. 124:515, 1956.

26. _____: Tissue Freezing and Local Cold Injury. Physiol. Rev. 37:233, 1957.

27. Mitchell, J.C.: Bradykinin (a Vasoactive Polypeptide). New. Eng. J. Med. 271:1057-1059, 1964.

28. Montgomery, H.: Physiological Effects of Uncomplicated Cold. Physiol. Rev. 34:127, 1954.

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

30. Owens, J.C.: Causalgia. Ann. Surg. 23:636, 1957.

31. Penn, I. and S.I. Schwartz: Evaluation of Low Molecular Weight Dextran in the Treatment of Frostbite. J. Trauma. 4:784-789, 1964.

32. Pichotka, J. and R.B. Lewis: Effect of Rapid Rewarming on Local Cold Injury. Armed Forces Med. J. 2:1293, 1951.

33. Quintanilla, R., F.H. Krusen and H.E. Essex: Studies on Frostbite with Special Reference to Treatment and the Effect on Minute Blood Vessels. Am. J. Physiol. 149:149-161, 1947.

34. Rosenfeld, J., J.L. Langohr, C.R. Owen and A. Cope: Circulation of Blood and Lymph in Frostbite and Influence of Therapeutic Cold and Warmth. Arch. Surg. 59:1045, 1949.

35. Shephard, J.T: Physiology of Circulation in Human Limbs in Health& Disease : Saunders ,1963.

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

37. Southworth, J.L.: The Role of Sympathectomy in the Treatment of Immersion Foot and Frostbite. New Eng. J. Med. 233:673,1945.

38. Ullman, J.R.: Americans On Everest. Lippincott Co., 1964.

39. Ungley, C.C.: Immersion Foot. Proc. Roy. Soc. Med. 36:518, 1943.

40. _____and W. Blackwood: Peripheral Vasoneuropathy After Chilling. Immersion Foot and Immersion Hand. Lancet. 2:447, 1942.

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

42. Zweifach, B.W.: Microcirculation of Blood. Scient. Am. 200:54-60, 1959.