International Journal of Pediatric Otorhinolaryngology 100 (2017) 77–85

Contents lists available at ScienceDirect

International Journal of Pediatric Otorhinolaryngology

journal homepage: http://www.ijporlonline.com/

Pathophysiology of esophageal impairment due to button battery ingestion

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ARTICLE INFO

Article history:
Received 15 April 2017
Received in revised form
14 June 2017
Accepted 23 June 2017
Available online 26 June 2017

Keywords:
Esophagus
Battery ingestion
Colliquation necrosis
Children
In vitro

ABSTRACT

Background: The increased use of button batteries with high energy densities in devices of daily life presents a high risk of injury, especially for toddlers and young children. If an accidental ingestion of a button battery occurs, this foreign body can become caught in the constrictions of the esophagus and cause serious damage to the adjacent tissue layers. The consequences can be ulcerations, perforations with fistula formation and damage to the surrounding anatomical structures. In order to gain a better understanding of the pathophysiology after ingestion, we carried out systematic studies on fresh preparations of porcine esophagi.
Methods: The lithium button battery type CR2032, used most frequently in daily life, was exposed in preparations of porcine esophagi and incubated under the addition of artificial saliva at 37 °C. A total of eight esophagi were analysed by different methods. Measurements of the pH value around the battery electrodes and histological studies of the tissue damage were carried out after 0.5–24 h exposure time. In addition, macroscopic time-lapse images were recorded. Measurements of the battery voltage and the course of the electric current supplemented the experiments.
Findings: The investigations showed that the batteries caused an electrolysis reaction in the moist environment. The positive electrode formed an acidic and the negative electrode a basic medium. Consequently, a coagulation necrosis at the positive pole, and a deep colliquation necrosis at the minus pole occurred. After an exposure time of 12 h, tissue damage caused by the lye corrosion was observed on the side of the negative electrode up to the lamina muscularis. The corrosion progressed up to the final exposure time of 24 h, but the batteries still had sufficient residual voltage, such that further advancing damage would be expected.
Conclusions: Button battery ingestion in humans poses an acute life-threatening danger and immediate endoscopic removal of the foreign body is essential. After only 2 h exposure time, significant damage to the tissue could be detected, which progressed continuously to complete esophageal perforation. The primary prevention of battery ingestion is therefore of particular importance.

1. Introduction

Oral ingestion of button battery cells can lead to serious medical conditions ranging from minor mucosal damage to esophageal perforation resulting in strictures [1], trachea-esophageal fistulas [2], vocal-cord palsy or even mediastinitis, spondylodiscitis and death [3]. Especially cases of batteries swallowed by infants can result in a serious medical outcome and permanent health effects [4]. In the past two decades, the incidence of button battery ingestion reported in the literature, and especially the percentage of major or fatal outcomes per year, has significantly increased [5]. Statistics show that button batteries lodged in the esophagus posed the greatest risk and required instant removal [6]. Analyses of clinical cases showed that button batteries over 18 mm in diameter can get trapped in one of the three anatomical esophagus

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http://dx.doi.org/10.1016/j.ijporl.2017.06.030
0165-5876/

constrictions if swallowed. The increasing number of such cases seems to be a result of the common use of 20 mm lithium button batteries in many electronic devices in our daily life, which are used in calculators, watches, remote controls, computers and even children's toys [7]. This is due to the specific design of these very flat batteries, which are easy to integrate into small appliances such as TV remote controls, and are low-maintenance due to their high energy density [8] and long shelf life [9]. Additionally, the evaluation of cases reported by the National Capital Poison Center in Washington, DC from 1990 to 2008 could show that major effects or even death after button battery ingestion mostly occurred in children at the age of between one and three years [6]. In healthy adults, the gag reflex usually prevents the accidental ingestion of foreign bodies or corrosive substances. Since this reflex has not yet been fully developed in young children, the risk of accidental battery ingestion is particularly high for them [7]. These facts indicate the necessity of prevention, especially by parents, and the importance of a better understanding of how batteries harm mucosal tissue.

The esophagus is a muscular canal about 25 cm in length (in adults), which extends from the hypopharynx to the antrum cardiacum of the stomach [10]. It is the narrowest part of the digestive tube and can be subdivided into three major sections: the cervical, the thoracic and the abdominal portion. Important anatomical structures adjacent to the esophagus, which can be damaged in the case of an esophageal perforation, are the trachea, the pericardium, the intercostal arteries, the azygos vein, the subclavian artery and the vagal nerves. The esophagus has three anatomical constrictions: (a) the esophageal inlet (14 cm from the incisor teeth), where the esophagus commences at the cricopharyngeal sphincter, (b) the crossing by the aortic arch and the left bronchus (25 cm from the incisor teeth) and (c) the lower esophageal sphincter, where it pierces the diaphragm (36 cm from the incisor teeth) (distance in adults). These areas have a special significance since swallowed foreign bodies, such as animal bones or coins, often remain trapped in the area of the esophageal constrictions and cannot be swallowed further into the stomach [11].

The wall of the esophagus includes four different tissue layers: (1) the internal mucous membrane, a thick layer of stratified squamous epithelium; (2) the submucosal layer beneath the mucous membrane containing the muscularis mucosae, nerves, blood vessels and mucous glands and connecting the mucous and muscular layers; (3) the muscular layer (tunica muscularis) which contains an external plane of longitudinal fibres and an internal plane of circular fibres; and (4) the fibrous tunica adventitia enveloping the esophagus by connective tissue.

The mucous membrane of the esophagus has a variety of submucosal glands, which provide a physiological protection against injury from foreign bodies or corrosive substances. When such harmful agents come into contact with the mucous membrane, mechanoreceptors and chemoreceptors are activated and lead to in increased secretion of mucins. The viscosity of the mucus increases and the endothelium is thus protected from chemical and mechanical damage [12]. This mechanism is triggered especially in contact with acid, and a drop in pH below 2 to help neutralise gastric acid in gastroesophageal reflux [13].

The aim of this study was an *in-vitro* analysis of battery damage to the esophagus, specifically, to understand the pathophysiology of mucosal injury due to button batteries lodged in the esophagus, and to determine the timeframe patients and clinicians have after ingestion until major mucosal damage occurs. To this end, CR2032 lithium button batteries were placed into esophagus specimens of domestic pigs (sus scrofa domestica), and incubated under physiological conditions. During exposition pH current measurements and time-lapse imaging were performed. The different chemical and electrical effects occurring at the contact point between the electrodes and the mucosa were also investigated. In addition, the determination of the short timeframe between the onset of exposition and the observance of major tissue damage, as well as the need for a quick clinical diagnosis and endoscopic removal of the foreign body if stuck in the esophagus of patients was addressed.

2. Materials and methods

2.1. Organ preparation

Eight esophagi from domestic pigs (sus scrofa domestica) were provided by a local butcher immediately after slaughtering (Landmetzgerei Mueller, Kleinrinderfeld, Germany). After resection of the pharynx and gastrophrenic parts, the thoracic portions of five esophagi were cut into eight segments each of 2 cm in length. Half of the specimens were prepared for battery exposure; the other half was used as the untreated control. Three esophagi were sliced longitudinally for time-lapse video recordings of battery exposure.

2.2. Button batteries

A total of 51 lithium manganese dioxide CR2032 button batteries (renata batteries®) (Fig. 1 a) with a nominal voltage of 3.0–3.2 V and a rated capacity of 235 mAh were used [8]. The operating temperature of these batteries is between −40 and +85 °C. The diameter of the batteries is 20 mm (surface = 3.14 cm^2) at the positive pole and 16 mm (surface = 2.01 cm^2) at the negative pole. The envelope is made from stainless steel and measures 3.2 mm in height. Between both battery poles lies an insulation layer of 0.5 mm diameter over a circumference of 5.8 cm. Modifications of the CR2032 batteries were prepared for current measurements (Fig. 1 b). The metal anode cap was coated by a very thin isolation varnish (Overcoat Pen, Chemtronics®). After complete drying, the integrity of the insulation was checked with a voltmeter across the area of the anode. A second battery of the same type was broken and the bare metal surface of its anode dissolved. This was glued with cyanoacrylate adhesive to the insulated pole of the test battery (Pattex® superglue, Henkel AG). In this way, the original anode of the test battery was doubled without changing the material type or significantly changing the technical design, and an electrical series circuit of an ammeter for measuring the electric current was thereby possible (Fig. 1 b). For this purpose, insulated measuring cables were soldered to both parts of the doubled anode.

2.3. In-vitro organ incubator

To analyse the mucosal impairment during battery exposure *in-vitro,* an organ incubator was designed to simulate *in-vivo* conditions (Fig. 1c). The incubator was made from an acrylic glass case (w × d*h = 30 × 20*5 cm), which could be sealed airtight. Photos and time-lapse video recordings during exposure could be taken from outside the transparent acrylic glass. The inside temperature was determined by a PT100 thermistor and regulated by a PID temperature controller (ATC30®, Aiks Electric). To keep the incubator temperature at the required level, a heating cable was installed inside the incubator (Hydor Hydrokable®, 25 W 230 V) and powered by the PID controller. All experiments were performed inside the described incubator at 37 °C.

2.4. Battery exposition process

The lumen of the intersections of each esophagus was moistened with an artificial saliva compound (Glandosane®, cell pharm GmbH). According to the manufacturer, Glandosane® contains, in