Determining best practice for technical assessment of hookah surface supply diving equipment during diving fatality investigation

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Abstract
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Introduction: This study aimed to develop a standard process and checklist for technical investigation of hookah diving equipment and apply it to Tasmanian hookah fatality investigations from the last 25 years.
Methods: A literature search was undertaken to identify technical reports and equipment investigations associated with diving accidents. The information was assimilated to create a process and checklist for specifically assessing the hookah apparatus. The checklist was then applied in a gap analysis of Tasmanian hookah diving fatality technical reports from 1995 to 2019.
Results: As no papers specifically describing technical evaluation of hookah equipment were identified, references evaluating scuba equipment were used to create a hookah technical assessment process incorporating unique features of the hookah. Features included: owner responsibility for air quality; maintenance, function; exhaust proximity to air intake; reservoir volume; output non-return valves; line pressure; sufficiency of supply; entanglement; hose severance risk; gas supply failure and hosing attachment to the diver. Seven hookah diving deaths occurred in Tasmania (1995–2019) of which three had documented technical assessment. Gap analysis identified inconsistent structure between reports with variability in the case descriptors. Missing technical data included: overview of the hookah systems; accessories; weights; how the apparatus was worn by the diver; compressor suitability; assessment of hookah function; breathing gas output and exhaust position relative to air intake.
Conclusions: The study demonstrated a need to standardise technical reporting of hookah equipment after diving accidents. The checklist generated may serve as a resource for future hookah assessments and inform strategies for preventing future hookah accidents.

Introduction

From 2001–2013, Australia had 126 scuba fatalities.[1] Although these events are uncommon, they cause significant distress for diver's families, fellow divers, and rescuers. Diving fatalities may also receive media attention which may impact on industries such as diving tourism, and emergency service resource deployment. All fatal accidents require investigation and there could be legal consequences if, for example, there were diving procedural errors, failures in supervision, or issues with the diving equipment.

Diving fatality investigations are intended to determine the factors that contributed to the death so that preventative strategies can be employed to mitigate future adverse events. It is important to conduct such investigations with diligence, utilising methods and procedures that are standardised and consistent with best practice, so that key information is not overlooked. Although somewhat dated, national guidelines have been produced by the Royal College of Pathologists Australasia (RCPA) detailing the process for undertaking autopsy in diving fatalities.[2]

The RCPA autopsy guide briefly refers to specific risks of scuba, hookah and rebreather "*apparatus*", but not the technical evaluation of such equipment. There is limited information regarding the assessment process for a deceased diver's equipment as part of the broader investigation.[2]

The proceedings of a 2010 Divers Alert Network (DAN) workshop on recreational diving fatalities[3] include a paper titled "*Equipment testing*".[4] The authors included very detailed resources in appendices titled: "*Open circuit scuba equipment evaluation forms*", and "*Rebreather evaluation protocol*" which provide checklists for equipment investigation as part of scuba and rebreather deaths.[5]

Equipment inspection checklists were also provided in the proceedings.[6] The workshop focused on scuba and rebreather equipment and there was no specific reference to recreational surface supply breathing apparatus (SSBA). One paper in the DAN workshop proceedings reported that 62 of 351 Australian fatality victims (1 in every 6 deaths) between 1972 and 2005 had been using SSBA.[7] Despite this high prevalence, the diving deaths workshop did not produce any guidance for evaluating the surface supply apparatus and specifically did not mention the hookah apparatus.[3]

Hookah is a very specific type of SSBA. It comprises a petrol, electric or diesel motor as part of a compressor that drives the air supply at low pressure to the diver along a long, flexible, non-kink air hose. The diver receives their air supply to a second stage demand regulator and scuba style mouthpiece, or to a full-face mask and oronasal demand regulator. The whole unit has multiple component parts that are specific to hookah, and it provides compressed air delivery to divers underwater and/or in confined spaces. There are very specific risks related to hookah apparatus that are either not commonly associated with or applicable to scuba or rebreather equipment.[8] These can include the reliance on a motor to deliver the immediate breathing gas supply, the potential for on-scene contamination of the gas supply while diving, a limited air reserve capacity and a low fixed line pressure in the supply line. In addition, there can be limitations on air flow determined by the connections to the compressor, the length, configuration and construction of the air supply line and the depth of the diver. The long supply hose may become kinked, entangled in the marine environment, severed by a boat propeller, or disconnected. Continuity and/or sufficiency of breathing gas can be reduced with increasing depth and/or multiple divers breathing from the same unit. Finally, the air supply compressor is relatively remote from the diver, being in a boat, on land or as part of a flotation device.

Tasmania has a large population of hookah divers, although the exact number is unknown. The hookah apparatus is utilised by the wild seafood industry (e.g., abalone and scallop divers), commercial divers, scientific divers, and recreational divers. In one series, 43% of cases of decompression illness treated at the Tasmanian state hyperbaric facility used hookah apparatus.[9] A recent Tasmanian case series demonstrated that the hookah apparatus was used by 29% (5/17) of divers who died – all being recreational divers.[10] General Australian data reveals that 18% (15/84) of all SSBA deaths from 1965–2019 inclusive occurred in Tasmania, at least 37% of these were diving recreationally.[11]

Occupational divers must adhere to Workplace Health and Safety (WH&S) regulations, and, in the case of commercial abalone divers in Tasmania, are guided by a specific Code of Practice.[12] There is, however, no legislation in Tasmania governing recreational hookah diving which is largely unregulated. In addition, there are no unified national data for Australia covering the number of occupational divers, the apparatus used, hours in the water, or diving accidents. Occupational divers are required to adhere to WH&S Regulations and Australian/New Zealand Standards, but auditing of compliance is infrequent. There is no central reporting requirement for diver numbers or number of dives. This has prevented useful comparisons between recreational and occupational diving accident rates. One study reported 84 SSBA deaths in Australia from 1965 to 2019, (31 recreational divers, 43 occupational divers and 10 unknown).[11] In the period 2000–2019, 14/23 SSBA deaths were recreational divers, flagging a possible trend of increased risk in the recreational population.[13]

Recreational hookah usage is not subject to WH&S legislation and recreational hookah divers are not required to demonstrate any form of training to operate or purchase their equipment, which can be easily bought from websites, or second-hand. There are no mandated maintenance schedules for recreational divers, the responsibility for safety and hookah equipment maintenance resting with the operator. From the authors' observations, hookah divers in Tasmania generally dive alone or in buddy pairs (sometimes using two hoses from the compressor, or a single hose with a 'Y' connector to two second stage regulators. With recreational hookah divers, it appears that tenders in the boat are considered optional. Many have constructed their own home-made apparatus, including one individual who was observed to be using a 40-litre beer keg as the air reservoir. Diving tends to take place along remote shores away from population centres, and mostly is for the purpose of catching seafood.

Faulty equipment has been implicated as a significant contributor to hookah diving fatalities.[10,11] Very little guidance is available covering the technical evaluation of the hookah apparatus during diving fatality investigations, or how to assess hookah apparatus functionality before it is used. A standard procedure for technical evaluation of hookah equipment could add value by guiding future best practice in this area.

The aims of this study were to: develop a standard process for technical assessment of hookah diving equipment as part of a fatal hookah diving accident investigation, based on best available evidence; produce a checklist for recording the technical evaluation of the hookah apparatus that covers all essential information to assist investigators; and use the checklist to undertake a gap analysis of documented technical reports of hookah diving deaths at Royal Hobart Hospital over the past 25 years, identifying ways to improve on previous investigations.

Methods

This study was accepted and registered as a quality improvement project with the Tasmanian Health Service (South) Quality Committee safety reporting and learning system (SRLS) – Project #44-2020. Because all information accessed in relation to previous accidents was available in the public domain as deidentified reports, ethics approval was not required.

A literature search was undertaken to identify guidance for investigating equipment in diving accidents of all types, so that relevant parts could be applied to the hookah apparatus. Details of the search are available from the authors.

The study methodology focused solely on literature applicable or specific to the technical evaluation of the hookah apparatus. Aspects of diving accident investigation that were not equipment related (e.g., environment, weather, thermal protection etc) were excluded.

The MEDLINE, EMBASE, PUBMED and EMCARE databases were searched for relevant documents published from January 1995 to December 2019. The literature search used the following terms (with synonyms and closely related words): *fatal, death, deceased, diving, diving deaths, equipment, surface supply / surface supplied, hookah apparatus, compressor, equipment failure, device failure, surface supply, investigation, audit, examination*.

The search was not limited by study design but was restricted to English language. Further studies were identified by examining the reference lists of articles and papers published in *Diving and Hyperbaric Medicine*, formerly *the South Pacific Underwater Medicine Society* (SPUMS) *Journal*, and *Undersea and Hyperbaric Medicine*. Also included were workshops proceedings from DAN, SPUMS, European Underwater and Baromedical Society (EUBS) and the Undersea and Hyperbaric Medical Society (UHMS). In addition, a hand search was conducted of texts in diving medicine specifically for chapters on diving deaths, and occupational codes of practice in Australia. Finally, a search was undertaken of references identified in papers located by the initial search providing access to other relevant articles. Manufacturer data sheets from commercial hookah producers were accessed (where available) to identify key functions that were relevant to technical assessment of the apparatus.

Information from the literature search was assimilated to produce a checklist for systematic assessment of hookah diving equipment. This included both the descriptive and functional assessment of the apparatus including hookah air output and quality. Key differences between scuba and hookah were identified and solutions applied to adapt the technical investigation to surface supply hookah apparatus.

Technical equipment reports provided to investigations of Tasmanian diving deaths 1995–2019 were accessed where a hookah apparatus had been used by the deceased diver. These assessments had been performed by technical staff in the Department of Diving and Hyperbaric Medicine at Royal Hobart Hospital and were available in a de-identified format. The technical reports were compared to the checklist as derived above to identify gaps in previous technical assessments for the purposes of quality improvement, and to identify possible gaps in the checklist.

Results

LITERATURE SEARCH

The search identified no papers that exclusively concentrated on hookah equipment investigation in the event of a diving death. Although some publications identified fatalities involving the use of hookah and surface supply equipment there was very little discussion, if any, on the investigation of actual equipment and this was the key reason for rejection of most papers.

We were unable to identify papers that specifically described hookah technical evaluation, nor a system of evaluating surface supply equipment in the event of a diving fatality. The processes for scuba fatality investigations as described in the DAN recreational diving fatalities workshop document were the only detailed description of equipment technical investigation identified by the literature search.[5,6] Although based on scuba, these evaluation forms provided very helpful practical guidance that was adapted to hookah diving equipment investigation. A specific checklist was developed by the authors to permit comprehensive and detailed analysis of hookah equipment.

The hand search also identified an instruction manual from one manufacturer of a hookah apparatus. This provided additional detail on the functional specifications of the equipment.[14] The Tasmanian Abalone Divers Code of Practice provided additional specifications which are requirements for hookah apparatus that were not covered by other references.[12] Both of the above were incorporated into the checklist as they covered areas that had not been identified by other references. A textbook from 2003 did not add additional information to the DAN dive fatality workshop.[3,15]

DEVELOPING A CHECKLIST FOR HOOKAH TECHNICAL ASSESSMENT

The checklist published by Barsky for scuba equipment in the DAN recreational diving fatalities workshop proceedings complimented the paper by Bozanic and Carver and provided a structure for visual inspection that could be applied to the hookah apparatus.[5,6]

The major headings for Bozanic's[5] article were:

(1) Epidemiological and site data
(2) Overview of the complete equipment system
(3) Dive cylinder including pressure
(4) Cylinder valve
(5) Buoyancy compensator
    Manufacturer data including specifications
    Condition report – all components

Configuration
Function testing including inflator function
(6) Weights – configuration, total amount, release capability
(7) Regulator
Manufacturer data and model number
Description and configuration
Service dates
First stage
Manufacturer data and model number
Serial number
Condition
Filters and covers
Second stage primary regulator
Manufacturer data and model number
Serial number
Condition
Filters and covers
Second stage secondary regulator
Manufacturer data and model number
Serial number
Condition
Filters and covers
Inflator hose
Condition
Connection to BCD and/or Dry suit
(8) Maintenance Records

Items 2–8 above were able to be adapted for hookah equipment technical assessment, further populated from published checklists in the workshop proceedings appendices. When creating a checklist for evaluating hookah equipment, scuba and hookah equipment were specifically compared. Parallels for the equipment when comparing scuba air versus hookah air are summarised in Table 1.

The key differences summarised in Table 1 were incorporated into the broad structure of the documents provided by Bozanic and Carver. The subheadings were expanded to permit detailed assessment of the equipment both structurally and when evaluating its function; populated from the key references, and the manufacturers' data sheet. The recommended checklist for technical assessment of the hookah apparatus following an accident appears in Appendix 1.

GAP ANALYSIS OF HOOKAH EQUIPMENT INVESTIGATIONS FOR TASMANIAN DIVING DEATHS

A recent paper reported five deaths in Tasmania between 1995 and 2015 where hookah equipment was utilised, and all these deaths involved equipment failure or inappropriate set-up.[10] An additional two divers died in Tasmania between 2015 and 2019 while using hookah apparatus, making seven cases in total in 25 years.[13]

Two of the earlier deaths were from the same incident and the report consisted only of a written assessment of air quality and a series of equipment photos so these could not be evaluated in detail. However, carbon monoxide (CO) poisoning was implicated, and it was apparent how this occurred, because the air intake was next to the exhaust. One death was due to a shark attack, and the equipment was not subject to a technical assessment. Another death (prior to 2001) had no technical report prepared. This left three deaths with technical assessment reports of the hookah equipment to evaluate for which gap analyses were undertaken using the checklist.

Table 2 summarises the key gaps identified in three available hookah technical reports. All three assessments did not report epidemiological or site descriptions and none reported weather or sea conditions. Details of these first two descriptors were available in the police reports. Exhaust intake position was not described in any report, although this could be deduced from pictures of the apparatus. No report included an assessment of hookah function. Of note was a progressive improvement in the level of detail of assessment between 2008 and 2019, particularly relating to the compressor, the air intake and regulator. The weight configuration/attachment description was available in only one of the three reports.

Discussion

The hookah apparatus is used by divers throughout Australia, recreationally and professionally, but has received very little attention in the medical literature.[11] Our literature search could identify only four papers of relevance to the study. Of 84 Australian surface supply breathing apparatus (SSBA) deaths in a 54-year period, 15 occurred in Tasmania.[11] There were seven Tasmanian hookah diving deaths from 1995–2019, all being recreational divers and which comprised 35% of all Tasmanian diving deaths.[10] In addition, from 2000–2019, 61% (14/23) of all Australian SSBA deaths were in recreational divers.[11] Tasmania's population makes up 2.1% of Australia's population, demonstrating recreational hookah deaths are over-represented in the island state.

Among other causes, previous studies have documented hookah equipment problems as important predisposing factors in causation of diving fatalities.[10,11] Given that the hookah equipment is supplying life-supporting air to the diver, the frequency of problems is of concern. It is also concerning that our literature review identified very little guidance on the technical evaluation of hookah equipment. This may be because other jurisdictions use hookah apparatus less frequently or have more effective safety systems. It is possible that some available dive fatality literature has under-reported hookah equipment problems because the assessments have not been undertaken using a systematic approach.

Footnote: Appendix 1 is available on the DHM website: https://www.dhmjournal.com/index.php/journals?id=314

Table 1
Comparison of technical features of scuba equipment compared to hookah; BCD – buoyancy control device

Equipment item/feature	Scuba	Hookah	Comments regarding differences
Origin of air	Air at or around dive shop or other high-pressure compressor	Air pumped from the local environment by the motor driven hookah pump. Often on anchored boat with potential to move with wind/current	Hookah air intake must be high and pointing into the wind, away from pump exhaust. Relative positions of intake and exhaust need to be monitored with boat movement/wind change
Air quality testing	At approved filling station; mandated by AS/NZS 2299.1	Responsibility of owner. Not mandated	Air quality of hookah may vary during the dive due to set up and environmental conditions
Air supply	Dive cylinder at up to 300 MPa air	Hookah pump at 800 kPa air	Scuba has first stage reducing valve to produce line pressure of 1,000–1,200 kPa. Not present in hookah so pressure may vary with compressor function
Air filtration	Post-compressor macro + charcoal filtration	Particle filter at intake, further filtration macro and charcoal at air delivery	Hookah owner/user responsible
Reserve air supply	Not routinely carried – reliance on buddy system and octopus regulators	Not routinely carried – reliance on small amounts of gas in hookah reserve cylinder.	Hookah divers may carry a secondary scuba cylinder or have reserve air cylinder linked to hookah reserve. Australian Standard 2299.1(2015) mandates secondary air supply
Contents gauge	Measures pressure in the scuba cylinder	Not required – relies on continuous pump operation	Scuba diver can anticipate falling air supply as contents of cylinder are used
Air hose	Usually ≤ 1 m long	Could be 50–100 m long	Hookah hose risks kinking, being severed or disconnected
Secondary air hose	Standard via a second low pressure hose – for emergency use	May be added attached to Hookah pump directly or via 'T' or 'Y' connector to supply second diver (not emergency)	Reduced flow if additional hoses added to Hookah from a single source, or via constrictive connectors. No backup for second diver if pump fails
Line pressure	Typically 1,000 kPa to 1,200 kPa	Typically 800 kPa	
Diver regulator	Second stage tuned to the scuba line pressure	Second stage tuned to the hookah line pressure	Regulators can provide 200+ litres per minute, dependent on the line pressure and reserve volume
Regulator attachment	Secured to cylinder via first stage and BCD	Secured by looping under or inside harness or weight belt	If the hookah hose is not effectively secured, there can be considerable drag and possibility of mouthpiece loss
Attachment of gear	Via BCD	Weight vest, harness or belt	System must be configured to easily establish independent buoyancy and/or dump weights.
Attachment of weights	Integrated within the BCD, or weight belt	Weight belt or weight vest	Weight vests not always designed for quick release
Adjustable buoyancy	Standard kit via BCD	BCD not routinely used. Buoyancy changes if weights ditched or lift bag used for catch	See above two points
Maintenance records	Cylinder test annually. Other maintenance not mandated	Not mandated – responsibility of owner	Requirement for cylinder test at testing station provides reminder to service other equipment

Table 2
Summary of gaps in three technical assessments of hookah diving fatalities

Descriptor	Investigation 1 gaps	Investigation 2 gaps	Investigation 3 gaps
Case identifiers. Date and location	Not reported but available in police report. Date included	Not reported but available in police report. Date included	Not reported but available in police report. Date included
Weather and sea conditions	Not reported	Not reported	Not reported
General overview of equipment system	Not described as a system except for report of fair to good working order	Not described	Described in detail
Compressor assessment including air output configuration	Not reported	Description limited to air filter, compressor motor, relief valve, absent non-return valves	Incomplete – limited detail. Described condition. Missed maintenance, pressure relief, air hose connections
Air intake, location, filter and air reserve	Not reported. Air intake reported as "*adequate vehicle type*" filter. No air reserve	Intake, location and air reserve not described. Filter described as "*inadequate water filter*". No redundancy	Described in detail. Intake, location and condition, air reserve volume described.
Air supply hose and regulator	Described in detail. 'Y' connector. Regulator - aged but good condition but not assessed if hookah specific	Described in detail, including hookah specific kinks	Described in detail, and also described not hookah specific. Covered supply to two divers in detail
Exhaust and position relative to air intake	Not described	Described minimal spacing between exhaust and air inlet	Not described
Accessories – weight harness/belt. Buoyancy	Described. Weight belt attaching air supply to diver. Excess weight. Difficult to jettison	Not described	Not described
Analysis of air quality	Assessed for CO_2 and oil but no other assessment. Stated: "*depleted compressor reservoir volume*"	Full assessment performed	Full assessment performed
Assessment of hookah function	Not done	Not done	Not done
Additional comments	Described regulator hose cut during retrieval of deceased diver from entanglement	Hose reels for regulators not available	Length of hose 153 m

Table 1 demonstrates that it is possible to compare characteristics of scuba and hookah equipment. For both apparatuses, the endpoint is delivery of air to the diver. The scuba diver usually obtains their cylinder gas from a supplier and, in Australia, the supplier must comply with Australian standards and work health and safety legislation, providing a layer of safety. However, the hookah diver is essentially responsible for their own gas supply which is pumped from the ambient environment where they are diving by the hookah pump.

The hookah apparatus has multiple components that could affect air purity and supply to the diver. The air intake must be high and pointing into a non-contaminated source and must be filtered to prevent foreign material entering the system. The pump exhaust must be distant and downwind from the air intake to prevent contamination with CO and other exhaust contaminants. The motor and compressor must be well maintained with sufficient fuel, because their continuous and correct operation is essential to keep the diver alive. The motor and compressor must be able to match the diver(s) requirements for air when exercising at the depth of operation. The system must have an adequate reservoir to minimise flow and pressure fluctuations, and all air hoses must be non-kink, of sufficient diameter, properly configured, free of holes, and connections must be always secure. Non-return 'check' valves are needed to prevent negative pressure injury if the diver's air supply is cut off. The hookah hose is long (up to 50 m), placing it at risk of entanglement or severance by propellers. The demand valve should be suitably attached to the diver to reduce displacement risk and needs to be tuned to the hookah output 'line pressure'.

Compared to the direct supply from a scuba cylinder via a first stage regulator and demand valve, the hookah supply process is complex. Therefore, it is not surprising that hookah accidents and fatalities occur when a component of the air supply system fails. Fatalities directly due to contamination of the breathing gas are rare in scuba divers,[16,17] although it is likely that some cases were missed due to lack of testing. Gas contamination has been positively identified as the primary contributor in only one of 444 (0.2%) Australian scuba deaths since 1965,[13] compared to 15/84 (18%) in SSBA diving deaths.[11]

Overall, there is a much higher prevalence of equipment problems in SSBA divers than scuba divers. For example, in a series of 126 Australia scuba deaths, 19% of predisposing factors and 12% of triggers were equipment-related, the breathing gas supply being affected in 15 (11%) of these.[18] This compares to equipment-related factors being identified as 48% of predisposing factors and 24% of triggers in Australian SSBA deaths, directly affecting the air supply in 43/84 (51%) of these fatal incidents.[11]

In the Australian SSBA deaths, the main source of problems were compressors which were often poorly maintained, poorly positioned, or inappropriately configured. Hence there is a definite need for a technical equipment evaluation process in the event of an accident. We adapted previously published processes from scuba accident investigation to produce a checklist to guide hookah equipment technical assessment. In the process of checklist production, we had to limit the amount of information collected, so that the process was confined to unique aspects of hookah diving.

The final checklist template (Appendix 1) was used to generate a gap analysis for three hookah fatality equipment reports from a single centre. All three reports identified causes of problems with the hookah diving systems and, also, highlighted flaws in the construction and maintenance. Within the study, a progressive improvement in detail of reporting occurred over time. This may be due to the experience gained with each successive investigation.

Although limited to three equipment evaluations from a single centre, the process identified multiple deficiencies in the reports. Epidemiological, site data, location descriptions, weather and sea conditions were reliant on police reports, which can often be variable and miss relevant issues. These reports had no standard structure and depended on the local investigating policeman's experience and familiarity with diving, which is often non-existent. In addition, there was a lack of information about the overall hookah system in two reports with deficiencies in description of air intake/exhaust positions (CO risk) in all three reports, and with only one report describing the diver's air hose/weight configuration. This is important for two reasons. First, many hookah divers use their weight belt to attach their air hose to their body. Second, nearly three quarters of all SSBA deaths in a prior series were still wearing weights when rescued or recovered.[11] These two issues may be related – a ditched weight belt may mean an unsecured air hose which may well lead to the loss of air supply and make the diver more reluctant to ditch their weights. In addition, two thirds of that study cohort were not wearing a buoyancy device.[11] Weighting/hose security and lack of buoyancy are factors that can be remedied to prevent diving accidents. A structured checklist could assist with identifying trends in accident data, and we believe this should be useful as a reference for future hookah accident investigations.

As far as we are aware this is the first time a process for hookah technical assessment has been documented. The checklist may require further refinement however, our current version at least ensures that the evaluation process is consistent. This initial work may serve as a basis for more thorough data collection and a deeper understanding of hookah accident causation, and future prevention.

LIMITATIONS

The checklist was created from limited resources and a small sample of hookah equipment investigations and, as a result, some pertinent inclusions may have been missed.

Conclusions

The hookah apparatus is significantly different from scuba equipment and carries higher risk for the diver. It appears to be over-represented in diving fatalities in Tasmania, with equipment failure and air contamination occurring more commonly than with scuba. There is currently no regulation or oversight of the use of the recreational hookah apparatus. To improve accident investigation, a formalised process for technical evaluation of hookah equipment (post-accident), which includes a data collection checklist template specific to hookah was created. The checklist may serve as a resource for future hookah equipment assessments and may inform strategies for preventing future hookah accidents.

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