Factors Contributing to Snorkel Drowning in Hawai‘i

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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.

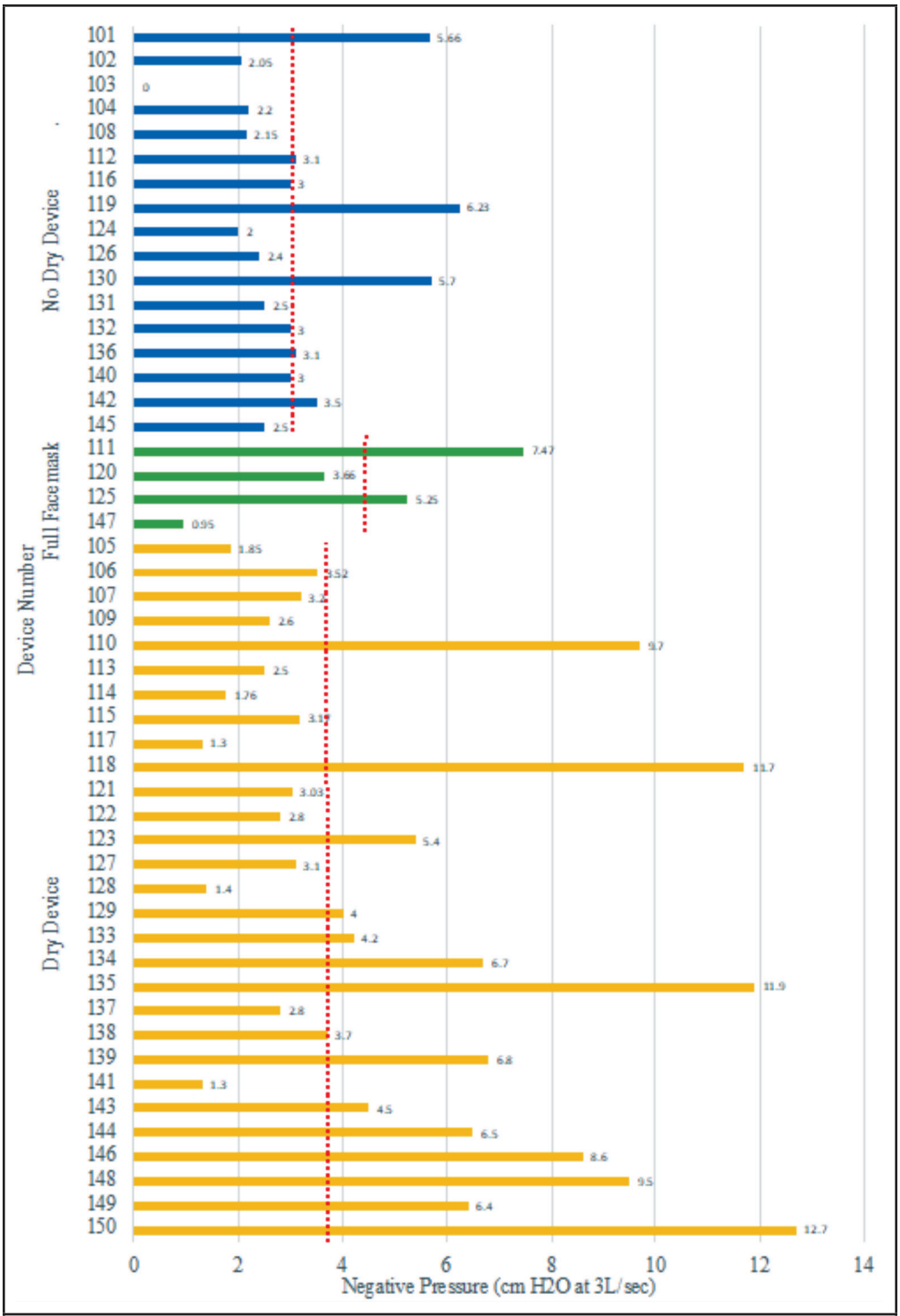

Figure 1. Separation of Negative Pressure Results Based on Snorkel Category Type

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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