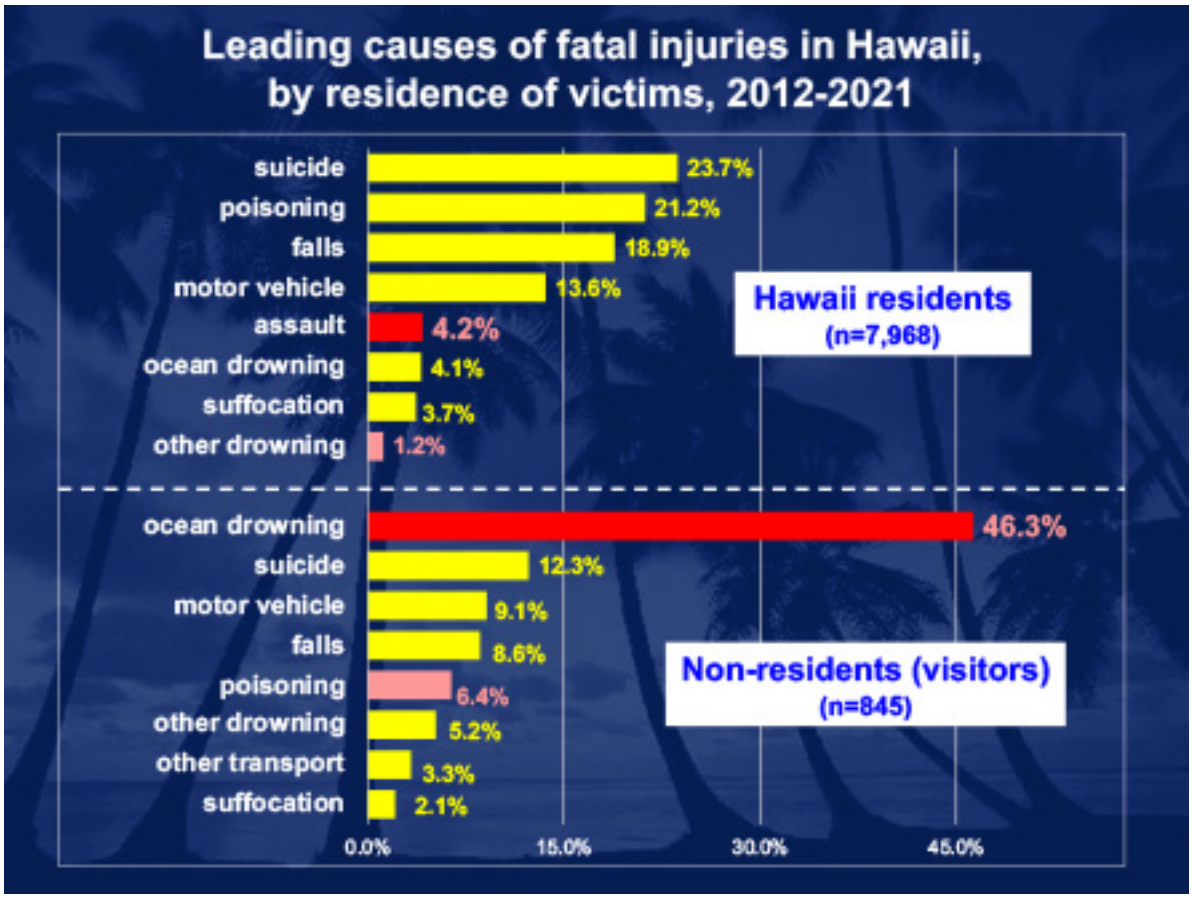
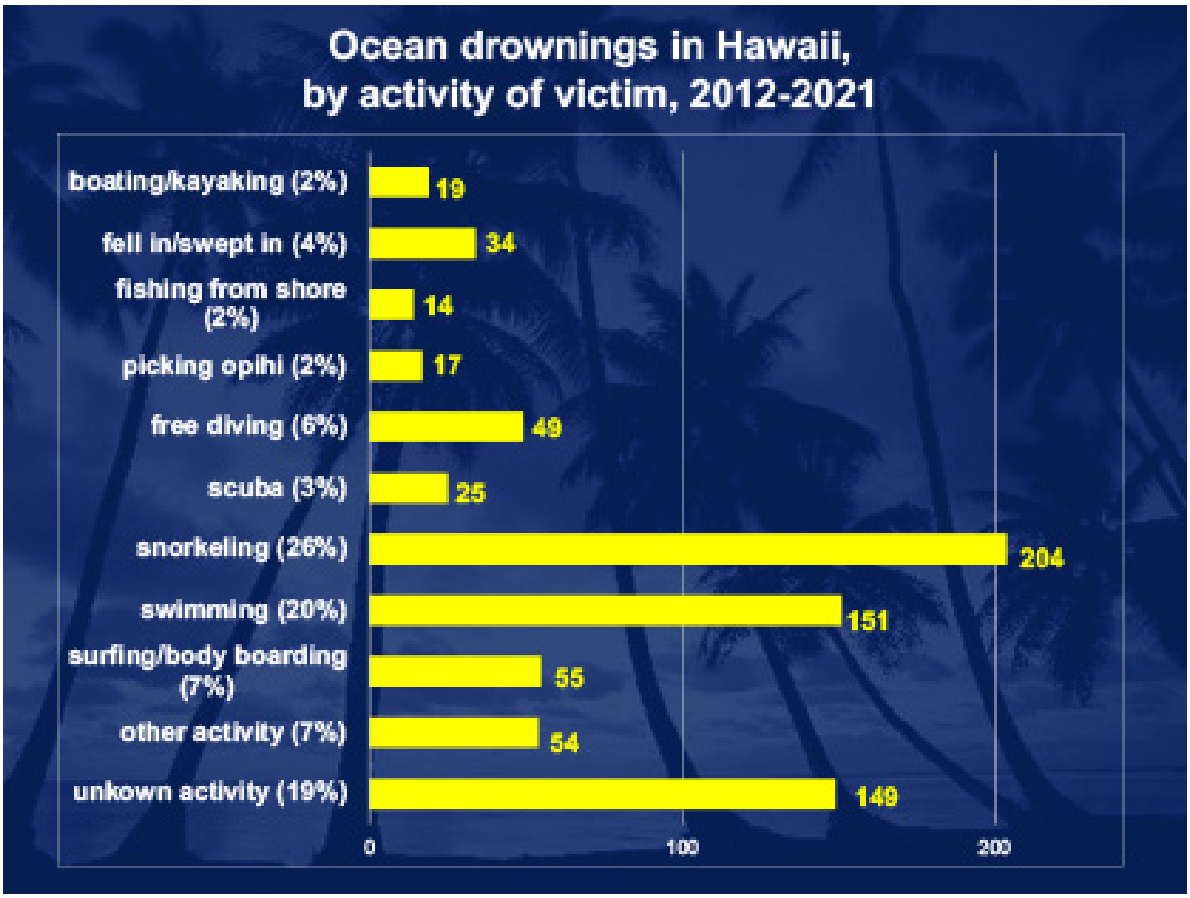
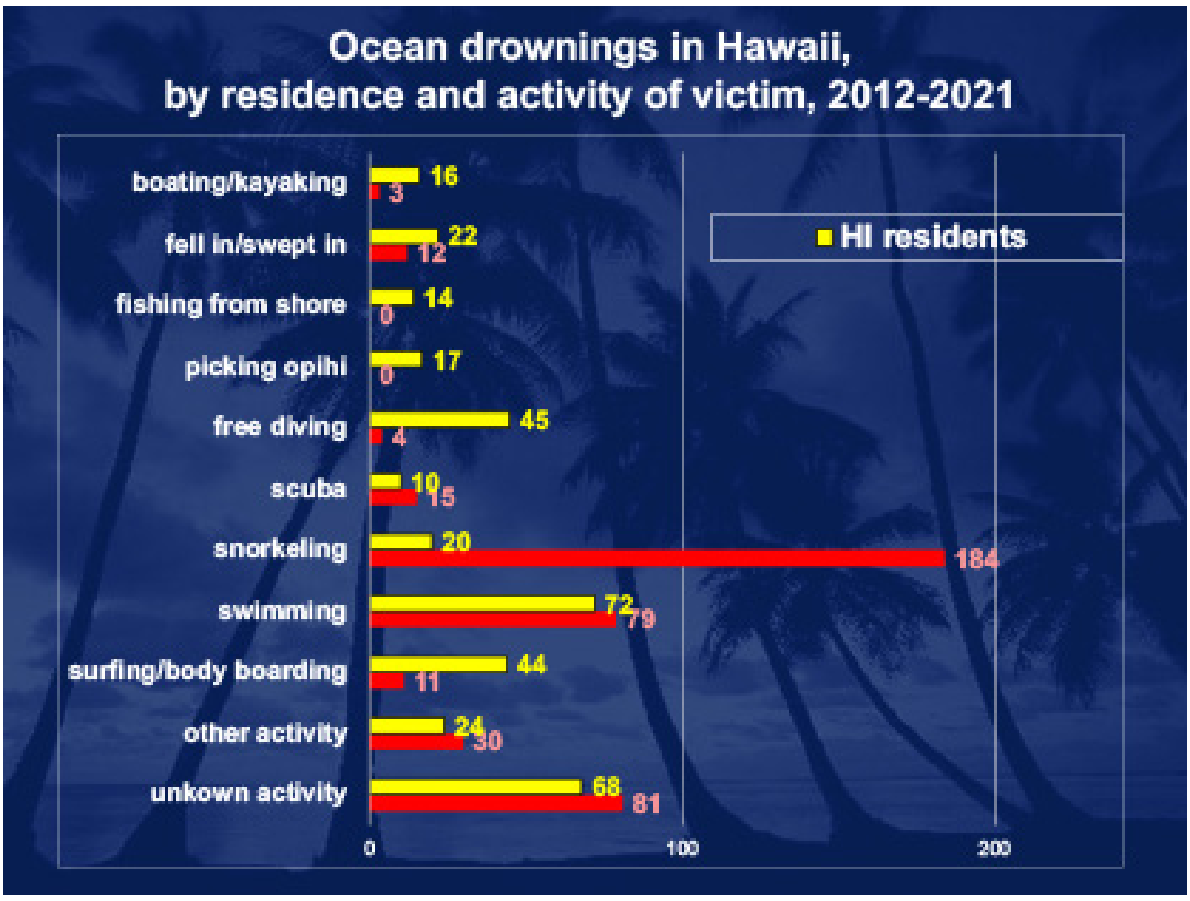
SNORKEL SAFETY STUDY

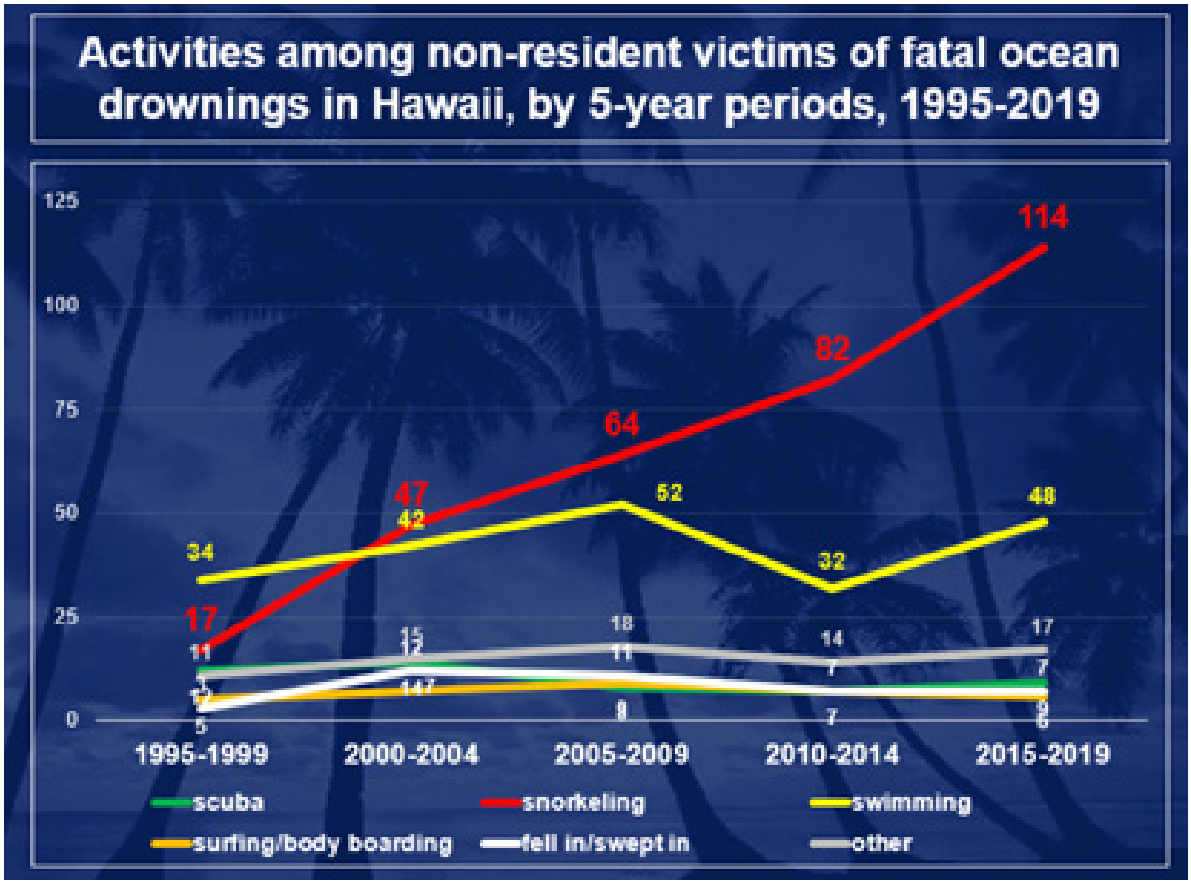
BACKGROUND

The Department of Health has collected data on drownings in Hawai'i for decades. They show a high incidence of snorkel-related drownings among visitors to Hawai'i. Many of the fatalities were mysterious in that they happened in mild ocean conditions and were not accompanied by signs of distress. The cause for this has been attributed to the assumption that generally visitors are less apt to be good swimmers, less apt to have snorkeling experience, and are unfamiliar with Hawaiian waters, or that they have suffered heart attacks or other health trauma. It is only recently that the matter has been methodically investigated.




Ocean drownings in Hawaii,
by activity of victim, 2012-2021
boating/kayaking (2%)
19
fell in/swept in (4%)
34
fishing from shore (2%)
14
picking opihi (2%)
17
free diving (6%)
49
scuba (3%)
25
snorkeling (26%)
204
swimming (20%)
151
surfing/body boarding (7%)
55
other activity (7%)
54
unkown activity (19%)
149
0
100
200


Ocean drownings in Hawaii,
by residence and activity of victim, 2012-2021
HI residents
boating/kayaking
16
3
fell in/swept in
22
12
fishing from shore
14
0
picking opihi
17
0
free diving
45
4
scuba
10
15
snorkeling
20
184
swimming
72
79
surfing/body boarding
44
11
other activity
24
30
unkown activity
68
81
0
100
200



In October 2017 the Hawai'i State Department of Health established the Snorkel Safety Sub-Committee to address public concern about snorkel-related drownings, especially among island visitors, initially Emergency Medical Services & Injury Prevention System Branch, Department of Health (DOH). Ralph Goto, retired Ocean Safety Administrator, was the chairman. Committee members were Dan Galanis, State Epidemiologist, DOH; Dr. Philip Foti, Pulmonologist, Colin Yamamoto, retired batallion chief of Ocean Safety, and Carol Wilcox, snorkel drowning survivor. Input was provided by representatives from ocean safety, first responders, the medical profession, community groups, survey participants, and interested individuals over the course of the sub-committee's work.

The Snorkel Safety Sub-Committee proposed a Snorkel Safety Study (Study) to "*determine the causes and risk factors associated with snorkel-related fatal and non-fatal drownings and develop appropriate safety messages.*" In January 2019, the Hawai'i Tourism Authority funded the Study with. Ralph Goto as Study Team Administrator, Philip Foti as Principal Investigator, Carol Wilcox Project Director, and Jeremy Burns as Survey Technical Advisor.

The Study has four components, the 1) the Snorkel Airways Resistance Analyzer (SARA) Investigation, 2) Medical Examiner's Office Reports Investigation; 3) Case Studies Investigation, and 4) Snorkel Safety Survey

In the first phase of the Sub-Committee's work, concluded in March, 2020, it:

- Convened two Snorkel Safety workshops (March 2018 and February 2020) (Goto)
- Developed a Snorkel Safety Survey (Survey) for those who have "gotten into trouble while snorkeling"(Wilcox)
- Designed the Snorkel Airways Resistance Analyzer (SARA) (Foti)
- Tested 50 snorkels with SARA (Foti, Wilcox)
- Examined Hawai'i Medical Examiner's Office's autopsies and reports for drownings in 2018 and 2019 (Foti)
- Interviewed individuals who experienced non-fatal drowning (Foti)
- Examined medical records of fatal and non-fatal drownings (Foti)
- Investigated physiological effects of immersion in water (Foti, Wilcox)
- Investigated physiological effects of recent travel (Foti)
- Identified health issues that might make snorkelers more vulnerable (Foti)
- Developed and posted the www.SnorkelSafetyStudy.com website (Wilcox)
- Summarized Survey responses from 36 participants (Wilcox)
- Submitted an interim report to DOH, Hawai'i Tourism Authority, Hawaiian Lifeguard Association, and posted it on the website. (Wilcox, Foti, Goto)

In the second phase, concluded in April 2022, the Snorkel Safety Study:

- Hired Pang Communications, LLC to improve the www.snorkelsafetystudy.com website and develop media outreach for the Survey.
- Expanded public awareness of the Survey via television, radio, webinar
- Published in the Hawai'i Journal of Health & Social Welfare, March 2022. *Factors Contributing to Snorkel Drowning in Hawai'i* (Philip Foti MD; Carol M Wilcox; Ralph S. Goto)
- Continued making the Snorkel Safety Survey available "… for those who have gotten into trouble while snorkeling."
- Conducted interviews with some Survey participants
- Summarized the updated Survey results with 131 responses
- Prepared a final report dated May 2022

Drowning: Aspiration or ROPE?

- *Pulmonary: relating to the lungs*
- *Edema: swelling caused by excess fluid accumulated in the body's tissues*
- *Pulmonary Edema: the infusion of fluids into the lungs*
- *Rapid Onset: loss of consciousness can happen in a matter of minutes.*

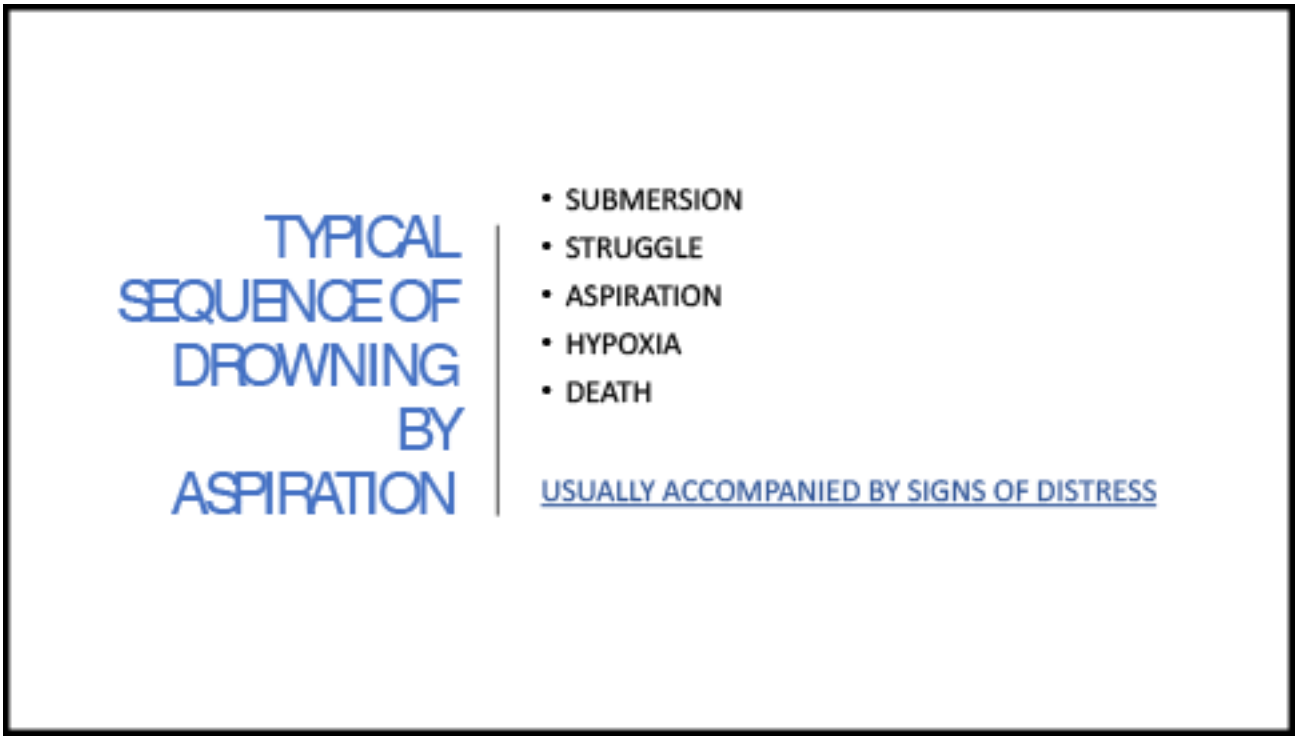
We commonly understand "drowning" to be a fatal event. In 2005, the World Health Organization developed a definition which is used in this report: "*Drowning is the process of experiencing respiratory impairment from submersion/immersion in liquid*." This expanded the meaning of drowning from a fatal event to a process that could be fatal or, if interrupted, non-fatal. It starts with submersion and typically involves a struggle to get to the surface. This is *Drowning by Aspiration*.

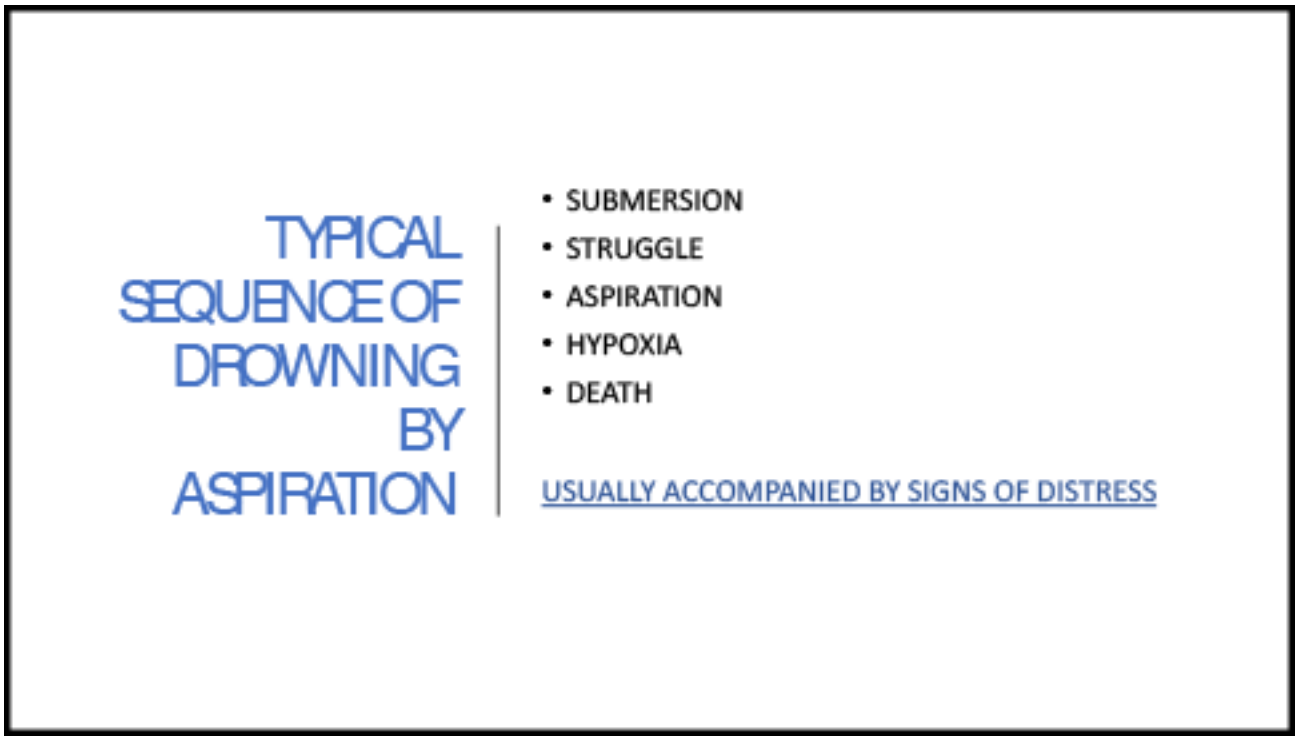
Sequence of Drowning by Aspiration: Submersion, Struggle for Air, Involuntary Aspiration (inhalation of liquid), Hypoxia (lack of oxygen), Cardiac Arrest, Clinical Death. Usually accompanied by signs of distress.

In Hawai'i it is not unusual to find an unresponsive snorkeler motionless, close to shore, in calm conditions, sometimes soon after entering the water, and without signs of distress. These are not the characteristics of Drowning by Aspiration.

The Snorkel Safety Study hypothesized that this quick and silent pattern of drowning was consistent with pulmonary edema, and that the snorkel itself may trigger and accelerate pulmonary edema. Briefly, pulmonary edema is the infusion of bodily fluid into the lungs which reduces its capacity to deliver oxygen to the body's system, leading to hypoxia (lack of sufficient oxygen), which can induce Rapid Onset Pulmonary Edema (ROPE). Rapid Onset as it is distinguished by its rapidly accelerating nature, which can be a matter of minutes.

Sequence of Drowning by ROPE: Pulmonary Edema, Hypoxia, Impairment of Neuro-Muscular Function, Loss of Consciousness, Death and Possible Aspiration. Few if any signs of distress.





Hypoxia is the ultimate cause of death in drowning, be it by Aspiration or by ROPE, but the path there, and the person's experience, is very different. Externally, the primary difference is the presence or absence of a struggle.

While the mechanics of Pulmonary Edema are technical and complex, the concept is simple. The lungs are defined by a fine, permeable membrane. Liquids and gasses travel in both directions through this complicated and exquisitely balanced membrane. During inhalation, oxygen is transferred from the lungs to the blood stream and then delivered to body tissue. In exchange, carbon dioxide that has built up in the blood (in capillaries carrying blood along one side of this membrane) is passed back to air spaces in the lungs and expelled during exhalation.

When breathing through a narrow tube, inhalation can result in significant Negative Transthoracic Pressure (NTP). A vacuum phenomenon develops within the lungs which draws fluid from surrounding capillaries into the air space of the lungs. The snorkeler experiences shortness of breath. If the person continues to breath through the snorkel, negative pressure persists; each inhalation draws more fluid into the air spaces resulting in less and less oxygen intake into the capillary blood. Blood oxygen is critically reduced.

Insufficient oxygen to the brain causes loss of muscle strength, confusion, and harbingers of death. The only thing left functioning is the heart, which tries desperately to pump oxygen. Loss of consciousness and clinical death ensues, often very quickly after the snorkeler experiences first signs of hypoxia.

Pulmonary Edema has been identified as a risk in other sports. In SCUBA it's known as Immersion Pulmonary Edema (IPE), in anesthesiology as Acute Negative Pressure Pulmonary Edema (ANPPE), in long distance swimming as Swimming Induced Pulmonary Edema (SIPE), and in mountain climbing as High Altitude Pulmonary Edema (HAPE). In snorkeling the study has termed it Snorkel Induced Rapid Onset Pulmonary Edema (SIROPE) or just ROPE.

FINDINGS

MYSTERIOUS DEATHS EXPLAINED

Summary of Key Findings

- Hypoxia from Snorkel Induced Rapid Onset Pulmonary Edema is the cause of some, probably most, snorkel-related fatal and near-fatal drownings. ROPE accounts for the lack of distress exhibited in many snorkel drownings. This is an important discovery with significant implications.
- Snorkel resistance and horizontal immersion are predisposing factors that can contribute to the onset of ROPE.
- Cardiac disease, in particular elevated Left Ventricle End Diastolic Pressure (LVEDP), has been identified as a risk factor for ROPE. This was confirmed through individual case studies, coroner's office records, and the Snorkel Safety Survey.
- High airflow resistance to inhalation adds to the risk of developing ROPE. Snorkels and full-face masks have a wide range of airflow resistance. The more you exert, the greater the resistance.
- Full-face masks pose no inherent advantage or disadvantage compared to other devices in terms of resistance to inhalation of air. They do, however, present a unique set of challenges.
- Autopsies are not a conclusive source of useful information for differentiating the mechanism of drowning.

Areas of Concern

- Exposure to reduced pressure during recent prolonged air travel may be a contributing factor.
- Snorkeling off of boats may present extra risk.
- New safety messages may be appropriate.

Snorkel Airway Resistance Analyzer (SARA)

Why do snorkelers get Pulmonary Edema more than swimmers, surfers, or everyday ocean frolickers?

The Snorkel!

Snorkel designs range from a simple basic tube to those with pleats, purging valves, pinched tubes, wet/dry apparatus and, more recently, masks with integrated snorkels, known as full-face masks.

The snorkel tube can generate resistance to inhalation. If the resistance is strong enough, and if it persists, it will result in Negative Transthoracic Pressure, i.e., reduced pressure in the lungs, which can lead to pulmonary edema.

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One of the Study's objectives was to determine how much resistance a snorkel exerts. Dr. Philip Foti designed the Snorkel Airway Resistance Analyzer (SARA) to measure snorkel resistance during inhalation. He tested 49 snorkels, including 16 simple snorkels, 29 snorkels with wet/dry apparatus, and four full-face masks. Each snorkel was tested at three levels of air flow to simulate various levels of inhalation rates.

Conclusion: You can't judge a snorkel by its looks. Snorkels and full-face masks have a wide range of airflow resistance. Generally, the simpler the snorkel the less resistance it generates. However other factors, sometimes not visible, such as the size at the narrowest opening, or the design of the valves, made visual determination of resistance unreliable. The more you exert the greater the resistance, which accelerates pulmonary edema.

A Survey of Snorkelers who have "Gotten Into Trouble"

When trying to identify the causes of getting into trouble while snorkeling, survivors of snorkeling incidents are uniquely positioned to answer these questions. To get these first-hand reports, the Study designed the Snorkel Safety Survey for people "who get into trouble while snorkeling." They report their own swimming ability, snorkeling experience, ocean conditions, equipment, recent travel, health, and things not yet considered. They provide a detailed account of what happened leading up to and during the incident. These specifics often suggest whether they experienced Drowning by Aspiration or Drowning by ROPE.

Companions of fatal drownings can provide equally important information.

Snorkel-related fatal drownings in Hawai'i are predominantly visitors and, among those, middle age males. The Survey respondent group does not conform to that profile. Rather, many respondents are Hawai'i residents, many are under 55 years of age, and there are roughly equal number of men and women. While the Survey does not shed clarity about why visitors are especially vulnerable, it does show that non-fatal snorkel-related incidents happen to residents more often than previously realized, to females almost as often as males, and that swimming or snorkeling ability or ocean conditions are not factors in most incidents.

By April 2022 there were 131 survey responses. They are summarized in section three in this report. They are evidence that some, probably most, fatal and non-fatal drowning were by hypoxia induced by ROPE.

Coroner's Office Investigation

Principal Investigator Dr. Foti reviewed Coroner's Office records for years 2018 and 2019 to see if it was possible to identify drowning by Aspiration and drowning by ROPE through autopsy reports. It was not. In either case the lungs are full of liquid, and death is by hypoxia. However, autopsies were helpful in identifying pre-existing health conditions, and confirmed a correlation of drownings with cardiac disease, in particular elevated LVEDP, which tends to manifest in older age groups and is most often asymptomatic when not severe. As a side note, there was very little indication of drug or alcohol being factors.

Individual Case Studies

While survey participants were asked but not required to give their names, most did, and many were willing to be interviewed and to share their medical history. These case studies provided invaluable information especially in two areas: preexisting health issues and whether ROPE or Aspiration occurred. The suspected correlation between heart conditions, specifically elevated LVEDP, and ROPE was corroborated in both men and women in these case studies. In several cases, the condition was not diagnosed until after the incident itself.

CO2 Buildup

For years attention has been given to the possibility that CO2 accumulation in the mask and snorkel and then the elevated blood CO2 level causes the snorkeler to become unconscious. CO2 buildup is not a physiologically viable explanation of snorkel-related drownings.

Recent Prolonged Air Travel

In a parallel line of inquiry, the Study considered the novel idea that recent prolonged air travel may be relevant in explaining the disparity between residents and visitors in the number of snorkel-related drownings. Hawai'i is different from most other snorkel resort destinations in that almost all visitors have spent at least 5 hours on an airplane at cabin pressure equivalent to up to 8500 feet elevation. Visitors traveling from anywhere except the west coast of the U.S. are often in the air much longer. There is evidence that exposure at these altitudes may alter permeability of the lungs' mechanisms that normally blocks development of pulmonary edema.

The idea that recent prolonged air travel may be a factor is hypothetical. It has a credible basis in physiology and would explain the otherwise inexplicable drowning statistics. Studies are needed to ascertain if extended exposure to altitude is indeed a risk factor.

Full Face Masks

The Study tested only four full-face masks. Within this limited scope of examination, full-face masks pose no inherent advantage or disadvantage in terms of resistance to inhalation compared to other devices. However, based on evaluation of design and first-hand accounts, there are several adverse features of full-face masks including:

- Cannot be removed easily in urgent situations even with quick release features
- Cannot "spit out" mouthpiece in urgent situations

- Cannot clear water from tube with sharp expiratory force maneuver
- Cannot dive beneath the surface safely
- Valve malfunction may lead to serious aspiration consequences

CONCLUSION

By far the most important finding of the Snorkel Safety Study is the confirmation that Rapid Onset Pulmonary Edema induced hypoxia is a mechanism leading to some, possibly most, fatal and non-fatal snorkel-related drownings. This conclusion is borne out by physiology, case studies, medical records, and first hand accounts. Heart Disease, especially elevated Left Ventricle End Diastolic Pressure, is a likely risk factor that can lead to ROPE. This was confirmed in autopsy reports and in case studies. ROPE explains many previously mysterious fatal and non-fatal snorkel-related drownings. New safety messages are suggested elsewhere in this report.

ACKNOWLEDGEMENTS

The study team extends sincere thanks to those who contributed their expertise, assistance, guidance, enthusiasm and knowledge to this study. We are deeply grateful for your contributions, and with apologies to those we have missed, mahalo to:

All Snorkel Safety Survey participants

Kauai, Maui, and Hawai'i Island Fire Departments

Ocean Safety and Lifeguard Services Division, City and County of Honolulu

Friends of Hanauma Bay

Pang Communications, LLC

Clutch Design, LLC

Jeremy Burns, Survey Technical Development

Hawai'i Tourism Authority

Laola Lake Aiu, Ronald Bregman, Dr. Alvin Bronstein, Jeremy Burns, Guy Cooper, Dr. Patrick Fujimoto, Tina Hamayasu, James Howe, Dr. Christopher Happy, Alan Hong, Sean Keeman, Gerald Kosaki, Dr. John Mickey, Audrey Newman, Susan O'Connor, Jessica Lani Rich, Tammie Smith, Kaala Souza, John Titchen, Leslie Turnbull, Bridget Velasco, Kalani Vierra, Colin Yamamoto.

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State of Hawai'i Department of Health, EMS & Injury Prevention System Branch

van Beeck, E.F., C.M Branche, D. Szpilman, J.H. Modell, & J.J.L.M. Bierens. 2005. "A new definition of drowning: towards documentation and prevention of a global public health problem." Bulletin of the World Health Organization, November 2005, 83(11) "The consensus was that the new definition should include both cases of fatal and nonfatal drowning. After considerable dialogue and debate, the following definition was adopted: 'Drowning is the process of experiencing respiratory impairment from submersion/immersion in liquid.'"

PHYSIOLOGY OF SNORKEL INDUCED RAPID ONSET PUMONARY EDEMA (SI-ROPE)

RELATIONSHIP BETWEEN SNORKEL-INDUCED RAPID ONSET PULMONARY EDEMA (ROPE) AND COMPROMISED INTEGRITY OF THE ALVEOLOCAPILLARY MEMBRANE DUE TO AIR TRAVEL

— Philip R. Foti, MD

Statement of the Problem and Rationale of Hypotheses

The alveolocapillary membrane (ACM) is semipermeable. Pressures on both sides need to be in more or less equal balance to maintain homeostasis. The presence of hypoxia (Pa O2 less than approximately 55 to 60 mm of mercury and oxygen saturations less than 85 to 90%) causes pulmonary arterioles to constrict in generalized but disorganized and heterogeneous fashion compared to the organized manner which adjusts to alveolar ventilation for maintenance of ventilation perfusion ratios as close to 1 as possible. For example, patients who developed pulmonary edema at altitude (high altitude pulmonary edema/HAPE) are likely to be subject to this mechanism.

The question exists as to whether marginal hypoxia at decreased cabin pressures during extended air travel could result in sub-clinical low-grade injury stressing the integrity of the ACM.

Snorkelers in prone swimming position experience negative inspiratory transthoracic pressures because of submersion and increased resistance to inhalation due to airway resistance in the snorkel. These individuals may be at increased risk of developing acute negative pressure pulmonary edema (ANPPE), especially if integrity of the ACM was adversely affected in advance of the snorkeling event. This could result in negative transthoracic pressures which exceed endocapillary oncotic

pressures thereby fostering intra-alveolar fluid accumulation. In such a model the snorkeler's dependent anterior (Volar) lung is subjected by gravity to increased capillary volume and pressure, transferring endovascular fluid through an already compromised alveolocapillary membrane because both positive intra capillary and negative intrathoracic pressure cumulatively exceed the oncotic pressure within the capillary lumina.

Further into this model, pulmonary plethora may be likely distributed to the dorsal, more ventilated aspects of the lungs (especially with effort-induced increase in cardiac output) so that widespread pulmonary edema and rapidly progressive hypoxia prevail, culminating in diffuse ROPE either interstitial, alveolar, or both.

Rapidly progressive pulmonary edema and increasing alveoloarterial gradient for oxygen causes increasing hypoxemia which could be accelerated by patent foramen ovale, septal

defect, anomalous venous return, pre-existing pulmonary hypertension, left ventricular diastolic dysfunction, mitral valvular disease and other medical conditions not apparent before entering the water.

Oxygen saturation measured in persons during high altitude flight in cabins pressurized to 8000 feet are often in the 86-91% range. Hypobaric chamber studies have shown that mean pulmonary artery pressure and vascular resistance increases in response to this level marginal hypoxemia, especially in older patients, who might have diastolic LV dysfunction. The degree of such response must vary with many factors including individual variations in neurovascular and humoral responsiveness to hypoxia. The passenger's habitat elevation could be another such variable.

I believe it is possible that long haul air travel under certain circumstances may a be a significant predisposing factor in Hawai'i because of its geographic location. Studies designed to better understand effect of air travel are needed to clarify this hypothesis.

RELATIONSHIP BETWEEN RAPID ONSET PULMONARY EDEMA (ROPE) AND CARDIAC DYSFUNCTION

— Philip R. Foti, MD

As referred to in the foregoing statement of hypothesis concerning mechanisms of predisposition to ROPE during air travel, the following comments expand on pathophysiology in individuals which may predispose them to ROPE formation:

- Many heart conditions, including those listed, may be occult because they are mild enough to result in no recognizable cardinal symptoms (shortness of breath & fatigue) at rest and during non-extraordinary exertion. In common they all may result in increased "back pressure" and/or volume of blood in the left ventricle, atrium, pulmonary veins and capillaries.
- Increase in capillary pressure can predispose to ROPE in the setting of negative transthoracic pressure; part of the sequence of events that allow for accumulation of fluid within alveoli which leads to hypoxia.
- One of the commonest causes for such an occult disturbance is often referred to as Left Ventricular Diastolic Dysfunction. Aging heart muscle, scarring, a history of hypertension, and numerous systemic disorders can lead to stiffening of the muscle so that it's normal compliance and capacity to "stretch" during the relaxed filling phase of the contraction cycle becomes restricted. The volume of blood accepted before the next contraction therefore decreases, but pressure increases just before contraction. These phenomena are accentuated as demand for cardiac output increases, but blood output capacity is accordingly reduced as well.
- Testing for diastolic dysfunction presents difficulties which may impede early detection in mild cases.

Factors Contributing to Snorkel Drowning in Hawai‘i

Philip R. Foti MD; Carol M. Wilcox; Ralph S. Goto

Abstract

Causes of the extraordinarily high and increasing incidence of snorkeler drownings in Hawai‘i have remained unexplained for years. Defining the mechanisms and factors predisposing to drowning while snorkeling is needed to provide recommendations to substantially mitigate the incidence of this form of preventable death. The mechanisms of drowning are described and insight into the predisposing factors are explored in this study. Methods included measuring snorkel airway resistance characteristics, case reports from the State of Hawai‘i Medical Examiner's office, and collating information by survey, principally from rescued survivors. This study identified 2 modes of drowning while snorkeling that need further investigation: accidental or inadvertent aspiration, and hypoxia resulting from acute negative pressure pulmonary edema. The incidence of drowning from mechanisms of hypoxia due to rapid onset pulmonary edema is an important focus of the study and a number of potentially significant predisposing factors are presented that need further investigation but provide bases that may become part of updated policies and practices for snorkelers to substantially lower the risk of death. This report is meant for both medical and public health information purposes.

Abbreviations

ACM = alveocapillary membrane
ANPPE = acute negative pressure pulmonary edema
HAPE = high altitude pulmonary edema
NTP = negative transthoracic pressure
ROPE = rapid onset pulmonary edema
SIPE = swimming induced pulmonary edema
SIROPE = snorkeling induced rapid onset pulmonary edema

Keywords

Aspiration, Hypoxia, Pulmonary Edema, Snorkels

Introduction

Hawai‘i is the focal point of numerous drownings, the great majority of which are ocean related, and involve snorkeling tourists over the age of 50. The Medical Examiner's Office has been assiduous in conducting postmortem examinations, but the nature of demise makes it difficult to reconstruct the reasons for drowning in most cases. Details of demographics of drowning elsewhere in the world have not been reported accurately, and the total number of deaths may be staggering. There are four mechanisms of drowning that may befall snorkelers: (1) trauma; (2) intervening acute medical adverse event; (3) inadvertent or accidental aspiration of water; and (4) hypoxia due to rapid onset pulmonary edema (ROPE). The first 2 are relatively uncommon and distinguishable from each other. Distinguishing between the last 2 of this list is difficult or impossible after death. Achieving the goals of this study requires that we determine as accurately as possible, methods of distinguishing between inadvertent aspiration and hypoxia due to ROPE in cases of drowning and near-drowning. Investigation of the possible reasons for death from available information in many cases indicates that the usually proposed explanations of these events (anxiety, panic, fatigue, inexperience, and lack of familiarity with ocean conditions, equipment and proper technique) are not adequate explanation for death from aspiration. For years the role of carbon dioxide rebreathing has been repeatedly implicated, but no science to support it as a serious contender has appeared. Recognizing ROPE as a mechanism of drowning has required documentation of cases of survivors of snorkeling induced ROPE (SIROPE) related hypoxemia. It has been suspected that the increase in negative transthoracic pressure (NTP) required to maintain adequate volumes of ventilation during immersion promote ROPE and hypoxia under these circumstances. Pulmonary edema results in hypoxemia which rapidly leads to weakness, loss of normal neurologic reflex responses, confusion, and diminished consciousness. The alveocapillary membrane (ACM) is permeable to water in both directions. Both endocapillary and alveolar pressures need to be more or less balanced to maintain homeostasis.

During inhalation, negative intrathoracic pressure is achieved by muscular contraction of the diaphragms and "bucket handle" motion of the ribs. This "vacuum" effect of increasing intrathoracic volume draws air into alveoli. When intraalveolar negative pressure is sufficient to exceed oncotic pressure of capillary contents, water flows toward the alveolus. When intracapillary pressure is substantially increased and/or ACM permeability is compromised, flow is toward alveoli unless intraalveolar pressure exceeds endocapillary pressure. When integrity of the ACM mechanically fails completely, capillary contents spill directly into alveoli. This type of acute negative pressure pulmonary edema (ANPPE) has been well described in scuba divers, by anesthesiologists and, more recently, is recognized in swimmers.[1] To our knowledge it has not been reported as a cause of death in snorkelers.

ANPPE is known to exist in larger mammals capable of high levels of ventilation and cardiac output during maximal effort, in which case it has been referred to as mechanical failure of the ACM.[2,3] In the case of scuba, it is referred to as immersion pulmonary edema (IPE), and in competitive swimmers SIPE (swimming induced pulmonary edema).[4] The connection between hypoxia due to these types of ROPE and that resulting from snorkeling activities has not been well documented or studied in the past. A literature search did find one 2017 case

report of hemorrhagic pulmonary edema ascribed to snorkeling.[5] Investigation of cases of individuals surviving these hypoxic episodes has led the team to believe that this mechanism of death is, indeed, reality. Clinical detection of hypoxia and oxygen desaturation with no sign of aspiration at the time of rescue, documentation of clinical and radiographic pulmonary edema rapidly resolving with or without oxygen and or diuretic therapy, and the lack of abnormal findings on cardiopulmonary testing cannot be otherwise explained. The incidence and pathophysiology involved, in addition to identifying the predisposing factors that increase the risk of its development are the scope of this study. Several of the potential causes for excessive NTP and ANPPE, which can contribute to or induce ROPE, include immersion, increased inspiratory resistance induced by various snorkel designs, and other factors. Snorkels are responsible for some increase in NTP depending upon the degree of resistance upon inhalation. Other factors, which are listed in the discussion section of this report play a role in increasing the risk of ROPE and include subclinical conditions which commonly go unrecognized because they produce little or no symptoms at usual levels of activity. Mountain climbers may be similarly affected from a form of ROPE referred to as high altitude pulmonary edema (HAPE).[6] There is reason to believe that these factors may affect air travelers as well. This is a preliminary report of findings because augmented education, messaging, and policy changes are urgently needed to diminish the risk of preventable deaths.

Methods

Three strategies were used to gain further information on the mechanisms of drowning among snorkelers: (1) snorkel airway resistance analysis, (2) medical examiner case reports, and (3) survivor-derived information. Because ANPPE is the common denominator for hypoxia under immersion circumstances, snorkel airway resistance analysis was achieved by designing and fabricating a device to measure negative pressures at various flow rates to test various snorkels to determine their potential contribution to negative transthoracic pressure. The device consists of a vacuum blower with adjustable flow, a flow meter, and a negative pressure transducer interposed between it and the mouthpiece of the snorkel. Because the number of varied designs of available snorkel devices is too numerous to count, the first 50 that were randomly received in the laboratory from various sources were tested at flow rates of 1, 2 and 3 liters per second. The results were recorded graphically in negative cmH_2O pressure, having been converted from kilopascals measured from the transducer. These were plotted on bar graphs at 3 liters per second for simplicity of review. These data were subjected to Mann Whitney statistical analysis. For each apparatus, the two technicians testing the snorkels who were familiar with various snorkel designs attempted to guess, after careful inspection, whether the device would test at high or low resistance. The technician estimates were recorded prior to testing. Pressure greater than $^{-}5$ cmH_20 pressure was designated as high. Estimates were compared with measurements on the analyzer to gain insight into how likely a would-be snorkeler might be expected to select a low resistance device by inspection alone.

The 50 devices were grouped into those with some form of dry device (designs in attempts to prevent water entering the snorkel tube), those with no dry device, and full-face masks. There were 29 dry devices, 16 without dry devices, and 4 different manufacture full face masks. One device was omitted from the analysis because it was lost and could not be confirmed to be dry or not.

State of Hawai'i Medical Examiner reports from the summer of 2017 to summer of 2019 were reviewed in detail by the principal investigator. The state's Medical Examiner is responsible for submitting reports from all the islands and, when it is possible, necropsies are part of the report in virtually all cases. Medical Examiner reports consist of findings compiled by an investigator and a final report, which includes autopsy findings, prepared by the medical examiner. Data available from these documents were collected in order to cross reference investigator reports with necropsy findings, and to analyze each case of snorkel drowning for clues as to which of the two mechanism categories (aspiration vs hypoxia) a given death could most likely be ascribed. Criteria for distinguishing between the 2 mechanisms included presence of observed struggle vs quiet cessation of activity and motion, water in the mask, details of descriptive accounts of ocean conditions, and predeath behavior. Cross referencing other information accumulated during review of cases showed no correlation between snorkelers and nonsnorkelers in reference to presence or absence of "foam cones," sinus fluid volumes and description, gastric volumes or contents, ambient sea conditions, or position in which victims were found. Foam cones refer to the shape of salivary and oral fluid foam which commonly collects with the base of the cone covering the oral aperture. They have been commonly described in the case of drowning when examination may be conducted within hours after the incident and have been accepted as a sign highly suggestive of drowning. Correlation between information contained in investigator's reports concerning details of travel data, prior illness, preincident behaviors and activities engaged in by victims, whether or not they were found by first responders with water in the mask, and in most cases the type of snorkel equipment used, was unsuccessful. The reasons for this lack of success was because of insufficient detail in the reports, but also because the descriptions of macro and microscopic finding of necropsies were unable to distinguish between the two mechanisms responsible for a given death. For example, 100% of all victims had pulmonary edema with varying degrees of hemorrhage, so no correlation could be made between degree of hemorrhage and the mechanism of drowning.

Survivor-derived information: 10 cases of nonfatal drownings were selected from respondents to a survey posted on our website and investigated in as much detail as possible.

The survey had been developed over a period of years by the study team in concert with the Hawai'i Department of Health subcommittee on Aquatic Safety, even before this study was formally underway. Individuals interested in reporting events were directed to the website by various lifeguard and other first responders, by information posted in specific areas (for example, Hanauma Bay), and by word of mouth and media exposure. Each case was thoroughly investigated in person and by telephone by the principal investigator and included interviews with survivors, rescuers, and other knowledgeable persons (eg, lifeguards, bystanders, and emergency medical services personnel). Institutional Review Board approval for this investigation was obtained through the Department of Health. Consent for contacting survey responders was requested on the survey itself. No one was contacted if consent was not clearly agreed to in the survey. Documents including hospital records, radiographs, and laboratory information were reviewed. It was determined that these cases represented examples related to ROPE (rather than aspiration) which would have proceeded to agonal breathing (with potential aspiration in the process of termination of brain life) if the snorkeler were not rescued. The survey report questionnaire had been developed and implemented to allow for ongoing sources of information to refine cumulative data concerning the details of importance in determining which mechanisms may be responsible and critical information concerning factors predisposing to ROPE. This survey is ongoing and on the study website. It is updated and upgraded as needed.

Results

Snorkel Airway Resistance Analysis: Figure 1 expresses all 50 random measurements depicted as the negative pressure required at 3 liters per second. Of the 15 snorkels tested with greater than -5 cmH_2O, 4 were guessed correctly (26%) and 29 of 35 testing less than -5 cmH20 pressures were guessed correctly (80%). The preliminary information resulting from these graphs suggests that, in general, airway resistance in a given snorkel device is very variable, depending on features of design, and variability is similar in dry, non-dry, and full-face mask devices. Estimates of resistance, although strictly anecdotal, do indicate that the accuracy of quantitating resistance subjectively suggests that the likelihood of a would-be snorkeler to guess if a given device will have high resistance is poor. Submission of bar graph derived data to Mann Whitney testing indicated no statistical differences.

Medical Examiner Case Reports: Of the 98 drowning reports reviewed, 32 were snorkel-related including 8 deaths which involved swimmers known to have advanced experience in snorkeling (Table 1). They were all known to be free divers and spear fishing fishermen. None was engaged in free diving at the time, to explain their events. Because of insufficient information in reports, it is uncertain as to how many were actually spear fishing at the time of the event that resulted in death. The position in which victims were encountered in snorkels was floating face down at the time of first encounter, except 2 who had full face masks. Utilizing the information available in each case, the team grouped cases into 3 categories: very likely, less likely, and definitely not related to hypoxia as the source of drowning. Of the 32 deaths, 15 were judged to be very likely the result of hypoxia due to ROPE, and 14 cases were considered as likely to be due to either ROPE or aspiration. Three were "not able to be definitely assigned" to either mechanism.

Survivor derived information: Documentation from10 cases reviewed as outlined above indicated that all but 1 of the subjects were over 50 years of age. Because of echocardiographic signs of diastolic dysfunction, 1 was referred for further investigation and eventually a biopsy proven diagnosis of myocardial amyloidosis confirmed. Otherwise, there were no certain indications of cardiovascular disease in any of the10 cases. Features commonly encountered in the 10 near drowning survivors documented to have had findings consistent with ANPPE induced by ROPE-related hypoxia are as follows:

- No history or sign of aspiration
- Initial symptoms of shortness of breath, progressive fatigue, and weakness
- Rapid development of diminishing mental alertness/near syncope
- Often associated with extraordinary effort
- Required assistance
- Oxygen desaturation at time of first responder or EMS arrival
- Hypoxemia and pulmonary edema documented after arrival at emergency facility
- Usually treated with diuretics and oxygen
- Resolution of pulmonary edema within hours
- No unusual findings on cardiovascular testing to explain the pulmonary edema were found in the 6 subjects who were evaluated in emergency facilities.

Extraordinary effort described included intentional swim training workouts in 2 cases, effort required to swim against strong current (3 cases), and long-distance swimming in 2 cases. The syndrome of dyspnea, fatigue, weakness and rapid deterioration of mental alertness was described in all cases, just before being rescued.

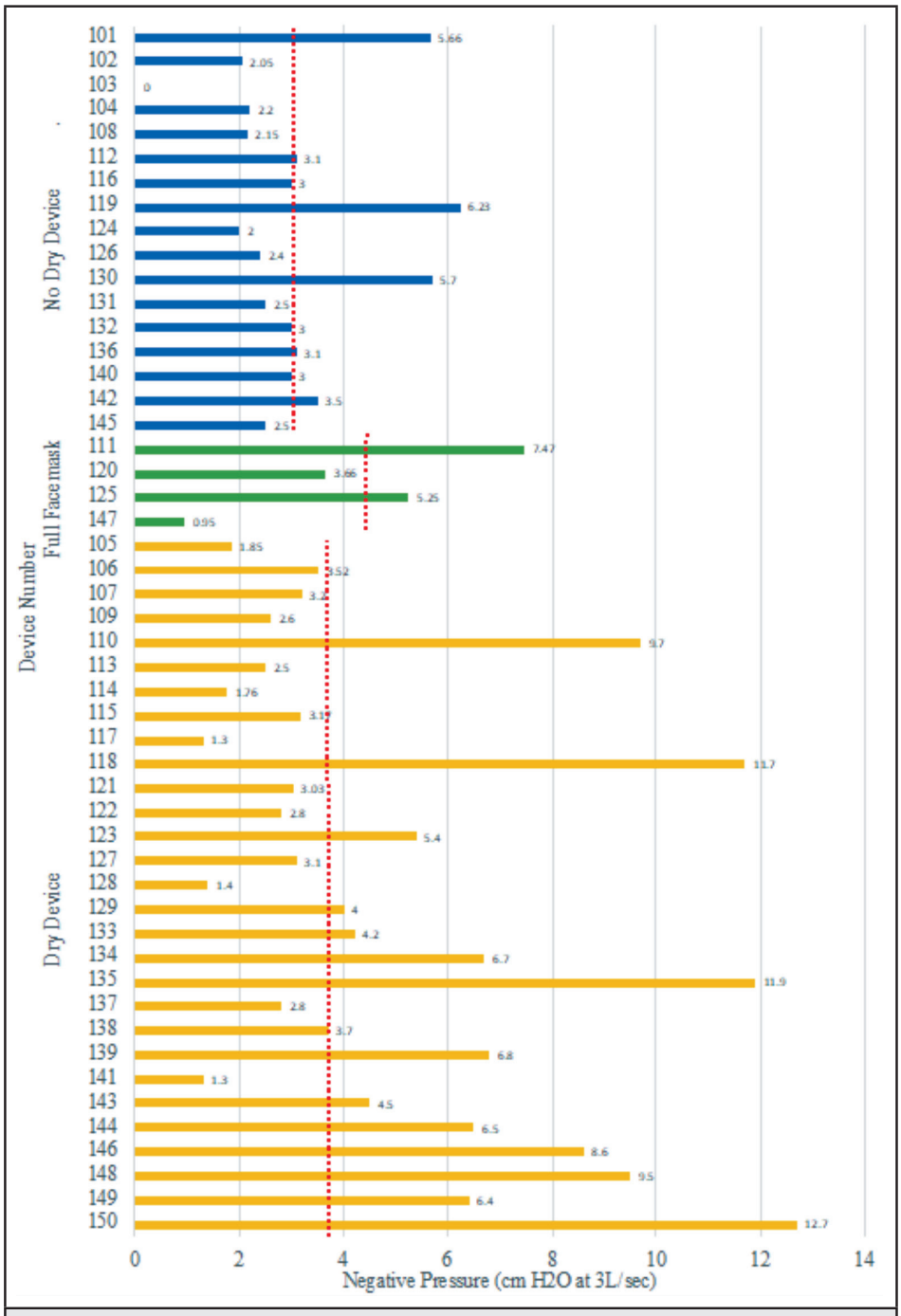

Figure 1. Separation of Negative Pressure Results Based on Snorkel Category Type

Blue = no dry device, Green = full-face mask, Yellow = dry device. Dotted Red line indicates the median negative pressure value per category: no dry device = 3.00, full facemask = 4.46, dry device = 3.7. There is no statistical significance in the difference of median based on Mann Whitney tests between full facemask and dry device (W = 55, *P* = .89), full facemask no dry device (W = 42, *P* = .37), and dry and no dry device (W = 310,p= *P* = .07).

Table 1. Demographic summary of snorkel-related deaths in Hawai'i

Grouping	Absolute number	Percentage
Gender		
Male	22	69
Female	10	31
Age		
<40	5	16
40-49	6	19
50-59	9	28
60-69	9	28
>70	3	9
Residency Status in Hawai'i		
Local resident	10	31
Visitor	22	69
Specific Activities		
Freediving/Spearfishing	8	25
Unspecified	24	75
Previous Travel		
No Information	25	78
>5 days	1	3
2 days	4	13
1 day	2	6
Cardiac Disease		
Cardiac disease likely to have increased left ventricular end diastolic pressure (LVEDP)	14	44
No clinical or autopsy evidence for cardiac disease	6	19
Insufficient cardiac information	12	38
Rating of Snorkel drowning for ROPE		
Very Likely	15	47
Likely (>50%)	14	44
Not Likely	3	9
Comorbidities of the six deaths not associated with pre-existing cardiac disease		
Bilateral Active Infectious Pneumonia	1	3
Amphetamine	2	6
THC	1	3
Alcohol	2	6

Data Source: Review of State of Hawai'i Medical Examiner's reports from summer of 2017 to 2019

Discussion

Snorkels, for the most part, offer relatively minor additional resistance to the NTP required to achieve usual inspiratory volumes during immersion. However, the major variation in snorkel resistance characteristics observed, and inability to estimate it by inspection, indicate that a substantial increase in required negative pressures may inadvertently become the case without the snorkeler's knowledge or ability to appreciate, especially at higher levels of work and minute ventilation. Immersion alone results in an increase in ambient pressure. For example, at 12 inches midthoracic depth, approximately 30 cm of H_2O pressure is added to the unsubmerged pressure of 1035 cm at sea level (eg, ±760 mmHg). In addition, the prone position results in redistribution of intravascular blood such that 500-700 ml accumulates in the pulmonary vasculature anteriorly, changing the pressure volume characteristics of the ACM.[7] At the same time, even with least resistance type snorkels, there is added some 3-5 cm of negative water pressure per breath, such that the NTP may be in the vicinity of minus 35 cm for each inhalation. At 10 breaths per minute, assuming 3 liters per second flow rate depending upon tidal volume and other variables, the cumulative negative pressure for that minute could total, conservatively, 350 cm of negative water pressure, or more. A snorkel causing high resistance adds to NTP accordingly. Sufficient negative pressure may be transferred to alveoli for a given period of time to result in focal hypoxia sufficient to trigger pulmonary arteriolar constriction.[8] Hypoxia-related pulmonary arterial hypertension and increased vascular resistance is generalized, heterogeneous and disorganized as compared to normal responses.[9] These mechanisms are suspected in HAPE as well. Results of medical examiners' reports and autopsies yield relatively little information of value in terms of distinguishing between accidental drowning and hypoxia-induced death. Nonetheless, the fact that 25% of the snorkeler deaths occurred to experienced divers tends to support the impression that inexperience, panic, anxiety, and lack of familiarity with equipment and techniques are not reasonable explanations in a significant number of cases.

Support for the hypothesis that a substantial number of such deaths are hypoxia related is also suggested by clinical and historical descriptions of information retrieved from investigators' reports. Necropsy does not provide information allowing for differentiation of accidental vs hypoxic causes. Histologic and other features of pulmonary edema, which was present in all cases, were not of assistance in distinguishing between the 2. Hypoxic causes may be more likely to occur in patients who have various cardiac conditions including diastolic dysfunction which may be a common predisposing factor. All but 3 cases were found floating face down at the time of first observation, except 2 which involved full-face masks. In the case of 1 victim found face up, there was no reported history of snorkel use. Whether full-face masks may pose additional risks needs further study but was not a focus of this investigation.

Survivor derived information provides the clues to the mechanisms of hypoxia as the cause for near-death. To date, we have insufficient information to draw conclusions of statistical significance concerning the frequency of hypoxia vs accidental aspiration-induced deaths. Ongoing analysis of surveys from nonfatal drownings, which include information targeting predisposing factors, will be more valuable as they increase in number.

The possible comorbid and nonpathologic states suspected to be predisposing contributing factors to precipitation of ROPE include elevated left ventricular end diastolic pressure, patent foramen ovale, septal defect, pulmonary hypertension, valve disorders and inherited or acquired variations in physiologic vascular, humoral and neurologic responses which control pulmonary vasoconstriction (eg, NO synthase activity, prostacycline, endothelin, mitochondrial function, and 2, 3 DPG levels). Of particular interest to Hawai'i is evidence that long distance air travel may result in many hours of exposure to sufficient hypoxemia to compromise the integrity and permeability of the ACM in subtle, subclinical fashion, making newly arrived snorkelers at greater risk in the several days after landing. Despite exhaustive search of literature, communications with the Federal Aeronautics Administration, National Aeronautics and Space Administration, National and International Airline Pilots associations, and aeronautics companies in the United States, no references of consequence were found to address this hypothesis. Hypobaric chamber studies have shown that especially in older patients, mean pulmonary artery pressure and vascular resistance increase in response to low grade hypoxemia associated with high altitude commercial travel.[10] The degree of such response must vary with many co-factors, including individual variations in physiologic responsiveness to hypoxia. The passenger's habitat elevation could be another such variable.

Conclusion

This preliminary report suggests that measurements of snorkel airway resistance show that airway resistance in a given snorkel can be markedly variable and cannot always be safely determined by inspection. Furthermore, snorkels with high resistance can increase transthoracic negative pressure sufficiently to induce or add to hypoxia due to ANPPE under certain circumstances which is a cause for near drowning and death while snorkeling. Consequently, the incidence of drownings and near drownings due to this mechanism is unknown at this time. Postmortem examination reports investigation indicate: (1) for the most part, necropsy findings are unable to determine whether a given snorkel death is due to accidental aspiration or ANPPE-induced hypoxia; and (2) improvement in recording clinical historical features as part of postmortem evaluations would be valuable. Ten case studies of survivors indicate: (1) ANPPE and hypoxia have been documented in survivors of near drowning experiences; and (2) predisposing factors exist, which are thought to be capable of adding to the likelihood of ANPPE in snorkelers. They include many factors which need further study: left heart and other occult medical condition, victim habitat altitudes, and possibly long-haul air travel are included in this list.

Conflict of Interest

None of the authors identify a conflict of interest.

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