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Comparison of Eight Types of Protective Clothing against Irukandji Jellyfish Stings

Lisa-ann Gershwin*†‡ and Karen Dabinett‡

†State Marine Stinger Advisor
Surf Life Saving
18 Manning Street
South Brisbane, Queensland 4101, Australia
lisa.gershwin@stingeradvisor.com.au

‡School of Marine Biology and Aquaculture
James Cook University
Townsville, Queensland 4811, Australia

ABSTRACT

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Marine stingers hospitalize approximately 100 people annually in tropical Australian waters, and are known to have caused at least 73 fatalities. Elsewhere in the tropical and temperate seas of the world, marine stingers pose a similar threat to human safety, and reported sting numbers are on the rise. Lycra body suits ("stinger suits") have been used for stinger protection since the early 1980s, but have not been formally tested as a barrier against Irukandji (*Carukia barnesi*) tentacles. Other products are being used and developed; however, no safety standards currently exist for this widely used form of protective equipment. Eight products were tested with live *C. barnesi*: a Lycra stinger suit used by Surf Life Saving, a product developed by ROBIS Pty. Ltd. and marketed as "The Stinger Suit", three different styles of nylon pantyhose, two sport products designed to "wick away" moisture and keep the wearer cooler, and a 0.5-mm neoprene wetsuit. Products were evaluated for seven common concerns relating to safety and practical wearability. Primary concerns, *i.e.,* those relating to performance of the fabric in preventing stings, include: ease of penetration by jellyfish tentacles, adherence of tentacles or body to fabric, and potential for crushing through the fabric. Secondary concerns, *i.e.,* those relating to overall usage as stinger-preventative clothing, include: durability or integrity of the barrier, whether the product is available as a one-piece garment, heat-retention properties, and product cost. In general, the tighter the fabric weave, the better tentacle exclusion, and the smoother the fabric, the more resistant to adherence. Lycra is vulnerable to crushing of tentacles through the fabric, but appears to be the best choice for routine-use stinger-protective clothing. Recommendations are made for safe use of protective clothing, as a basis for development of an Australian Standard in protective clothing for marine stinger safety.

ADDITIONAL INDEX WORDS: *Stinger suits, PPE, marine stingers, marine safety, beach safety, aquatic safety, tropical tourism, health hazard, safety hazard, box jellyfish.*

INTRODUCTION

Marine stingers (*i.e.,* stinging jellyfish) are the number one health hazard in tropical Australian waters (P. DAWES, personal communication; J. GARDINER, personal communication; M. KENWAY, personal communication; B. MCCALLUM, personal communication; G. TREW, personal communication), resulting in over 100 hospital presentations per year and a death every few years. Two types of marine stingers are regarded as life-threatening: *Chironex*-type box jellyfish, attaining body sizes over 30 cm, with up to 60 2-m tentacles that can kill children and adults within 2–3 minutes; and Irukandji-type box jellyfish, as small as 1 cm in body size, with just four fine tentacles, but causing a constellation of systemic symptoms including intense lower back pain, nausea, vomiting, shooting spasms, waves of body cramps, difficulty breathing, profuse sweating, and a feeling of impending doom, and in some cases, severe hypertension documented as high as 280/180 (FENNER and CARNEY, 1999). Two deaths and numerous episodes of critical illness including pulmonary oedema and toxic heart failure have been attributed to this latter group of jellyfish (CORKERON, PEREIRA, and MACROKANIS, 2004; FENNER and HADOK, 2002; HUYNH *et al.,* 2003).

The risk of stinging associated with *Chironex*-type box jellyfish has been significantly reduced in tropical Queensland through the use of stinger-resistant swimming enclosures (MOSS and STARK, 1983); however, mechanical issues such as clogging and "sailing" have prevented successful deployment of fine-mesh nets for Irukandji exclusion (K. MOSS, personal communication). Thus, these enclosures do not provide protection from Irukandji stings. Furthermore, about one-third of Irukandji stings occur in reef and island environments where these enclosures are not practical, even if the mechanical issues could be resolved.

In tropical Australia, reducing the risks posed by jellyfish is a high priority for Surf Life Saving (SLS), tourism operators, local governments, health and emergency professionals, and others concerned with providing a safe and enjoyable recreational experience to the public or a safe occupational environment to their employees. One of the primary recom-

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* Present address: Australian Marine Stinger Advisory Services, P.O. Box 5559, Townsville, Queensland 4810, Australia.

mended methods of protection from jellyfish stings is protective clothing (personal protective equipment [PPE]). Before the early 1980s, two pairs of nylon pantyhose were used, one worn normally, and the other worn over the arms with a hole cut out in the crotch for the wearer's head. In the early 1980s, a full-body Lycra suit was introduced by a collaboration of researchers from James Cook University, Townsville General Hospital, and SLS (Harrison *et al.,* 2004; Williamson *et al.,* 1996). The principle aim of these was to reduce the body surface area accessible to tentacles, thus eliminating the subcutaneous deposition of venom and access to small blood vessels, which are central to the lethality of the sting. Common vernacular in northern Australia labels these "stinger suits".

These stinger suits have been widely used by SLS and local researchers, providing a thicker layer of protection than pantyhose, more durability, and better ultraviolet (UV) protection. However, stinger-protective clothing has not been widely adopted by the general recreational public; it has been estimated that less than 5% of Queensland beach users wear any type of stinger protection (Australian Lifeguard Service, unpublished notes; L. Gershwin, unpublished notes).

Other types of clothing that have been used for stinger PPE include neoprene wetsuits, sport clothing designed to "wick away" the moisture, and a product marketing itself as "The Stinger Suit," which became commercially available in 2003; this full-body suit is made of a 1-mm mesh, thus readily allowing heat exchange, and is sold at half the price of a Lycra suit. The makers of this suit, ROBIS Pty. Limited, obtained two enthusiastic endorsements from a researcher (Seymour, 2002, 2004), and further requested that SLS evaluate their product.

Concerns with PPE

Sinclair (2003) found that Lycra body suits may retain heat, causing potential heat-stress problems for lifeguards and lifesavers on patrol. Similar concerns have not been raised, but would be expected, with neoprene wetsuits, which are designed for heat retention and are vapor-impermeable.

Furthermore, even covered skin can be stung. The mechanisms of stinging in events where protective clothing was worn appear to include: tentacles and other medusa body parts being crushed through fabric, allowing stinging cells to come into contact with human skin (L. Gershwin, unpublished sting notes; Surf Life Saving, unpublished sting notes; Williamson *et al.,* 1996, p. 103 footnote); free stinging cells in the water penetrating the fabric (*i.e.,* no apparent tentacle contact; L. Gershwin, unfortunate personal experience; M. Kingsford, unpublished personal experience); disrobing of clothing without neutralising adherent tentacles, which were then drawn over exposed skin (L. Gershwin, unpublished sting notes); and of course, breaches in the barrier through runs or tears in the fabric (L. Gershwin, unpublished sting notes). However, despite occasional breaches, evidence exists that protective clothing usually offers an effective barrier against jellyfish stings: in the Whitsunday region, stings were reduced from 38 the year before Lycra and neoprene suits were widely adopted to 7 in the first year of heavy usage (Whitsunday Marine Stinger Management Committee, unpublished statistics). Similarly, the authors and other members of their collecting team have not had Irukandji syndrome, despite many hours of successful collecting over the past 9 years, while wearing Lycra or neoprene suits.

There is also the common question of, "what about my hands, feet, and face?," which are not covered by a standard Lycra or neoprene suit. Of 101 Irukandji stings in 2005–2006 Queensland season, sting site was available for 66; of these, 46 (69%) were stung on a part of the body that would have been covered by a standard Lycra suit; an additional three would have been prevented with foot protection such as booties (Irukandji Sting Database, maintained by various researchers).

Current Standards for Stinger PPE

Although most organizations recognize the need for stinger safety, different organizations have different standards. Surf Life Saving recommends a full body Lycra suit for normal recreational activities, and requires two Lycra suits or a neoprene wet suit, plus booties and gloves, for monitoring on high-risk days (Dawes *et al.,* 2006). James Cook University requires no less than 0.5-mm neoprene wetsuit, plus booties, gloves, and a hood, for sampling in stinger-infested waters (Arbouin *et al.,* 2004), but has no protocol for nonstinger researchers. Other research organizations recommend protective clothing but have no formal protocol. The Australian pearling industry has been extremely proactive in terms of occupational safety, and has widely adopted full-body protection in terms of neoprene or a dual-layer polypropylene fibre suit, plus booties, gloves, hood, and a type of mask that they have developed called a "stinger guard", thus eliminating exposed skin. In the public recreational sector, protective clothing is recommended by charter operators and beach managers, but no uniformity currently exists. Although many different types of occupational and public sector safety equipment are governed by Australian Standards, no such standard currently exists for stinger safety equipment.

Objectives of This Study

This study was initiated by SLS management, in response to a request from ROBIS to test their product, and in the interest of evaluating the relative effectiveness of Lycra PPE compared with other readily available products. The objective of this paper is to provide a preliminary comparison of different clothing products in the context of seven specific concerns.

Concern 1: Penetrability of the fabric. Quite simply, how easily will tentacles pass through the suit? Ideally, the mesh size would be as fine as possible; at the very least, smaller than the tentacles they are meant to exclude (in this case, *Carukia barnesi* tentacles are about 200–250 μm [$\frac{1}{4}$–$\frac{1}{5}$ mm] in diameter).

Concern 2: Adherence to the fabric. If a tentacle or jellyfish body sticks to the fabric, then the jellyfish remains positioned near the wearer, increasing the chances of a sting event. In general, rough fabrics act like Velcro to tentacles and the threads of stinging cells, whereas the smoother a fabric is, the more resistant to adherence it is likely to be.

Concern 3: Crushing of the tentacles through the fabric. For example, crushing may occur at rubbing points such as under the arms or between the legs, when delicate gelatinous structures are pulverised into a mucus-like substance and forced through the fabric, with consequent sting and envenomation. The difference between penetration (concern 1) and crushing (concern 3) is that penetration is the structure in its whole form, whereas crushing is the structure in its pulverised form; the functional difference from a risk management point of view is that a finer mesh size would be required to prevent a pulverised tentacle from being crushed through, than for an intact tentacle to penetrate. Because *C. barnesi* nematocysts are 25–40 μm long, and *Chironex fleckeri* nematocysts are 50–90 μm long (GERSHWIN, 2006), in theory, any fabric with a mesh greater than 25 μm would be vulnerable to the crushing of tentacles. As a general rule of thumb for the typical user, this would include any fabric in which water or air can pass through without being forced.

Concern 4: Durability of the fabric. If the fabric runs or tears, or the seams split, then the integrity of the barrier is compromised. As a general rule, heavier fabrics tend to be more durable than lighter fabrics.

Concern 5: Whether products are available as one-piece garments. Several extremely serious sting events, including one fatality, have occurred where the jellyfish has been trapped under a billowing shirt or loose shorts, causing repeated stings (SURF LIFE SAVING, unpublished sting notes). Similarly, a two-piece garment may untuck under water, exposing bare skin, thus reducing the effectiveness of the product. A one-piece garment may help reduce these types of accidents.

Concern 6: Heat retention of the fabric. Fabrics can absorb heat from the sun, especially with darker colours, and can prevent heat loss from the skin—both effects increase the chances of hyperthermia or "feeling hot" in a person wearing these fabrics. If the person feels uncomfortable, the garment is likely to be removed upon each exit from the water, reducing the chances that it is resuited for the next water entry, and also increasing the chances of bringing adherent tentacles into contact with exposed skin during disrobing. In general, heavier fabrics tend to retain more heat than lighter fabrics.

Concern 7: Product cost. If the product is expensive, it is less likely to be widely adopted.

MATERIALS AND METHODS

Carukia barnesi, the common Queensland Irukandji jellyfish, was chosen as the test subject (Figure 1). Its tentacles are approximately 200 μm in diameter when relaxed; it occurs both coastally and on the reefs and islands; and its body size (1 cm) make it small enough to get through protective stinger-resistant swimming enclosures. Most other dangerous jellyfish species have thicker tentacles, so *C. barnesi* is a good model animal for a minimum standard.

Fabric selection was based on the criteria of either already having been used by the public for stinger protection, or being a logical choice for stinger protection. Product names are given for scientific repeatability, but do not imply and may not be used for product endorsement.

Fabrics were microscopically observed, by wrapping around the "lid" of a standard (90 mm) glass petri dish, then securing the fabric to one side so that the testing surface was snug but not stretched (*i.e.,* to approximate tension similar to that of a properly fitting garment). The product was then placed into a large (150 mm) glass crystallizing bowl; the bowl was filled with seawater that *C. barnesi* medusae had been raised in (and thus well acclimated to), and a mature (or nearly so) specimen of *C. barnesi* with intact tentacles was gently placed onto the testing surface. The "bottom" half of the petri dish was placed over the testing surface to keep the animal from swimming away (Figure 2). The whole testing unit was then carefully submerged into a large bucket of seawater and rotated gently, to free any bubbles caught in the system, then gently transferred to the stage of a Leica dissecting microscope to commence the testing procedure.

Each observation lasted a minimum of 10 minutes, during which time the tentacles interacting with the mesh were filmed through the eyepiece of the dissecting scope with a Sony Handycam DVD-201. Additionally, still images were captured with both the Sony Handycam and a Nikon CoolPix 995 through the eyepiece of the same scope. All video and image results have been archived and are available upon request.

Continuous variables were subjectively scored on a 1–5 scale, 1 being the least and 5 being the greatest, in either an advantageous or disadvantageous context, *i.e.,* a +5 would be more advantageous than a +3, whereas a −5 would be more disadvantageous than a −3. Binary variables were scored as 1 or 5, similarly in both contexts. Scoring in this way was chosen over a 1–10 method because many aspects considered carry serious disadvantages that would be masked by simply scoring low on the 1–10 scale; this scoring system allows for comparison of whether advantages outweigh disadvantages.

These seven concerns addressed in this study are divided into primary concerns, *i.e.,* those relating to the actual stinger-protective quality of the fabrics, and secondary concerns, *i.e.,* those that affect the products' overall functionality as stinger-protective clothing. Although not directly tested, the secondary concerns are included because they help provide a more complete understanding of relative utility of various types of stinger-protective clothing; however, testing them should be a high priority for future research.

Primary Concerns

Concern 1: Penetrability of the fabric (binary). If the mesh size of a product was sufficiently large to allow intact tentacles to freely penetrate, it was scored as penetrable; if not, it was deemed to be impenetrable in this context (but see concern 3, regarding penetrability of crushing).

Concern 2: Adherence to the fabric (continuous). Assessment was based on adherence of bell and tentacles, or tentacles in numerous places, or if adherence occurred rapidly. In most cases, jellyfish had to be forcefully removed once adhered. Incomplete adherence occurred when tentacles were dragged over ridges and valleys in the fabric and were

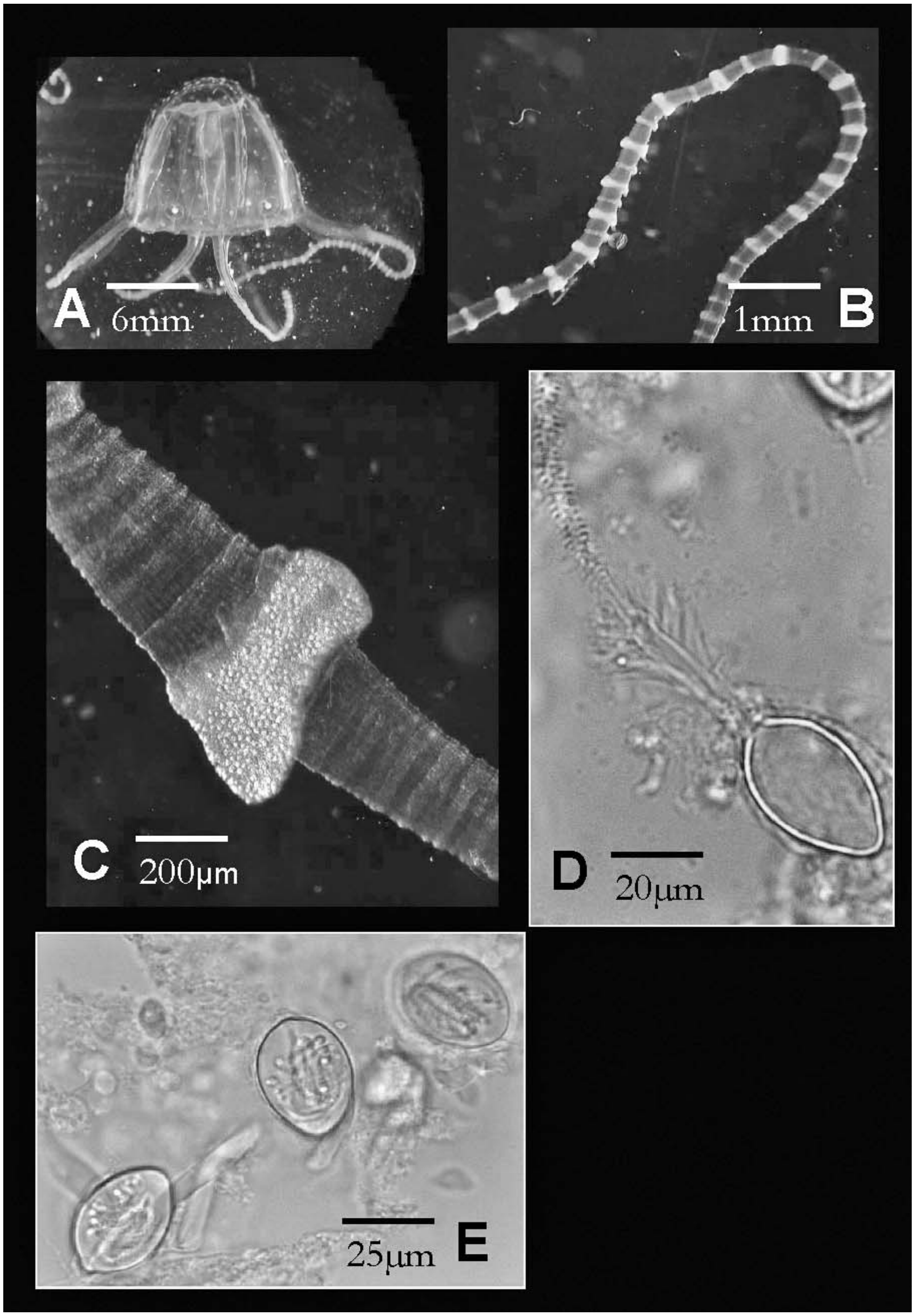

Figure 1. *Carukia.* A. *Carukia barnesi,* adult specimen, approximately 11-mm bell height, photographed under dissecting microscope. (Figure 1A copyright is owned by the author.) B. *Carukia barnesi,* tentacle under dissecting microscope; note bands of stinging cells. Uncontracted tentacle diameter is approximately 250 µm (¼ mm). When completely relaxed, major bands are approximately 2 cm apart. C. *Carukia barnesi,* close-up of a tentacle section under microscope; the bright-coloured dots on the band are the stinging cells themselves (approx. 25 µm long). D. *Carukia shinju* tentacular nematocyst, discharged. E. *Carukia shinju* tentacular nematocysts, undischarged. **For a color version of this figure, see page 150.**

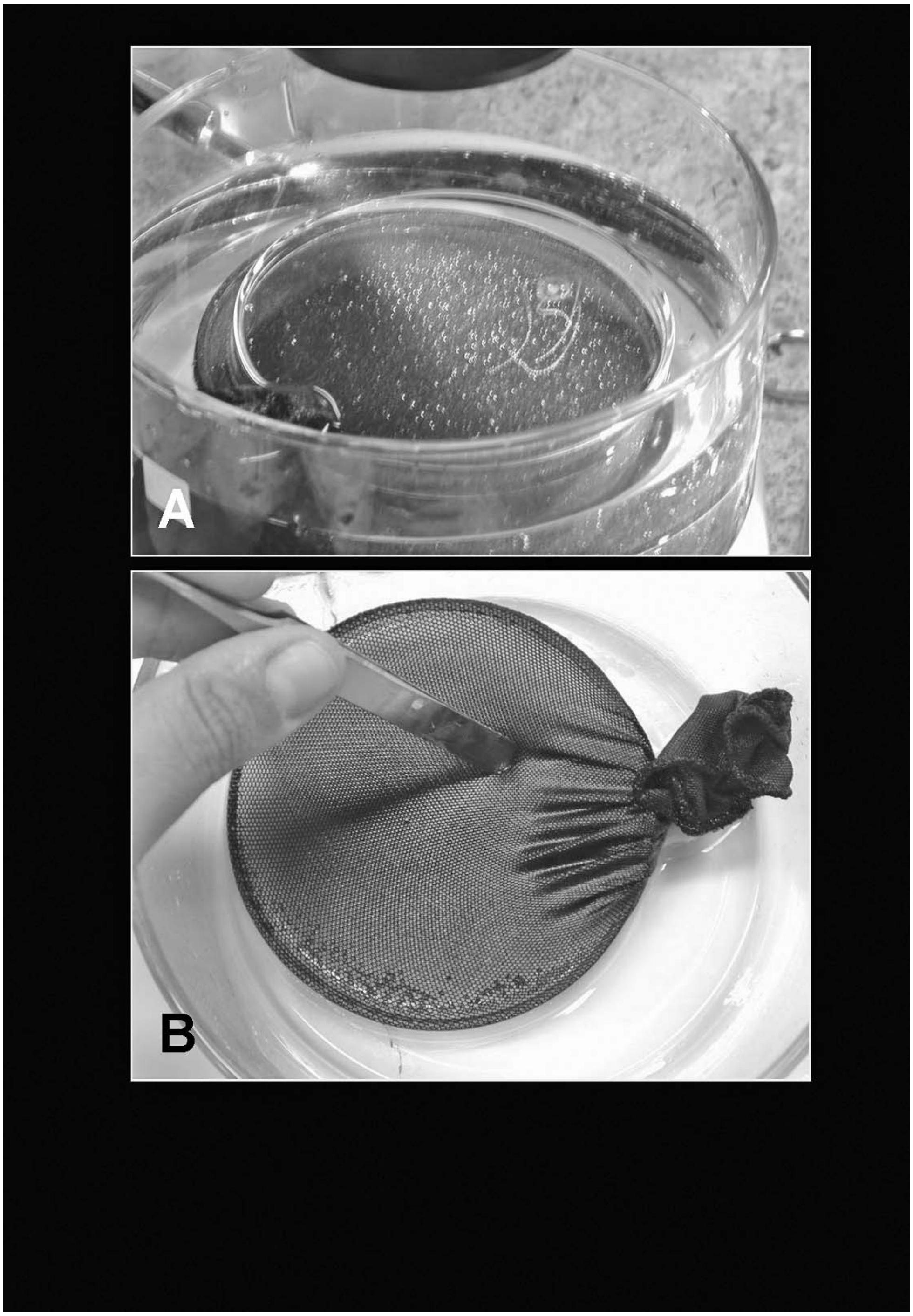

Figure 2. Testing apparatus. A. Testing chamber; note fabric stretched across petri dish, with smaller petri dish cap to keep medusa from swimming off testing surface, all placed inside a larger glass bowl. B. Testing chamber, uncovered. Forceps used to illustrated tautness of fabric, pulled snug, but not stretched to expansion. Garment in this figure is the ROBIS product, but all products were tested at a similar snugness. It should be noted that some body types and activities would stretch fabrics more than others. **For a color version of this figure, see page 151.**

"caught", but were not actually ensnared or entangled in fibres.

Concern 3: Crushing of the tentacles through the fabric (continuous). Assessment was made on whether crushing was likely to be somewhat resisted by the fabric (*e.g.,* thicker fabrics) or not resisted at all (*e.g.,* thinner, more see-through fabrics).

Secondary Concerns

Concern 4: Durability of the fabric (continuous). Assessment was based on likelihood of the fabric to run (*e.g.,* pantyhose) or rip (*e.g.,* delicate fabrics), or to split at the seams (*e.g.,* unreinforced sewn fabrics).

Concern 5: Whether products are available as one-piece garments (binary). One-piece garments were scored as highly advantageous (5); two-piece garments were scored as highly disadvantageous (5).

Concern 6: Heat retention of the fabric (continuous). Assessment was based on likelihood of the wearer becoming overheated. Rapid overheating scored higher on the disadvantage scale than slower overheating, whereas good heat dispersal properties scored with greater advantage.

Concern 7: Product cost (continuous). Products were assessed from inexpensive to expensive, according to the cost of a full suit, if available only as two-piece.

SLS Lycra Body Suit

The sleeve from an old, repeatedly worn and laundered SLS Lycra suit was tested. These are thicker than the standard commercially available Lycra suits. A red section was tested preferentially over yellow, to provide contrast for filming. Whether the "wornness" factor of the suit had any effect was not tested, as most suits would be worn repeatedly in normal SLS operations.

ROBIS Stinger Suit

A new and previously unused glove was tested straight from the package. A black suit was used, to provide contrast for filming. Whether the "newness" of the glove had any effect was not tested, but is believed to possibly present an unnatural situation, since most suits would be likely to be worn repeatedly.

Fine, Sheer Pantyhose

A new and previously unused anklet-style garment was tested, marketed as Kolotex Kicks Fresh Anklets. The darkest colour found was used, to provide contrast for filming. Whether the "new" factor of the garment had any effect was not tested, as most pantyhose products would be unlikely to be worn repeatedly.

Thicker-Threaded Pantyhose

A new and previously unused anklet-style garment was tested, marketed as Kayser Razza-matazz Opaque Anklet. The darkest colour found was used, to provide contrast for filming. Whether the "new" factor of the garment had any effect was not tested, as most pantyhose products would be unlikely to be worn repeatedly.

Silky Pantyhose

A new and previously unused knee-hi-style garment was tested, marketed as Kmart NOW Legwear Sheer Anklets. The darkest colour found was used, to provide contrast for filming. Whether the "new" factor of the garment had any effect was not tested, as most pantyhose products would be unlikely to be worn repeatedly.

Nike Dri-Fit Sport Shirt

A new and previously unworn sport shirt was tested. This product had two types of mesh, one with a closed weave and the other with regularly spaced small holes; a section of the shoulder area was used for testing, so that both types of mesh could be tested simultaneously. Whether the "new" factor of the garment had any effect was not tested, but is believed to possibly present an unnatural situation, since most PPE of this type would be likely to be worn repeatedly.

ScubaPro 0.5-mm Neoprene Wetsuit

The wrist section of a new and previously unworn 0.5-mm blue neoprene wetsuit was tested. Whether the "new" factor of the garment had any effect was not tested, but is believed to possibly present an unnatural situation, since neoprene PPE would likely be worn repeatedly.

Low Alpine Dry Zone Trek Wear

The wrist section of a new and previously unworn gray-coloured Low Alpine brand trekking shirt was tested. Whether the "new" factor of the garment had any effect was not tested, but is believed to possibly present an unnatural situation, since PPE of this type would likely be worn repeatedly.

Comparative Ranking of Tested Products

The categories of envenomation reduction that we have identified, and are further explained in the objectives section above, include (1) impenetrability of fabric weave; (2) resistance of tentacle adherence to fabric; (3) possibility of crushing tentacles through fabric; (4) durability of fabric, *i.e.,* integrity of barrier; (5) whether available in one piece; (6) heat-retention properties; (7) cost of the product.

Each product is ranked for each of the above categories on a scale of 1 to 5 as follows: For advantages, 1 = poor, 2 = substandard, 3 = satisfactory, 4 = above standard, and 5 = excellent. For disadvantages, 5 = poor, 4 = substandard, 3 = satisfactory, 2 = above standard, and 1 = excellent.

The different items tested are summarized in Table 1, along with their advantages and disadvantages. An overall assessment is based on the general probability of reducing envenomation, given the seven factors of concern. Items are ranked in the table with the highest overall protection at the top, and the lowest overall protection at the bottom. Numerical ratings are summarized in the bottom of each overall assessment section.

Table 1. *Comparison of clothing products used for protection against jellyfish stings.*

Item	Advantage	Disadvantage	Overall Assessment
ScubaPro 0.5-mm neoprene wetsuit	(1) Impenetrable (5) (2) Tentacles cannot crush through fabric (5) (3) Very durable (5) (4) Available as one piece (5)	(1) High risk of overheating (5) (2) Tentacles may adhere to surface (4) (3) Expensive ($150–200) (5)	Advisable for high-risk conditions, but too hot for normal conditions {20/14}
SLS-issue Lycra body suit	(1) Tentacles cannot penetrate mesh (5) (2) Quite durable (4) (3) Available as one piece (5) (4) Relatively inexpensive ($60–70) (4)	(1) Poor heat dispersion (3) (2) Tentacles may catch on surface (3) (3) Tentacles can be crushed into mesh (3)	Recommended for normal level of stinger protection {18/9}
Low Alpine Dry Zone trekking shirt	(1) Tentacles cannot penetrate mesh (5) (2) Tentacles do not catch on mesh (5) (3) Cool (4) (4) Quite durable (4)	(1) Tentacles may be crushed through fabric (3) (2) Not available as one-piece suit (5) (3) Expensive ($60 shirt) (5)	Recommended for situations where one-piece Lycra is not practical {18/13}
Nike Dri-Fit sport shirt	(1) Tentacles cannot penetrate mesh (5) (2) Tentacles do not catch on mesh (5) (3) Cool (4) (4) Quite durable (4)	(1) Tentacles may be crushed through fabric (3) (2) Not available as one-piece suit (5) (3) Expensive ($60 shirt) (5)	Recommended for situations where one-piece Lycra is not practical {18/13}
Pantyhose: Kmart NOW Legwear Sheer Anklets (silky)	(1) Tentacles cannot penetrate mesh (5) (2) Tentacles do not catch on mesh (5) (3) Cool (4) (4) Inexpensive (<$10) (5)	(1) Tentacles may be easily crushed through fabric (5) (2) Not durable (5) (3) Not available as one-piece suit (5)	Recommended for low-activity situations; reduces tentacle adherence {19/15}
Pantyhose: Kayser Razza-matazz Opaque Anklets (thick, black thread, nonsilky)	(1) Tentacles cannot penetrate mesh (5) (2) Cool (4) (3) Inexpensive (<$10) (5)	(1) Tentacles somewhat prone to catching on fabric (4) (2) Tentacles may be easily crushed through fabric (5) (3) Not durable (5) (4) Not available as one-piece suit (5)	Low to moderate level of protection; better than cheaper pantyhose {14/19}
Pantyhose: Kolotex Kicks Fresh Anklets (thin, sheer thread, nonsilky)	(1) Tentacles cannot penetrate mesh (5) (2) Cool (4) (3) Inexpensive (<$10) (5)	(1) Tentacles prone to catching on fabric (5) (2) Tentacles may be easily crushed through fabric (5) (3) Not durable (5) (4) Not available as one-piece suit (5)	Better than nothing, but high risk of tentacle adherence, increasing sting possibility {14/20}
ROBIS Pty. Limited Stinger Suit	(1) Lightweight and cool (5) (2) Available as one-piece suit (5) (3) Inexpensive ($25–40) (4)	(1) Tentacles drape into open mesh and plunge through it, *i.e.*, highly penetrable (5) (2) Body and tentacles adhere to surface (5) (3) Tentacles would easily crush through fabric (5) (4) Not durable (5)	Equivocal on prevention of lethal *Chironex* envenomation, but may promote *Carukia* sting by trapping tentacles; not recommended for most activities {14/20}

RESULTS AND SPECIFIC REMARKS

Seven of the eight products tested are permeable to crushing of tentacles or other medusa body parts, potentially resulting in envenomation. The only product known to the authors at this time that would be completely impermeable would be neoprene, which is typically regarded as too hot for normal wear.

All products tested have mesh that is too fine to allow intact penetration of tentacles, except the ROBIS Stinger Suit product.

About half the products are believed to be durable enough for normal activity, *i.e.,* the protective integrity of the product remaining intact; all three pantyhose products are believed to be too delicate for normal active wear.

SLS Lycra Body Suit

Carukia barnesi tentacles were not able to penetrate the Lycra mesh (Figure 3A). There was a notable "stickiness" of the tentacles to the product, believed to be the result of attempts at horizontal movement by the jellyfish over the ridged surface of the product, *i.e.,* the tentacular bands were easily caught in the "valleys" and could not get over the

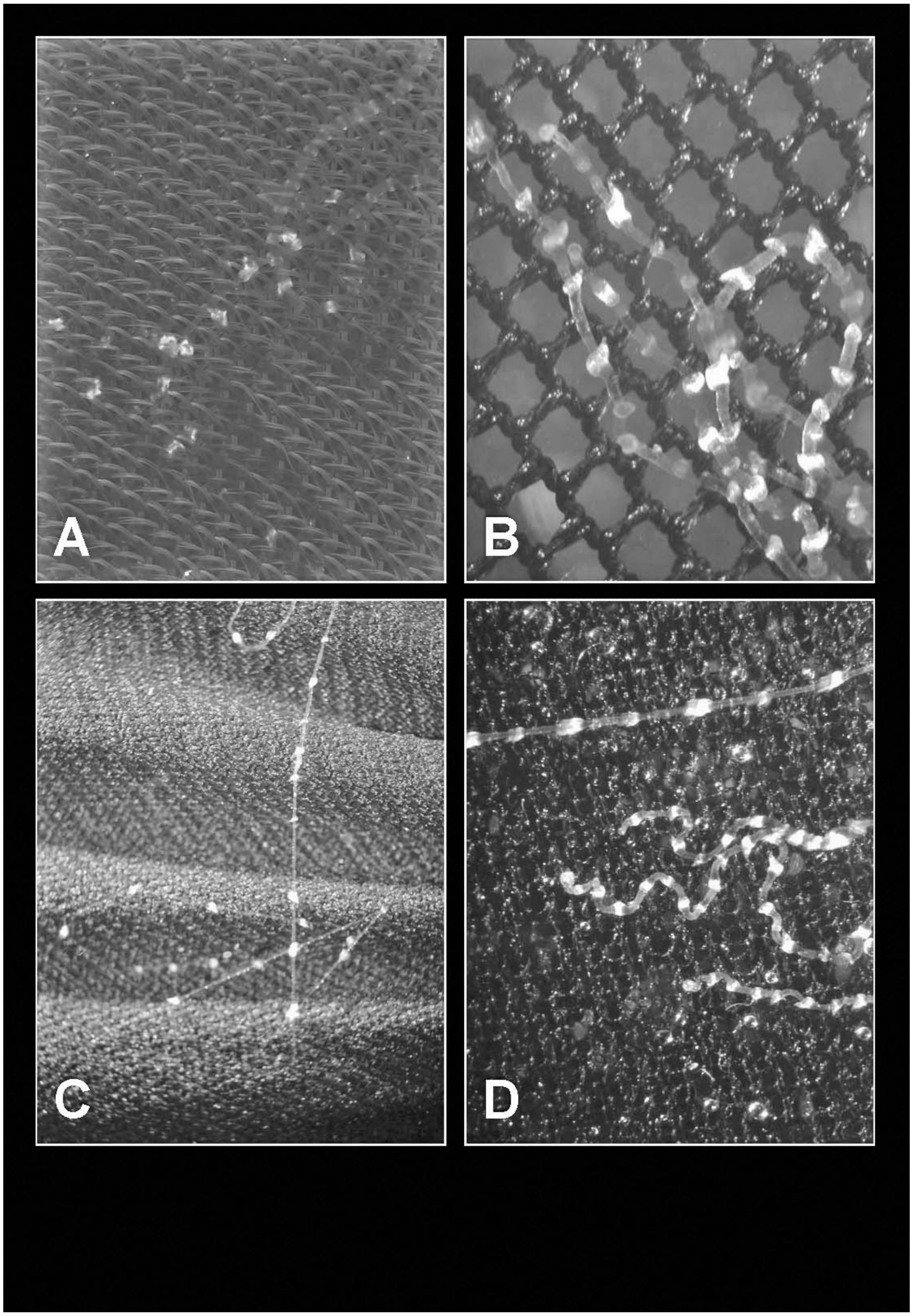

Figure 3. Product results. A. *Carukia barnesi* tentacles and the Surf Life Saving Lycra PPE. Note tentacles stretched because of catching in the mesh (upper left), compared with unstretched tentacles (lower right), evidenced by distance between major bands. B. *Carukia barnesi* tentacles and the ROBIS Pty. Limited Stinger Suit. Unstretched mesh diameter is about 1 mm. Note tentacles draping into mesh (lower left and centre), and tentacle tip plunging into mesh (upper right). C. *Carukia barnesi* tentacles and fine, sheer pantyhose. Note many places where tentacles are caught on mesh. D. *Carukia barnesi* tentacles and the thicker-threaded pantyhose. Note stretched tentacle that has caught on the mesh (right). **For a color version of this figure, see page 152.**

"mountains" of the fabric. It is possible that this is an artefact of the suit being used rather than new, but this was not tested and remains unknown. It is also possible that it is an artefact of moving slowly over a corrugated surface, but would be unlikely to have this effect in a more natural context, *e.g.,* with water movement; the effect that this could have in a natural situation is unknown, but must be regarded as a possible hazard.

ROBIS Stinger Suit

Carukia barnesi tentacles easily and readily penetrated the ROBIS mesh, observed both as draping of the tentacle into the mesh at numerous points along the tentacle, as well as plunging of the tentacle tips through the fabric to considerable depths (Figure 3B). It was also observed that the tentacles actively probed around while inside the mesh, raising the possibility of further injury. Furthermore, periodically the animal would rapidly contract the tentacles, pulling them out of the mesh, but retraction of the tentacles was sometimes hampered by brief catching on the mesh.

Carukia barnesi bells repeatedly adhered to the mesh, providing an opportunity for the animal to become stuck to the garment long enough for tentacles to penetrate the mesh, or medusa body parts to be crushed through the fabric, in a real-life recreational situation.

These results differ substantially from the findings of SEYMOUR (2002, 2004), who concluded that the Stinger Suit "does afford the wearer a significant amount of protection, which . . . equates to similar levels of protection as seen by Lycra suits" (SEYMOUR, 2004). He specifically stated that *C. barnesi* was tested (SEYMOUR, 2004), although the methodology of these tests was not provided.

Fine, Sheer Pantyhose

Carukia barnesi tentacles were not able to penetrate the fine, sheer pantyhose mesh (Figure 3C). However, the tentacles became so complexly adhered to the mesh that they had to be removed with dissecting tools and in the end, a tentacle was lost to the process. We believe that the "roughness" of the fabric surface acts like a Velcro adhesion and is prone to tentacle capture.

Thicker-Threaded Pantyhose

Carukia barnesi tentacles were not able to penetrate the thicker-threaded pantyhose mesh (Figure 3D). However, like the fine, sheer pantyhose, but to a somewhat lesser extent, the tentacles became adhered to the mesh. We believe that the "roughness" of the fabric surface is similarly prone to tentacle capture.

Silky Pantyhose

Carukia barnesi tentacles were not able to penetrate the silky pantyhose mesh, which is semiopen on the outer surface with finer cross-fibers below (Figure 4A).

During the testing, the tentacles were observed to be caught (evidenced by the struggling medusa against tightened tentacles); however, after testing this was recognized to be due to two artificial factors, one of which may be risky and one which is not. One of the tentacles was terribly entwined in a loose thread from a "run" in the pantyhose caused by the jellyfish-holding container during transfer of the medusa to the testing chamber. Loose threads from such a run could thus pose a hazard during normal use. Another tentacle was later observed to have been caught by the edge of the upper petri dish where it lay against the mesh at the outer edge of the testing chamber; this situation would be unlikely to pose a normal hazard. Repeated subsequent attempts at sticking the tentacles and bell to the mesh were unsuccessful.

Nike Dri-Fit Sport Shirt

Carukia barnesi tentacles were not able to penetrate either of the styles of the Dri-Fit mesh during testing; however, we believe that under some circumstances the chance for penetration through the "holed" mesh would be possible (Figure 4B). Neither the bell nor tentacles were observed to stick the product.

ScubaPro 0.5-mm Neoprene Wetsuit

Carukia barnesi tentacles were not able to penetrate neoprene; it is believed to be fully impenetrable to tentacles and loose nematocysts (Figure 4C). Some adhesion of tentacles to product surface was observed; however, because penetration and crushing would be unlikely to occur with this product, this is believed to create a hazard only in terms of unsafe disrobing practices.

Low Alpine Dry Zone Trek Wear

Carukia barnesi tentacles were not able to penetrate the Low Alpine product during testing; we believe that this product is comparable with Lycra in protection from tentacle penetration (Figure 4D). However, neither the bell nor tentacles were observed to stick the product, making it a good option.

Comparative Ranking of Tested Products

A comparison of the advantages and disadvantages is presented in Table 1. It should be noted that there is a trade-off between penetrability of fabric and heat retention, with the highest level of protection (neoprene) also highly likely to cause heat-related health problems, but the highest level of heat-related protection (Stinger Suit) also likely to allow penetration of *Carukia* tentacles. It is therefore our recommendation to consider the seven factors enumerated above in light of particular desired activities when choosing PPE. We strongly support the use of items listed in the first five rows, where we believe the advantages outweigh the disadvantages. We further recommend a full-body Lycra suit as the ideal stinger-protective clothing, in that it provides reasonable protection against tentacle penetration, it is available in a one-piece suit, thus preventing trapping of jellyfish against the skin, and it is relatively widely available at a low cost.

DISCUSSION

At this time, the number of nematocysts required to cause full-blown Irukandji syndrome is unknown, but is likely to be

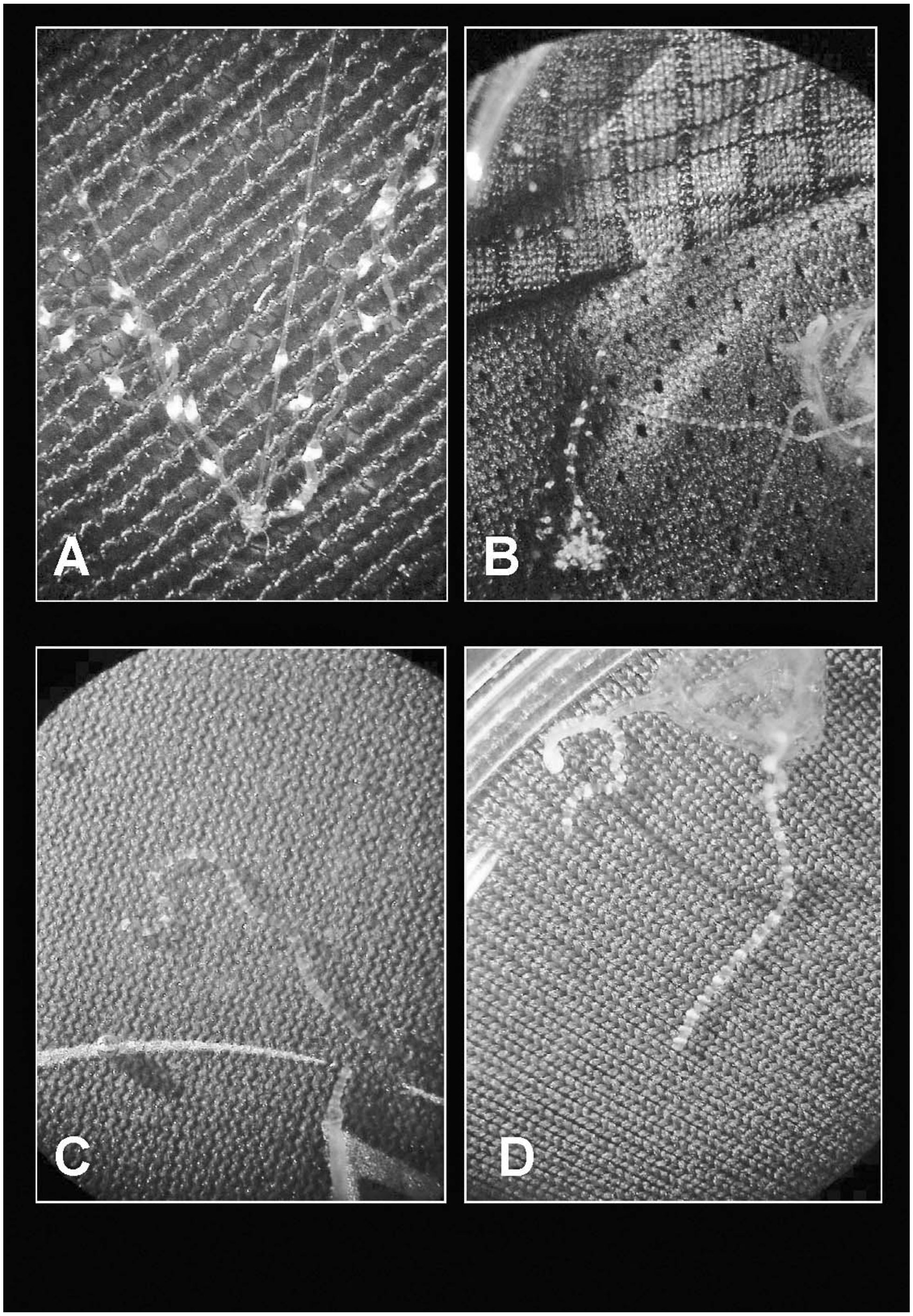

Figure 4. Product results. A. *Carukia barnesi* tentacles and the silky pantyhose. Note the tentacles entangled in a loose thread from a run (centre and bottom), and a stretched tentacle caught in the edge of the testing chamber (beyond photo, to left). Once these two issues were resolved, the tentacles and bell could not be made to stick to the fabric. B. *Carukia barnesi* tentacles and the Nike Dri-Fit sport shirt. Note two types of weave in the test area, a weave with regularly spaced small holes to the left, and a closed weave to the right. C. *Carukia barnesi* tentacles and the ScubaPro 0.5-mm neoprene wetsuit. D. *Carukia barnesi* tentacles and the Low Alpine Dry Zone trek wear. Note that in both the neoprene and trek wear, the weave is too tight to allow tentacles to readily penetrate. **For a color version of this figure, see page 153.**

very small, perhaps on the order of tens or hundreds, given the small wounds typically visible (Williamson *et al.,* 1996). Thus, a conservative approach would be to prevent even small fragments of tentacle or bell from coming into contact with human skin. Fabrics that allow tentacles to penetrate intact, or products that allow gap openings, are particularly vulnerable to envenomation accidents.

Adoption of Stinger-Protective Clothing

Numerous explanations have been proposed for the lack of public adoption of Lycra stinger suits: they are too hot, they are too expensive, they are not readily available at the beaches or on charter boats, they are not fashionable, and they prevent the wearer from getting a suntan. Essentially, resistance may be grouped into either acceptability, accessibility, efficacy, or safety; many of these are legitimate concerns, and products and procedures to overcome them are being examined.

Acceptability

The issues of acceptability, *i.e.,* fashionable PPE and sunbathing, are perhaps the most complex of all. Lycra provides significant protection from the sun's UV rays; this can be viewed as a positive attribute by those wishing to limit their exposure to the sun and reduce their risk of developing skin cancer, but a negative attribute by those wishing to get a good suntan. One possible solution for those wishing to get a suntan would be to wear the suit while in the water, thus protecting from too much sun and from stingers at the same time, but to remove the suit while sunbathing on the beach for brief periods.

Current designs for stinger-protective clothing are simply not flattering for just about all body types. Stinger PPE may become fashionable as better designs become available and as people become more comfortable with wearing it as a normal part of their aquatic activities. Currently, most advertisements show scantily clad models; perhaps integrating sun safety and stinger safety into marketing messages will help to integrate these two important aspects into the mainstream.

Accessibility

Most charter operators now carry Lycra or neoprene suits, available either free of charge or for a nominal cleaning fee to divers and snorkelers. Similarly, most dive shops have Lycra or neoprene suits for hire. Protective clothing at beaches has proven more difficult to implement, and as yet, as far as we are aware, only Cable Beach in Broome, Western Australia, has a formal beach hire for PPE. We applaud this proactive approach to stinger safety, and hope that other regions throughout the tropics where stingers are most abundant will adopt such programs.

Efficacy

Current designs of protective clothing cover from neck to wrists to ankles, leaving most people with a natural concern about stings to the hands, feet, or face. It has been estimated that 75% of stings from the 2001–2002 season would have been prevented if protective clothing had been worn (P. Pereira, widely distributed Powerpoint presentation). Indeed, box jellyfish stings typically occur on the legs, because box jellyfish typically swim near the bottom, and Irukandjis typically swim near the surface, so most stings occur on the parts of the body at the water's surface (Gershwin, unpublished data).

Some of the larger charter operators are now using Lycra suits made with hoods and gloves integrated into the suit, which not only increase the protective quality, but also increase the wearer's feeling of protection (informal community survey, Airlie Beach markets, October 2007).

A product was developed by the pearl divers in Western Australia that they call a "stinger guard". This neoprene face mask is worn in conjunction with a hood, and has a large hole fitted around the mask, and a smaller hole in a Velcro-fastened quick-release flap fitted to the regulator or snorkel. Thus, the exposed skin can be reduced to very near zero. Another option, which is used by many divers in conjunction with a full-body suit, is to rub a thick layer of zinc cream or petroleum jelly over the exposed skin of the face and hands; Burnett and his colleagues (1968) studied the effect of petroleum jelly on sting prevention, concluding that it mechanically blocks the discharging nematocyst thread, and that the thickness of ointment necessary to prevent a sting is greater if tentacles are in motion. Thus, it appears possible to reduce sting potential to very low levels by wearing full PPE and applying a generous layer of petroleum jelly to the remaining exposed skin.

Safety

A study by Sinclair (2003) suggested that Lycra suits may cause heat-related illness in children, who do not thermoregulate as efficiently as adults. In practice, however, children tend to make frequent visits to the water while at the beach, thus minimizing problems associated with heat retention (G. Gage, personal communication).

The bigger concern might be with neoprene, which is required by James Cook University and SLS because of its quality of being impenetrable. A full discussion of thermal stress is beyond the scope of this paper, but it can be extremely serious and should be considered in all activities where stinger-protective clothing is being used.

Mechanisms for Suit Activity

Several mechanisms have been proposed for how the suits actually protect from stings: (1) that suits provide a physical barrier between jellyfish and skin (Williamson *et al.,* 1996), (2) that suits fool the jellyfish into thinking that the wearer is neither predator nor prey by taking away the "taste" of a living organism (Rose, 2005), (3) or that the colour red acts as a repellent against jellyfish (Ficara, 2005; Jeffery, 2005; Robinson, 2005). The first mechanism prevents a significant sting regardless of whether the nematocysts discharge, whereas the second and third rely on the jellyfish or its inanimate nematocysts to make the right decision to prevent envenomation.

There are, to date, no published scientific works addressing the issue of colours as jellyfish repellents, and yet, the notion persists in the common knowledge on the basis of several news articles about dangerous stingers being repelled by the colour red (Ficara, 2005; Jeffery, 2005; Robinson, 2005). Recent studies indicate that some jellyfish may see different colours (Coates *et al.,* 2006; Garm *et al.,* 2007); however, even if a repellent quality could be demonstrated in controlled experiments, its utility in the real world would be questionable. Uncontrollable variables would persist such as current speed and direction, unpredictable human body movements, differential alertness of jellyfish specimens, and differential height in the water column between jellyfish and red swimwear.

"Taste" has been invoked as the mechanism by which the Stinger Suit works, *i.e.,* it masks the "predator or prey taste" of the wearer (Barnes, 1967; Kinsey, 1986; Rose, 2005). The idea is not without a basis: sea anemones quite famously do not sting their anemone fishes, and *Ch. fleckeri* has been said to sting or withhold according to its mood, and may ignore glass, metal, sand, rocks, *etc.,* when unexcited (Barnes, 1967). Indeed, a whole body of literature exists on the science of nematocyst discharge and inhibition, and is believed to involve a delicate combination of chemical and mechanical stimuli as well as the satiety of the animal (Lentz and Barrnett, 1962; Mariscal, 1974; Picken and Skaer, 1966; Williamson *et al.,* 1996). However, nematocysts also discharge long after their owner is detached or the tentacles are dried (Hartwick, Callanan, and Williamson, 1980; Williamson *et al.,* 1996), indicating that under some conditions discharge may be purely mechanical (Picken and Skaer, 1966), and *Ch. fleckeri* tentacles typically stick to the sides of collecting containers, even clean ones (L. Gershwin, unpublished notes), indicating that they do not only sting animate targets. Even if they sometimes ignore objects when unexcited, there is no assurance that any given encounter will not excite the animal. According to Picken and Skaer (1966), experiments with *Hydra* demonstrated that, "mechanical stimulation discharged some nematocysts, but many more were discharged if a mechanical stimulus was applied in the presence of a food extract." Thus, a product seeking to mask the human taste might conservatively be expected to have a very fine mesh, so as to eliminate gaps between the mesh, which do taste human; in that case, whether the product does or does not eliminate the taste, it would be effective in reducing contact when the animal is agitated. Nonetheless, the interesting question of taste inhibition has not been scientifically demonstrated to offer complete protection from box jellies or Irukandjis, or for any type of protective clothing.

Whereas the above two mechanisms rely on the jellyfish or its nematocysts to make the right decision to prevent a sting, the barrier mechanism gives control over envenomation back to the user. Although the processes involved in nematocyst discharge are clearly complex, on the most basic level, nematocysts work on a hair-trigger mechanism, with the stiffened shaft and flexible tubule coiled inside the capsule and everting, or turning inside out, with up to about 40,000 times the force of gravity, when the cnidocil is stimulated (Halstead, 1971; Holstein and Tardent, 1984; Kass-Simon and Scappaticci, 2002). The farther away a nematocyst is from skin at the time of discharge, the less velocity the shaft will have for penetration. Irukandji nematocyst shafts are about 25–45 μm long, and *Ch. fleckeri* shafts are about 50–90 μm long (Gershwin, 2006). Therefore, in theory, a barrier greater than 90 μm thick should significantly reduce the opportunity for envenomation; this has not been formally tested, but identifying the parameters of protection should be a high priority for future research.

In general, future research should focus on methods of integrating protective clothing into mainstream behaviour, and on finding an optimal fabric type that balances the requirements of protection from nematocysts with thermal stress safety. It is highly desirable that an Australian Standard for stinger protective equipment be developed.

PRIMARY CONCLUSIONS

Penetration: All products tested except the ROBIS product are too fine-meshed to allow tentacles to penetrate the fabric under normal circumstances; tentacles draped into and plunged into the ROBIS product, providing a potential hazard for increased envenomation by trapping the tentacles against the wearer's skin. Future studies should seek to quantify the number and depths of penetrations, and put this into context of real-world sting risk.

Adherence: The two "nonsilky" pantyhose products clearly promoted tentacle adherence; tentacle bands were caught horizontally in the texture of the SLS Lycra garment; the bell readily adhered to the ROBIS product. Prolonged adherence to garments could enhance probability of envenomation by two methods. First, prolonged contact with garments could increase probability of tentacle penetration or crushing of medusa body parts, simply by still being in contact with the fabric. Second, attachment of tentacles could result in detachment from the medusa, and subsequent envenomation during disrobing from unnoticed tentacles. Future studies should seek to quantify the frequency and duration of adherences of different fabrics, and put this into context of real-world sting risk.

Crushing: All products tested except neoprene are penetrable to medusa body parts crushed into the fabric, such as might occur during activity inside the elbow, under the armpit, or between the legs, resulting in envenomation. The only product currently known to us to resist tentacle crushing complications is neoprene, which appears to provide an impenetrable barrier.

SECONDARY CONCLUSIONS

Durability: The three pantyhose products appear to be too delicate for normal occupational and recreational activity, resulting in runs, seam splits, or other lapses in barrier integrity; the ROBIS product might also be considered too delicate for repeated wear during normal activity. Neoprene appears to be the most durable of the products we tested.

One-piece: Neoprene, Lycra, and the ROBIS product are marketed as a one-piece garment, whereas the other products currently are not. Care must be taken with two-piece garments to minimise billowing or gap openings, to ensure that jellyfish cannot become trapped between the clothing and the wearer's skin.

Heat retention: All products tested are believed to be cooler than neoprene, and thus more likely to be wearable for prolonged periods during occupational and recreational activities.

Cost: Neoprene and the sport products retail above $100; Lycra retails for between $50 and $100; the ROBIS product retails at about $30; pantyhose retail at less than $10. High-cost items are less likely to be replaced with minor rips or tears, whereas low-cost items are probably more likely to be replaced, but possibly also more likely to develop integrity breaches.

RECOMMENDATIONS

Protective clothing should be worn during occupational or recreational activity in waters where marine stingers may be present, particularly for people who may be at heightened risk, such as children, pregnant women, and people with hypertension.

Because Irukandji tentacles are approximately ¼ mm, protective clothing with a mesh size greater than ¼ mm may provide inadequate protection.

Care should be taken to minimise gap openings where skin may become exposed or where whole animals or tentacles may become trapped against the skin, *e.g.,* between tops and bottoms of two-piece suits, or between gloves and sleeves, booties and leggings, or hoods and masks.

Adherent tentacles may come into contact with skin during disrobing; thus, all precautions must be taken to neutralize any adherent nematocysts before disrobing. Safe PPE disrobing practices to minimise stings from adherent tentacles: rinse with vinegar or freshwater (*i.e.,* tap water); wait 60 seconds before disrobing.

We assert that the term "stinger suit" should revert to being in the public domain in the generic context, as it has been used for over 20 years by SLS and other organizations concerned with marine stinger management, *i.e.,* to mean any type of stinger-protective clothing; the name should not be available for exclusive corporate use.

Note: No product endorsement of any kind is implied or should be inferred from these tests. These tests were conducted in the interest of scientific enquiry and public safety only, with no commercial contribution of any kind.

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