ANALYTIC INDICATION OF THE IMPRACTICABILITY OF WATERBORNE CHEMICALS FOR REPELLING AN ATTACKING SHARK
A Second, Confirming Look

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Chemical shark repellents for use by operational military personnel must be of such high potency that the size and weight of a life jacket packet will not degrade the wearer's performance of duty. Considerable research effort has been devoted to developing an effective replacement for the discontinued Shark Repellent Compound (Shark Chaser) of World War II. Earlier systems analyses indicated that actual incapacitation of an attacking shark would require inordinate quantities of recognized poisons. Recent studies on potent marine toxins, such as secretions from the Moses sole (Pardachirus marmoratus) and related surfactant chemicals, have indicated need for reanalysis of the potential of waterborne chemicals for repelling sharks. Parametric studies by others of three-dimensional diffusion in the ocean permit us to estimate the repellent release rate required to maintain a minimum effective concentration of chemical at the outer boundary of a specified volume of water surrounding a potential attack victim. Realistic restrictions on the release rate dictate a minimum effective concentration of chemical at the outer boundary of a specified volume of water surrounding a potential attack victim. Realistic restrictions on the release rate dictate the potency necessary for any candidate repellent chemical to be seriously considered as a possible replacement for Shark Chaser. Such analytic reasonings clearly indicate that the potency reported for Moses sole secretion and related detergents to be two to three orders of magnitude too low for such substances to serve as practical shark repellents in the classic continuous release mode. The following guidelines in terms of realistic estimates of minimum acceptable potencies are proposed for future development of chemical shark repellents for use by military personnel in the field:

1. the candidate repellent material would have to be essentially instananeous effective at a concentration no greater than 0.1 g/m³ (100 parts per BILLION), or
2. where the effect is less than instantaneously produced, the exposure integral (i.e., time-to-effect multiplied by the concentration required for effective repellency) should be no greater than 0.1 second g/m³.
SUMMARY

OBJECTIVE

Investigate the practicability of waterborne chemicals for repelling an attacking shark.

RESULTS

Parametric studies by others of three-dimensional diffusion in the ocean permitted us to estimate the repellent release rate required to maintain a minimum effective concentration of chemicals at the outer boundary of a specified volume of water surrounding a potential attack victim. Realistic restrictions on the release rate dictate the potency necessary for any candidate repellent chemical to be seriously considered as a possible replacement for Shark Chaser. Such analytic reasonings clearly indicate potencies reported for Moses sole secretion and chemically related detergents to be two to three orders of magnitude too low for such substances to serve as practical shark repellents in the classic continuous release mode.

RECOMMENDATIONS

The following guidelines in terms of realistic estimates of minimum acceptable potencies are proposed for future development of chemical shark repellents for use by military personnel in the field:

1. The candidate repellent material would have to be essentially instantaneously effective at a concentration no greater than 0.1 g/m³ (100 parts per BILLION), or

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INTRODUCTION

Naval personnel, divers in particular, cope with a variety of shark problems with weapons ranging from billy clubs to modified firearms. Such anti-shark devices require very deliberate, coordinated actions by the user, and the resulting deterrent effects are highly localized and directional. The true shark repellent in the Navy context is not a chemical weapon for ACTIVE aggressive use against sharks. Instead, it is a nondirectional PASSIVE means for increasing the prospects of survival and rescue at sea by cloaking the potential attack victim in an enveloping cloud of repellent.

There is a firm, very demanding requirement for any practical shark repellent intended for use by operational military personnel:

The active principle must be of such high potency that enough of it for effective action over a reasonable period of time can be compounded into a packet of such size and weight as to be compatibly attached to a standard military life jacket and not by its presence significantly degrade the ability of the wearer to perform his duties.

For the Shark Repellent Compound (Shark Chaser) of World War II, such stringent packaging requirements led to a flat cake of chemicals less than 1 inch thick, measuring only about 3 by 4 inches. This life jacket packet contained only about 170 grams of what was then considered to be active ingredients, compounded so as to dissolve fairly evenly over a period of about 3 1/2 hours (Ref. 1).

Postwar studies on Shark Chaser seriously questioned its overall effectiveness and ultimately led to cancellation of its procurement by the Navy in 1976 (Ref. 2), largely in response to specific recommendations for such action by the Office of Naval Research (ONR) (Ref. 3). The ONR concluded further that "an effective substitute for Shark Chaser is clearly needed." The United States Air Force, in preparing to withdraw Shark Chaser from its own inventory, officially "emphasized that there still is a need for an effective shark repellent" (Ref. 4). Considerable effort in both basic and applied
research has been devoted over the past two decades towards this as yet unsatisfied requirement (Ref. 5).

Baldridge (Ref. 6, 7) presented a strong case against the practical use of incapacitating drugs for prevention of shark attacks on persons floating at the surface of the sea. Baldridge studied many highly toxic materials to develop a sense of the dose required to produce in sharks clearly discernible behavioral manifestations of physiological responses. Dose was taken to mean the integral of drug concentration with respect to time, \( \int C dt \), that a shark would experience in traversing a positive concentration gradient in its approach to the center of dispersion of a waterborne drug. Baldridge concluded on mathematical analysis that, even under optimal conditions, an inordinate quantity of drug would be required to establish an enveloping cloud strong enough to incapacitate an incoming shark. About 24 kg (50-55 lb) of drug would have to be held in just the volume of water that a shark would penetrate in only the last 10 seconds of its approach to a man floating at the center of the cloud of drug. This would be equivalent to about 140 packets of repellent the size of Shark Chaser.

With such clear indications of impracticability, Baldridge did not regard it necessary in his earlier analysis to consider the aggravating effects of currents or the problem of maintaining the repellent field over a period of time by continuous release of chemicals.

This early analysis cast considerable gloom on the prospects of developing a practical shark repellent of the enveloping cloud type. But, it specifically did not exclude "the possibility of developing in the future a highly effective ... repellent ... which acts at extremely low concentrations to trigger a desirable behavioral response..." (Ref. 7).

Recent studies (Ref. 8 - 13) on the toxic secretions of the Moses sole (Pardachirus marmoratus) and related detergent chemicals (Ref. 14,15,16) have suggested the possible existence among such substances of an extremely fast-acting superpotent repellent. Baldridge (Ref. 7) has cited
this repellent as essential in overcoming the patently unacceptable material demands inherent in the classic mode of repellent deployment.

So, we have taken another mathematical look at the scenario of repellent use to place Moses sole secretions and detergents in proper perspective and to propose guidelines for future development of practical shark repellents suited to Navy purposes. Because equations describing diffusion in the open ocean are now available (Ref. 17), we could consider the problem of maintaining the chemical field over a period of time by continuous release of the repellent.

Unlike in Baldridge's earlier treatment (Ref. 7), the repellent chemical has been assumed in the present analysis to be instantaneously effective once the shark has been exposed to a threshold concentration. The repellent release rate and the resulting magnitude of repellent concentration that would be maintained at the outer boundary of a given volume of water surrounding the potential victim are of particular interest. Realistic restrictions on the release rate would then dictate the level of potency required for any candidate repellent chemical to be seriously considered by the Navy as a possible replacement for Shark Chaser.

**ANALYTIC CONSIDERATIONS**

We assumed the endangered person to be floating in a calm sea while releasing a repellent chemical from a point source at the rate of $R$ grams per hour. The repellent concentration decreases with distance from the point source, falling to a value of $C$ grams per cubic meter at the outer boundary of a volume of water, $V$ cubic meters. The concentration being maintained at the boundary layer of a volume considered minimal for effective protection of the potential victim was taken to be the lowest level of chemical that will instantaneously elicit the desired repellent response from an approaching shark.

Based on the Carter-Okubo (Ref. 18) transport equation, James, Mikhail, and Schrock (Ref. 17) have developed computer codes for evaluating radioactive concentration fields resulting from continuous point source releases in the
open ocean. Although designed specifically for studying three-dimensional spread of radioactive contamination, their calculations are equally valid for other substances, including the intentional release of a chemical such as a shark repellent. From a reasonably typical set of ocean parameters determined in dye release experiments, empirical equations were constructed relating approximate boundary concentrations, release rates, and the volumes enclosed within those isoconcentration contours. Of particular pertinence to the present analysis is the following equation (Ref. 17):

\[ V = 1.18 \times 10^{-6} \left( \frac{R}{C} \right)^{2.05} \]  

for \( V > 1 \text{ m}^3 \) and \( 10^3 < \left( \frac{R}{C} \right) < 10^6 \)

Equation 1 states that, under steady state conditions in the infinite (three-dimensional) ocean environment, a release rate of \( R(\text{g/hr}) \) will support a concentration of \( C(\text{g/m}^3) \) at the outer boundary of a volume, \( V(\text{m}^3) \), said boundary concentration being independent of the actual shape of that volume.

Consideration of a restricted semi-infinite ocean environment, rather than three-dimensional infinite water space, would be more appropriate to a source (potential attack victim) floating at the surface of the sea. In the idealized repellent scenario, for example, the man would be surrounded by a hemisphere of protected water rather than the sphere that characterizes idealized three-dimensional dispersion. For this semi-infinite condition, we have approximated the reflecting effect of the surface by doubling the concentration expected from Equation 1 for any particular release rate at the boundary (other than at the sea surface) of a halved volume, giving rise to

\[ C = 1.83 \times 10^{-3} \left( \frac{R}{V} \right)^{-0.488} \]  

In optimizing our analytical conditions, we have assumed that the superpotent repellent chemical would be instantaneously effective once the shark has been exposed to a threshold concentration maintained at a reasonable minimal distance from the potential victim. That minimal distance was taken
to constitute the outer boundary of a man-enveloping protected volume of about 6 m$^3$ (approximately equal to the volume of a cylinder of 1 m radius and 2 m depth or a hemisphere of 1.4 m radius).

We have further assumed that the present weight specifications for the Navy's life jacket repellent packet could be no more than about doubled and have the product remain an acceptable item of survival gear for use by operational personnel; that is, a maximum release rate over a 3 1/2-hour period of about 100 g/hr.

Using Equation 2, we then calculated that such a release rate, under semi-infinite steady state conditions, would support a repellent concentration of only about 0.076 g/m$^3$ (i.e., 76 parts per billion) at the subsurface boundary layer of a minimal protected volume of 6 m$^3$.

We have also calculated like Baldridge (Ref. 7), that a steady release of 100 g/hr into a hemispherical field would provide an incoming (45.9 m/min swimming speed) shark with an exposure integral of only about 0.23 sec g/m$^3$ between radii of 8.7 m and 1.0 m; i.e., the last 10 seconds of its approach to the potential victim. We fully recognized that, in the more realistic survival scenario, the repellent patch would most likely not be hemispherical, but instead would be hemiellipsoidal, with a much smaller vertical (depth) dimension. Such a flattened pattern would provide a significantly lower exposure integral to a shark approaching from the depths than would an idealized hemispherical repellent dispersion.

DISCUSSION AND CONCLUSIONS

Clark's observations (Ref. 8,9,10) clearly indicate that several species of sharks are very reluctant to devour P. marmoratus, to take otherwise attractive bait fish when presented near enough to a live Moses sole as to be essentially in direct contact (i.e., separated by less than 10 centimeters), or even to strike bait fish when confronted with a sudden flood of an unspecified concentration of the sole's toxic secretion. Such qualitative studies,
however, provide little definitive information on the minimum concentration of sole secretion needed to produce discernible behavioral manifestations of repellency in large, dangerous sharks.

Primor, Bonaventura, and Bonaventura (Ref. 12) made quantitatively controlled studies of a captive Atlantic sharpnose shark (Rhizoprionodon terraenovae). When placed in tankwater containing P. marmoratus secretion at concentrations as low as 10 g/m³, the shark displayed an immediate but brief burst of hyperactivity, followed by clear signs of continuing physiological stress. These authors also found that pardaxin, an active component of the sole secretion, elicited indications of marked discomfort in a dogfish (Squalus acanthias) when administered directly to the head region of the dogfish at a concentration of 25 g/m³.

Primor, Zadunaisky, and Tu (Ref. 13), using small S. acanthias, determined LD₅₀ (1 hour exposure time) tankwater concentrations of Moses sole secretion and pardaxin to be approximately 344 g/m³ and 219 g/m³, respectively.

Equation 2 permitted us to calculate that a release rate of 13-13 kilograms per hour would be needed to maintain a concentration of 10-25 g/m³ Moses sole secretion (or pardaxin) at the boundary layer of a minimal protected volume of 6 m³. This would require the potential attack victim to carry a supply of sole secretion 300-700 times the weight of a Shark Chaser packet.

The aforementioned concentrations of Moses sole exudates of 10-25 g/m³ reported to elicit immediate indications of repellency and 219-344 g/m³ for lethality after 1-hour exposures are not remarkably low. In fact, the concentrations are comparable to the potencies of some readily available off-the-shelf chemicals. Baldridge (Ref. 6) exposed captive lemon sharks (Negaprion brevirostris) to tankwater concentrations of 10-60 g/m³ MS-222 (the methanesulfonic acid salt of ethyl 3-aminobenzoate) or 9-36 g/m³ quinaldine (2-methylquinoline), both well-known shark narcotizing agents. The sharks responded quickly with erratic swimming accompanied by splashing and gill-flexing in the corners of the tank, with the snout lifted into the air up
to the pectoral fins. Less than 2 g/m$^3$ of strychnine nitrate would be expected to produce lethal convulsions in young lemon sharks after an exposure of 1 hour. Similar clear indications of avoidance were elicited from young lemon sharks by sodium cyanide at tankwater concentrations less than 1 g/m$^3$.

In studies suggested by the high surfactant qualities of the secretions of Moses sole, Gruber and Zlotkin (Ref. 14) found synthetic detergents such as sodium dodecylsulfate to strongly repel lemon sharks. However, for the effects to be elicited rapidly, concentrations of about 800 g/m$^3$ were required.

Based on observations of minimal noticeable response to the commercial surfactant sodium lauryl sulfate, Smith and Nelson (Ref. 15) calculated "effective concentration thresholds (EC$_{50}$)" of 28 g/m$^3$ and 80 g/m$^3$ for the horn shark (Heterodontus francisci) and the swell shark (Cephaloscyllium ventriosum), respectively.

Nelson, Gruber, and Smith (Ref. 16) presented surfactants to blue sharks (Prionace glauca) in the open ocean. The sharks received sudden bursts of sodium lauryl sulfate solutions either from squirts directed to their faces, or from detergent-filled balloons, which ruptured in their mouths when taken along with bait. A concentration of 0.5 percent was required by both methods of delivery for any obvious indications of repellency, with as high as 10 percent needed for very rapid, marked effects.

Our calculations clearly indicate that concentrations of 10-80 g/m$^3$ required to elicit minimal evidence of repellency by Moses sole secretions or surfactants such as sodium lauryl sulfate (sodium dodecylsulfate) are at least TWO TO THREE ORDERS OF MAGNITUDE TOO HIGH for such substances to be seriously considered as the basis for a practical shark repellent packet for use in the classic continuous release mode.
The reported success of the Moses sole in avoiding being devoured by sharks could be due to the close range at which it ejects its repellent secretions, i.e., essentially straight into the mouth of the shark in a manner leading to a relatively high local concentration of toxin.

Injection of chemicals at high concentrations directly into the mouth of the shark could be a useful approach for development of antishark weapons for use by divers (Ref. 16). However, the value of such weapons to a person floating at the surface would be severely limited. Their use would require highly coordinated actions by the person under conditions of extreme stress, and then only after prior sighting of the shark.

Something as simple as a thin plastic envelope could possibly be used to maintain a high local concentration by preventing a repellent from rapidly diffusing before the shark penetrates the enclosure. In effect, the Shark Screen, developed many years ago by Johnson (Ref. 19) for use by Navy aircrews, serves just such a purpose.

An extreme variation of the retaining barrier principle, which in a way mimics the Moses sole, would be to package the repellent material directly within the clothing of the user in a manner permitting its rapid release when bitten by a shark. Clearly, this method of second-strike protection would have drawbacks with potential human victims, for the user must accept the consequences of the free first bite. On the other hand, this approach might very well have serious merit in protecting valuable oceanographic instruments that are at times damaged or lost as a direct result of repetitive shark strikes (Ref. 20, 21).
On the basis of our analytic considerations, we are proposing that for any chemical or natural product to be worthy of costly, intensive evaluation by the Navy as a possible active component of a life jacket shark repellent packet to replace Shark Chaser,

1. the candidate repellent material would have to be essentially instantaneously effective at a concentration no greater than \(0.1\ \text{g/m}^3\); i.e., 100 parts per BILLION, or

2. where the effect is less than instantaneously produced, the exposure integral (that is, time-to-effect multiplied by the concentration required for effective repellency) should be no greater than 0.1 second \(\text{g/m}^3\).

The latter proposed guideline would be equivalent to observing clear indications of repellency after exposing a shark of reasonable size for a maximum of 10 seconds to a tankwater concentration no greater than 10 parts per billion.

At the very low assumed molecular weight of 100 for the candidate repellent, a concentration of 10 PPB \((0.01 \text{ g/m}^3)\) would equate to \(10^{-7}\) molar.

The magnitude of the task and the degree of impracticability inherent in its accomplishment is brought into clear focus when one realizes that concentrations of \(10^{-7}\) molar begin to test the recognized lower functional limits of the shark's chemoreceptors (Ref. 22, 23). Extremely rapid response of the total animal in terms of a radical change in behavior (repellency) is yet another matter, most likely requiring far more than minimal assault on the chemical senses of the shark.
REFERENCES


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