REVIEW ARTICLE

Prehospital Use of Ultrathin Reflective Foils

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Ultrathin reflective foils (URFs) are widely used to protect patients from heat loss, but there is no clear evidence that they are effective. We review the physics of thermal insulation by URFs and discuss their clinical applications. A conventional view is that the high reflectivity of the metallic side of the URF is responsible for thermal protection. In most circumstances, the heat radiated from a well-clothed body is minimal and the reflecting properties of a URF are relatively insignificant. The reflection of radiant heat can be impaired by condensation and freezing of the moisture on the inner surface and by a tight fit of the URF against the outermost layer of insulation. The protection by thermal insulating materials depends mostly on the ability to trap air and increases with the number of covering layers. A URF as a single layer may be useful in low wind conditions and moderate ambient temperature, but in cold and windy conditions a URF probably best serves as a waterproof outer covering. When a URF is used to protect against hypothermia in a wilderness emergency, it does not matter whether the gold or silver side is facing outward.

Keywords: survival blankets, space blankets, heat exchange, hypothermia, insulation

Introduction

Ultrathin reflective foils (URFs), often referred to as “space blankets” or “survival blankets,” were first designed and brought to market in the mid-1960s. Although they were primarily used in cryogenics and space applications, their potential usefulness as a medical product was rapidly recognized. URFs are widely used in emergency medicine in an attempt to protect patients from heat loss, and in operating rooms to prevent intraoperative hypothermia.^{1–3} While trade names and descriptions of these foils suggest that they possess insulating properties, there is no evidence that they are effective. The only evidence in favor of their use is theoretical calculations and a few small clinical studies.^{4–7} By the 1970s, the unreasonable enthusiasm

diminished, but reflective foils are still common in first aid kits, rescue kits, and emergency medical equipment.^{1,8} We discuss the uses and limitations of ultrathin reflective foils in prehospital medicine.

Structure and Properties of URFs

The main component of a URF is a polyethylene terephthalate (PET or PETE). Some URFs use Mylar, a biaxially oriented PET which is thicker and stronger than standard PET. During the process of vacuum metallization, the foil is covered by a layer of aluminum, which confers reflective properties. Although the typical thickness is only about 10 to 15 micrometers (0.01–0.015 mm), the foil has a relatively high tensile strength, flame retardancy, and resistance to penetration by water vapor or air.^{9,10} Some believe that high reflectivity of the metallized side, ranging from 90 to 97%, is responsible for the thermal resistance properties (the ability of a material to resist heat flow).^{4,11} The other side can be coated in any

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color, typically gold or orange for mountain rescue and media uses or olive-green for military use. In the 1970s, trials of metallized foils for rescue purposes were conducted based on the mistaken assumption that the reflective layer would reflect radio waves and could be detected by radar. Both theory and practice revealed the uselessness of foils in these sorts of applications.⁹ More recently, it became apparent that reflection of visible light by URFs increases detectability in search and rescue missions performed when there is good visibility, while reflection of infrared radiation increases detectability when there is poor visibility.^{11,12} Metallized foils transmit only 1 to 8% of visible light and about 1% of ultraviolet B radiation (280–315 nm). URFs can provide protection from snow blindness from high solar radiation.¹²

In addition to URFs, there are also so-called “heavy reflective blankets” available for everyday use. Unlike ultrathin foils, these are thicker (about 1 mm), more rigid, and stronger with a synthetic or natural nonwoven filling or with the reflective layer applied as 1 layer of a multilayer system. Advanced multilayer systems, with corrugated aluminum foil providing air insulation between individual layers, are also available. We do not discuss heavy reflective blankets further in this review.

Principles of Heat Exchange

According to the second law of thermodynamics, heat always flows from an object at a higher temperature to an object at a lower temperature. If there is a difference between the temperature of a given object and its surroundings or a neighboring object, heat exchange will take place until the temperatures reach equilibrium.⁴ Heat exchange between neighboring objects can only be slowed, not eliminated. Heat is transferred by 4 mechanisms: convection, conduction, evaporation, and radiation (Figure 1).

All objects emit thermal radiation. The kinetic energy of heat is converted into electromagnetic radiation, at a wavelength that depends on the temperature of the object (Wien’s law). Human bodies emit mostly infrared radiation (heat) with a wavelength of 5 to 20 micrometers.¹³ Unlike convection and conduction, in which direct contact is necessary for heat transfer, radiation does not require the presence of any medium between objects that are exchanging heat. Radiative heat exchange can occur in a vacuum. Reflection can limit absorption of radiated heat, even in space.

The power of the radiation emitted by a body as electromagnetic waves is proportional to the surface area (S) and to the fourth power of surface temperature (T_{sur}) in degrees Kelvin:⁴

Figure 1. Mechanisms of heat loss. Authors’ own graphic.

$$P_{rad} = \sigma \epsilon S (T_{sur})^4$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$) and ϵ is the emissivity of the surface, the ratio of the energy radiated from a material’s surface to that radiated from a perfect emitter, known as a black body. A surface emissivity of 1 defines a perfect black body. The emissivity of human skin is very high (0.98). The emissivity of most fabrics is about 0.75.^{13,14} Electromagnetic radiation can cause both heat loss and heat gain. Bodies can absorb heat from objects in the environment, such as the sun, a radiator, or a fire. Heat balance is the difference between heat that is dissipated and heat that is absorbed.

Maintenance of core temperature is critical for human physiology. The amount of heat loss depends partly on the temperature of the skin surface. The human body responds to cold by vasoconstriction of the skin, lowering surface temperature. Vasoconstriction can limit skin blood flow to less than 10% of baseline.¹⁵ This defense mechanism attempts to keep core temperature constant at $37 \pm 0.5^\circ\text{C}$. Skin temperature can vary widely, decreasing by an average of 10°C during cooling and more in hypothermia.¹⁶

Because the power of radiation is directly proportional to the fourth power of surface temperature in degrees Kelvin, even a small change in body surface temperature can lead to a large change in the amount of radiated heat.⁴ Radiant heat loss from uncovered skin in windless conditions can account for about a quarter of total heat loss. After longer exposure to cold, once skin temperature has decreased, radiation generally accounts for less than 5% of heat loss.¹⁷

In a cold environment, the temperature of the outer layer of clothing must be considered. Heat transfer takes

Figure 2. Simplified model of heat transfer through a fabric system. Top image: Heat loss increases when the system is compressed and there are no air spaces. Bottom image: Less heat is lost through a closely applied multilayer fabric system covered with reflective foil. Authors' own graphic.

place from the skin surface to the innermost layer of clothing and then to each subsequent overlying layer of clothing (Figure 2). A thermal gradient builds up between the temperature of the innermost surface and the temperature of the outermost surface. The higher the temperature of the outermost surface, the worse the insulation and the higher the heat loss to the environment.^{5,18,19}

Practical Aspects of Protection from Heat Loss

The magnitude of heat loss from the body by various mechanisms depends on many factors, including weather conditions, clothing, body position, and individual physiology. The mechanisms and rates of heat loss can change rapidly. In a windless, cold environment, when air movement is minimal, a significant amount of heat is lost by radiation. When a person is lying on or is otherwise in contact with a cold surface, significant heat is lost by conduction. Heat loss by conduction also increases if clothing is wet.^{18,19} Any movement of surrounding air, especially wind, increases heat loss by convection.²⁰

Advertising for reflective foils sometimes claims that they decrease heat loss by 90%. This would be true only if there were no mechanisms of heat loss other than radiation and if the effective reflectivity of the coating was almost perfect. Aside from the impossibility of eliminating heat loss by conduction, convection, and evaporation, the surface of the foil is not perfectly reflective.^{8,9} The most important factor that affects the effectiveness of a foil to limit heat loss is the method of application.

Reflective foils have been used for years to decrease heat loss during the perioperative period.^{2,3} In this application, the foil is usually placed directly on the skin or on clothing, such as underwear. If the reflective side is separated from the body surface, there is a trapped air layer between them where heat exchange occurs largely by radiation. Little heat is lost because radiant heat is reflected back to skin or clothing and reabsorbed. If the foil is in direct contact with the body, it gains heat by conduction, rapidly reaching body temperature. As a "second skin," the foil loses heat by radiation and by convection.^{20,21}

In emergency medical services, URFs are placed on accident victims, directly over clothing, or as the outer layer of multilayer insulation. Heat from the body flows across the air space between skin and fabric and then through the fabric system to the outer surface of the fabric system (Figure 2). During this process, heat is transferred by conduction, convection, evaporation, and radiation.^{20,22-26} Although radiant heat can penetrate fabrics, it also can be absorbed or scattered.²² At the outer surface of clothing exposed to air, heat is lost by convection and radiation. If a URF is the outermost layer, it reflects radiation emitted by the adjacent outermost insulating layer. If the insulation is effective, radiation from the outer layer to the foil is minimal.¹¹ In addition, emissivity of fabric is lower than that of skin, limiting radiation of heat.¹³

Conduction through clothing or other coverings is affected by the properties of the fabrics and by the construction of the textile assemblage with fabric layers and trapped air. The thermal insulating capacity of a clothing ensemble depends mostly on its ability to trap air. The amount of insulation generally increases with the number of covering garments.^{11,20,23} Thermal insulation is directly proportional to the thickness of the ensemble (about 1.3–1.5 clo·cm⁻¹). Maximum heat flux is reduced by up to 80% when the air gap is increased from 0 to 1 mm. The marginal decrease of heat flux caused by further increasing an air gap tends to become smaller as the gap is increased. In thicker air layers (>10 mm), convection may occur, increasing heat loss.^{23,24} Movement of trapped air can also be caused by body movement or by external factors, such as mechanical pressure or wind.

Table 1. Advantages and disadvantages of URFs

<i>Advantages</i>	<i>Disadvantages</i>
<ul style="list-style-type: none"> • Small packed volume • Lightweight • Waterproof • Windproof • Can be an element of multilayer insulation • Can increase detectability in search and rescue missions • If used over the eyes, can protect from snow blindness 	<ul style="list-style-type: none"> • May tear in a strong wind • May tear from contact with sharp objects • Reflectivity is decreased by condensation of vapor at the inner layer of the foil • Provides little protection from conduction • Has limited effectiveness as a single layer, especially in windy conditions • No data on performance in field conditions

If the URF is wrapped too tightly, the volume of trapped air is reduced, increasing the conductivity of the clothing and decreasing the thermal gradient. In a cold environment, the result is an increase in heat loss.^{5,19-21} Securing a patient to a backboard or stretcher can also cause folding or bunching of the insulation, increasing heat loss when the volume of trapped air is reduced.²¹

Placing a vapor barrier, such as a URF, outside an insulating layer can potentially increase heat loss by causing condensation of water on the inner side of the vapor barrier. Repeated cycles during which moisture in contact with the skin absorbs heat, evaporates, and then travels to the outer layers, where it condenses and returns to the skin surface, can cause heat loss. This mechanism is called the “heat pipe effect.”^{25,26} Moisture in textiles decreases thermal insulation when it replaces air because water has 25 times greater thermal conductivity than air. In cold conditions, condensation and freezing of moisture accumulating on the inner side of the URF significantly impair its reflectivity.^{8,9} Also, folds, creases, and other defects can change reflection directionality, decreasing overall reflectivity.²¹

A URF can protect against wind and rain, but unlike a rigid covering, it can be distorted by even light air movement.^{5,9} The resultant mixing of trapped air increases convective heat loss. A single layer of URF provides an additional 1 to 3 clo, depending on wind speed. In a windless environment, a URF can provide protection equivalent to that provided by a woolen blanket. Moderate wind ($2-3 \text{ m}\cdot\text{s}^{-1}$) decreases protection by as much as 40%, and strong wind ($>8 \text{ m}\cdot\text{s}^{-1}$) by up to 55%. In moderate or strong wind, reflection from metallized foils becomes negligible and the overall thermal protection of metallized foils is the same as non-reflective polyvinyl chloride foils of the same thickness.⁵

Most commercially available foils have a surface area of about 2.8 m^2 . This is too small to cover most patients with a single foil. It is usually necessary to use 2 or 3 foils, making it impossible to create an air- or watertight covering. Leakage between foils increases convection

and allows moisture to penetrate the covering, increasing heat loss.

Gold to Cold?

Theoretically, a foil should be used with the silver side toward the patient and the gold side facing the environment, but reflectivity (0.97–0.99) does not differ significantly between the 2 sides.^{27,28} The emissivity of the gold side is about half that of the silver side ($\epsilon=0.02$ vs 0.04). At a given foil temperature, the radiative power of the gold side is about half that of the silver side.^{28,29} The clinical importance of this phenomenon is limited. Reducing emissivity is of marginal significance when there is high heat loss via conduction and convection.⁸ Transmission of radiation by URFs in near, middle, and far infrared wavelengths is very low.^{11,12} It does not matter whether the gold side or the silver side is facing outward when a rescue blanket is used to protect against hypothermia in a wilderness emergency.^{9,12}

Clinical Studies

We found only 7 clinical studies of URFs in field conditions.^{5-7,9,30-32} Most of the human studies had a small number of subjects.^{9,30-32} Because the subjects were not hypothermic, skin surface temperatures were likely higher than they would have been in hypothermic subjects. Individual studies do not describe exactly how the reflective foils were placed, limiting the ability to compare results among studies. One study found no significant difference among protective materials in 2 weather conditions.⁹ Heavyweight blankets and URFs provided protection from sun, wind, and rain. Blankets were durable, while URFs tore easily. Neither had any advantage over simple polyethylene bags for insulation in a cold environment. The mean decrease in skin temperatures with URFs was similar whether the reflective side faced in or out. Condensation formed on the inner

surface of the foil early in each exposure and rapidly froze, especially at lower air temperatures. In another study, a casualty bag incorporating a URF did not decrease heat loss.³⁰ The calculated insulation value of the complete casualty bag was close to the predicted value for textile layers without the URF. In a study of subjects with different combinations of passive insulation with and without a reflective foil, adding URF inside 1 or 2 blankets provided better thermal insulation in the wind than the blankets alone.³² There was less decrease in thermal insulation caused by moisture inside the coverings when a waterproof reflective sheet or bubble wrap was used inside blankets. In a randomized trial of prehospital thermoregulatory interventions, all trauma patients receiving passive insulation, including reflective blankets, had a decrease in core temperature during transport.³¹

Four studies used thermal manikins.^{6,7,18,32} In one study, rescue foil improved thermal protection when added to woolen blankets, but URFs used alone had no significant benefit.⁶ Another manikin study compared 4 insulating blankets and 1 warming blanket. A URF was more effective than a polyester ambulance blanket, but less effective than bubble wrap, a heavyweight blanket, or the heating blanket.⁷ Another study showed that thermal protection in low wind conditions was proportional to the thickness of the insulating layers, although URFs had higher insulation than expected.⁵ Convective heat loss increased with increased wind velocity. In moderate and high wind conditions, thermal insulation was best preserved by waterproof, rigid systems capable of resisting compression. A URF used as a single layer achieved thermoneutrality in a low wind environment at temperatures as low as 10°C. In cold, windy conditions, URFs are probably most useful as windproof outer covers.

Are URFs Useful in Prehospital Medicine?

It is unclear whether URFs have a legitimate role in prehospital medicine. They have advantages and disadvantages (Table 1). A fundamental problem is the unfounded belief of many medical personnel that URFs have unique properties. Clinical research suggests that URFs lack meaningful advantages over other materials for the prevention and treatment of hypothermia,^{6,9,30,31} or have only minor advantages.^{5,7,32}

Summary

Thermal insulation is proportional to thickness and to the ability of an insulating material to maintain compartments with trapped air in and between fabrics. Ultrathin foils

likely have the same level of effectiveness as other waterproof materials of similar thickness used in pre-hospital medicine. An ultrathin foil alone does not significantly limit heat loss. The insulation properties of an ultrathin foil can be altered by factors such as wind or by moisture condensation on the inner side. In clinical practice, it does not matter which side, silver or gold, faces outward.

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