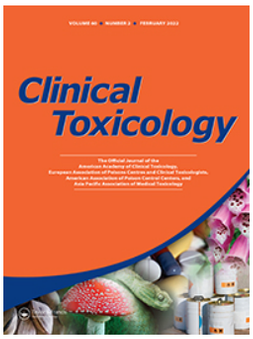

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REVIEW

Bowel obstruction following ingestion of superabsorbent polymers beads: literature review

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ABSTRACT

Rationale: Superabsorbent polymers are marketed as toys, and cases of ingestion in children are increasingly reported. Even if these cases are usually considered benign, bowel obstruction has been reported.

Objective: To investigate the exposure characteristics, clinical presentation, management, and outcome of patients who developed bowel obstruction following ingestion of superabsorbent polymer-made products.

Methods: Databases were searched (no start date – 2020/01/31) using the following keywords: ("superabsorbent" OR "polymer" OR "hydrogel" OR "crystal" OR "jelly" OR "Orbeez" OR "beads") AND ("ingestion" OR "obstruction" OR "perforation") AND ("intestinal" OR "bowel"). All cases of bowel obstruction following superabsorbent polymer-made product ingestion were included.

Results: ***Report selection:*** We found 25 reports reporting 43 cases of bowel obstruction following superabsorbent polymer-made product ingestion. All the reports were retrospective, including 20 case reports and 4 case series. ***Patient characteristics and clinical presentation:*** Age ranged from 6 to 36 months, and the female/male sex ratio was 1.3. The median delay between the ingestion of the product and the onset of the first symptoms (available in only four reports) was 1.0 [0.7;1.8] day (from 15 h to 2 days). The median delay between the onset of gastrointestinal symptoms and hospital admission, available for all but 15 patients, was 3 [2;4] days (from 15 h to 30 days). The reported symptoms were persistent vomiting in all cases, associated with constipation (11/43), diarrhea (1/43), abdominal pain (1/43), and clinically assessed dehydration (14/43). Abdominal palpation found abdominal tenderness or distension in 11/43 and 28/43 patients, respectively. An abdominal mass was palpated in 3/43 patients. Two patients presented with fever, and three patients developed seizures. ***Characteristics of exposure:*** Ingestion of superabsorbent polymer-made products was reported by relatives on hospital admission in only 10/43 cases. Based on imaging and/or surgically/endoscopically removed products, all were bead-shaped objects. The median number of beads removed (available in 27/43) was 1 [1–2] (range from 1 to 6). Their median diameter (available in 21/43 patients) at the time of the diagnosis of bowel obstruction – i.e., at hydrated state – was 30 [30;36] mm (range from 25 to 65 mm). ***Imaging findings:*** Abdominal radiography, performed in 31/43 patients, never showed evidence of foreign body ingestion Abdominal computed tomography scanning, performed in 10/43 patients, visualized an intraluminal mass in 5/10 cases. Abdominal ultrasound performed in 34/43 patients allowed visualization of a rounded intraluminal image that corresponded to a bead in 28/34 patients but led to a correct diagnosis of foreign body-induced bowel obstruction in only 15/34 cases. One case reported the contributory use of abdominal MRI. Beads were always located in the small bowel (from the duodenum to the terminal ileum). ***Removal of beads*:** Bead removal required endoscopy in 2/43 cases and surgery in 41/43 cases (enterotomy or resection in 36/43 and 5/43 cases, respectively). In 3/36 cases, additional enterotomy was performed to remove beads that had not been found during the first surgery. The delay between the onset of gastrointestinal symptoms and removal procedures ranged from 1 to 7 days. ***Outcome:*** Except for two fatal cases, the outcome was favorable.

Conclusions: Ingestion of superabsorbent polymer-made beads can be responsible for fatal bowel obstruction in children related to the increase in bead size within the intestinal tract. Diagnosis is made difficult by the radiolucent properties of the beads. The management of bowel obstruction probably most often requires endoscopic or surgical procedures. Children under 4 years of age are probably the most at risk of developing bowel obstruction.

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Rationale

Superabsorbent polymers are cross-linked hydrophilic polymers that can retain up to several hundred times their dry weight in contact with a water-containing liquid [1]. Consistently, superabsorbent polymer-made products can increase by 150–1500 times their dry size [2].

These products were first used in agriculture in the 1950s to maintain soil moisture. Since then, superabsorbent polymer-made products have been used in a wide variety of applications, including hygiene products (baby diapers, incontinence pads, or sanitary napkins) [3]. More recently, superabsorbent polymer-made beads have been marketed as ornamental products and toys [4]. Their candy-like translucent colors, soft and slippery texture makes them both attractive and easy to swallow for children [3]. Cases of ingestion of superabsorbent polymer-made beads are increasingly reported to Poison Control Centers (PCCs) [4–6].

Most marketed superabsorbent polymer-made beads are cross-linked sodium polyacrylate. After ingestion of these beads, no systemic toxicity is expected, and no case of toxicity has been reported with exposure by the oral route in both humans and animals [4–9]. However, given the ability of these beads to swell in contact with a water-containing liquid, mechanical complications are to be expected, and cases of bowel obstruction following ingestion of these products have been reported [2,10]. Some superabsorbent polymer-made toys were withdrawn from the market in the United States in 2013. Then, the Australian Competition and Consumer Commission recommended that these beads should no longer be marketed as toys, and they launched an alert campaign on their risks in 2015 [11,12].

Objectives

The objective of this systematic review was to investigate the exposure characteristics, clinical presentation, management, and outcome of patients who developed bowel obstruction following ingestion of products made from superabsorbent polymers.

Materials and methods

We conducted the review according to the PRISMA guidelines on systematic literature review [13]. Three databases (Pubmed, Embase, and Google Scholar) were searched (no start date – 2020/01/31) using the following keywords: ("superabsorbent" OR "polymer" OR "hydrogel" OR "crystal" OR "jelly" OR "Orbeez" OR "beads") AND ("ingestion" OR "obstruction" OR "perforation") AND ("intestinal" OR "bowel").

We included all English and French reports (abstracts or full texts) involving patients who developed bowel obstruction following the ingestion of superabsorbent polymer-made bead products. We performed the first selection to identify reports specifically reporting exposure to these products, based on titles and/or abstracts. Thereafter, we performed a second selection to remove duplicates and animal reports. Finally, we removed reports reporting exposure to superabsorbent polymer-made products without ingestion, reports reporting products not causing bowel obstruction after ingestion, and reports reporting the ingestion of these products and bowel obstruction related to another foreign body. Two independent investigators (WC and DV) performed this selection, and any disagreement was resolved by mutual consensus.

For each report included in the review, we collected and entered the following data in a Microsoft® Excel (Redmond, USA) database: author name, country, year of publication, demographics, exposure characteristics, clinical presentations, imaging findings, management, and outcome.

Results were expressed as median and [interquartile range] (continuous variables), or percentages (non-continuous variables). Statistical analysis was performed using *R* software, 3.5.3 version (Project for Statistical Computing).

Results

Report selection

Overall, 3751 references were found, including 157 in Pubmed, 2594 in Embase and 1000 references in Google scholar (only the 1000 first references were screened for this database) (Figure 1). We performed the first selection to select reports reporting SAPs-made products exposure, based on titles and/or abstracts, and removed 3609 records. We then removed duplicates ($N = 30$) and animal reports ($N = 4$). After reading the full texts or abstracts, we removed reports reporting ear canal obstructions ($N = 2$), ingestions without bowel obstruction ($N = 14$), and bowel obstructions not related to the ingestion of superabsorbent polymer-made products ($N = 67$). Overall, 25 reports reporting 43 cases were considered for analysis: 20 articles with English full-text [3,10,14–31], three articles with English abstracts but not English full-texts (two in Russian and one in Korean) [32–34], and two conference abstracts (one in English and one in French) [5,35]. The first report was published in 2011 [22]. All the included reports were retrospective, including 20 case reports [3,10,17–30,32–35] and 4 case series [5,14–16,31].

Patient characteristics and clinical presentation

Age was available in all reports, except for one case series of 15 patients which provided only the mean age and age range [31] (Table 1). In the reports providing age individually, the median age was 15 months (interquartile range: [10;18]) [3,5,10,14–30,32–35]. In the case series, the mean age was 2 years [31]. Overall, the age ranged from 6 to 36 months and the female/male sex ratio was 1.3 [3,5,10,14–35]. The median delay between the ingestion of the SAPs-made product and the onset of the first symptoms, only available in four reports, was 1.0 [0.7;1.8] day (from 15 h to 2 days) [3,10,14,22]. The median delay between the onset of gastrointestinal symptoms and hospital admission, available for all but 15 patients [31], was 3 [2;4] days (from 15 h to 30 days). The reported symptoms were persistent vomiting in all cases [3,5,10,14–35], associated with constipation in 11/43 cases

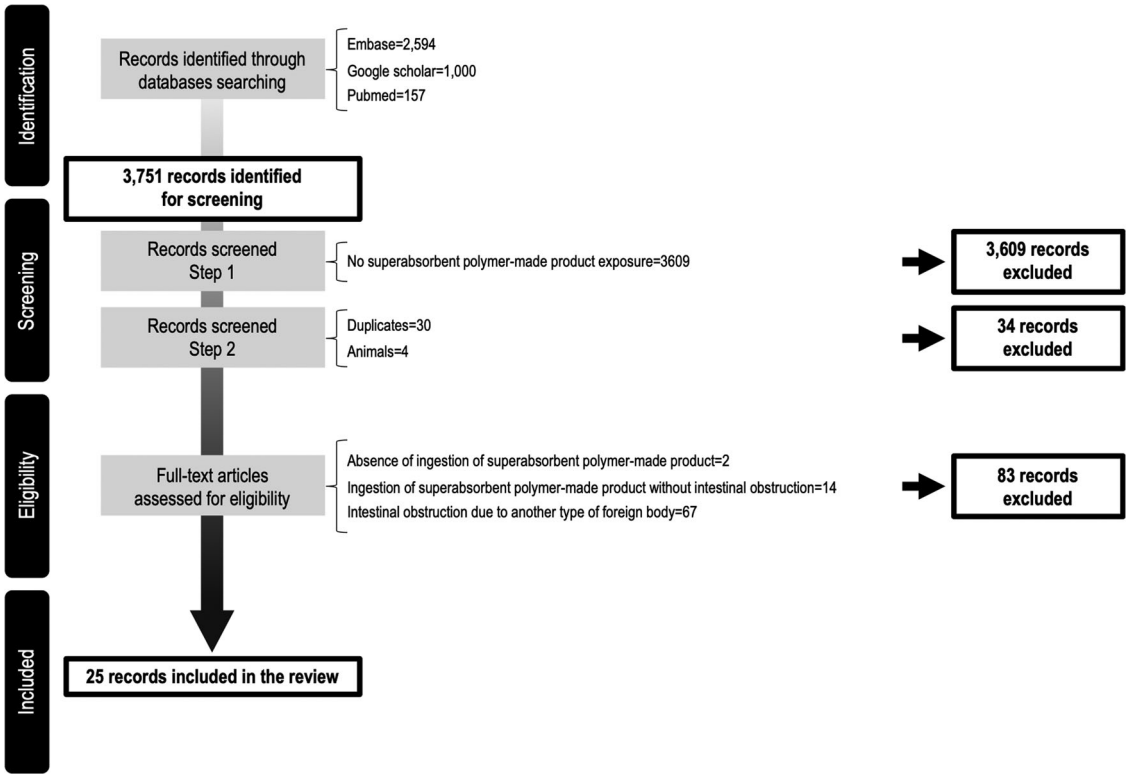

Figure 1. Flow chart of the reviewing process. (SAPs: superabsorbent polymers).

[3,10,16,21,22,26,28,29,32,33], diarrhea in 1/43 case [5] and abdominal pain in 1/43 case [26]. Fourteen patients had clinically assessed dehydration [3,5,14,16,17,20,22,24,28, 29,31, 32,34], and two patients presented with fever [28,29]. Abdominal palpation found abdominal tenderness or distension in 11/43 [3,10,16,17,22,26,27,29,33,34] and in 28/43 [10,15–17,20,22,24,26,29,31–34] patients, respectively. An abdominal mass was palpated in 3/43 patients [20,25,32]. Three patients developed seizures [25,32,34].

Characteristics of exposure

Ingestion of these products was declared by relatives on hospital admission in only 10/43 cases [3,10,14,23,31] (Table 1). In two other cases, relatives remembered the ingestion after the products were removed. [21,22]. In two other cases, the presence of superabsorbent polymer-made products in the vomit before hospital admission pointed to foreign body ingestion [30,35]. Based on imaging and/or surgically/endoscopically removed products, all were bead-shaped objects, so that superabsorbent polymer-made products will be henceforth referred to as superabsorbent polymer-made beads. Except for two cases involving *Water Balz* (DuneCraft Inc., Chagrin Falls, Ohio, USA) [10] before it was withdrawn from the United States market [36], and *LiquiBlock*™ *Rainbow Beads* (Emerging Technologies Inc., Greensboro, USA) [30], the brand of the removed beads was unknown.

The beads involved were sold for ornamentation in 8/43 cases [3,14,17,18,21,22,27,33], like toys in 3/43 cases [5,10,25], and for industrial use in 1/43 cases [30]. In the 31/43 remaining cases, the purpose of the beads was unknown. The median number of beads removed, available in 27/43 patients, was 1 [1–2] (range from 1 to 6) [3,5,10,14–30,32–34]. Their median diameter (available in 21/43 patients) at the time of the diagnosis of bowel obstruction (ultrasound imaging: $N = 5$ [17,25–27,33]), or at the time of removal (endoscopy or surgery: $N = 16$ [3,5,10,14,16,20,23,24,28–30,32,34]) – i.e., at hydrated state – was 30 [30;36] mm (range from 25 to 65 mm; in case of ingestion of several beads, the largest diameter was considered).

Imaging findings

Abdominal radiography, with ($N = 7$) or without oral contrast ($N = 36$), was performed in 31/43 patients and showed air-fluid levels and/or bowel dilatation, but none showed evidence of foreign body ingestion [3,5,10,15–22,24–31,33,34] (Table 1). In one case, gastrointestinal perforation was suspected with the presence of free gas under the diaphragm [22]. Abdominal computed tomography scanning, with ($N = 4$) or without ($N = 6$) oral contrast, was performed in 10/43 patients [16–19,21,25,28,29,34,35] and visualized an intraluminal mass in 5/10 cases [16,18,21,25,34]. In two cases, cyst duplication was evoked [16,18]. Abdominal ultrasound, performed in 34/43 patients [3,5,14–18,22,25–27,29,31–34] and allowed visualization of a rounded intraluminal image that could correspond to a SAPs bead in 28/34 patients [3,5,14–18,25–27,31–33], but led to a correct diagnosis of foreign body-induced bowel obstruction in only 15/34 cases (including at least two cases in which ingestion of the object was known) [3,14,15,27,31]. Based on abdominal ultrasound, evoked diagnosis were pancreas pseudocyst, ovarian or mesenteric cyst, enteric duplication, neoplasm, or enterocystoma [15,16,26,31–33]. One case reported the contributory use of

Table 1. Reports reporting cases of bowel obstruction following SAPs beads ingestion.

Studies	Demographics			Clinical presentation											Exposure characteristics			Imaging findings							Management		
References	Nb	Age (months)	Sex	Delay between symptoms onset and hospital admission (days)	Fever	Dehydration	Vomiting	Constipation	Diarrhea	Abdominal pain	Abdominal tenderness	Abdominal mass	Abdominal distension	Seizure	Witnessed ingestion	Nb of SAPs bead removed	SAPs bead maximal diameter (mm) at hydrated state	Abdominal radiograph	Vizualization of the bead	Ultrasound	Vizualization of the bead	CT-scan	Vizualization of the bead	Bowel obstruction location	Delay between hospital admission and removal procedures (day)	Procedure use to remove the SAPs beads	Outcome
Mirza et al. [22]	1	18	M	2	Yes	Yes	Yes	Yes	.	.	Yes	.	Yes	.	.	3	Unknown	Yes	.	Yes	.	.	.	Ileum	2	Resection	Recovery
Mirza et al. [21]	1	6	M	25	.	.	Yes	Yes	.	.	.	.	.	.	.	1	Unknown	Yes	.	.	.	Yes	Yes	Proximal jejunum	25	Enterotomy	Death
Moon et al. [3]	1	18	F	4	.	Yes	Yes	Yes	.	.	Yes	.	.	.	Yes	1	30*	Yes	.	Yes	Yes	.	.	Jejunum	4	Enterotomy	Recovery
Zamora et al. [10]	1	8	M	0.625	.	.	Yes	Yes	.	.	Yes	.	Yes	.	Yes	1	35*	Yes	.	.	.	.	.	Terminal lileum	2,625	Enterotomy	Recovery
Muthukumaran et al. [20]	1	18	F	2	.	Yes	Yes	.	.	.	.	Yes	Yes	.	.	1	30*	Yes	.	.	.	.	.	Proximal ileum	2	Resection	Recovery
Anderson et al. [29]	1	17	F	2	Yes	Yes	Yes	Yes	.	.	Yes	.	Yes	.	.	6	65*	Yes	.	Yes	.	Yes	.	Proximal jejunum	2	Enterotomy	Recovery
Komatsu et al. [25]	1	15	M	3	.	.	Yes	.	.	.	.	Yes	.	Yes	.	1	35	Yes	.	Yes	Yes	Yes	Yes	Duodenum	3	Endoscopy	Recovery
Pham et al. [30]	1	10	F	1	.	.	Yes	.	.	.	.	.	.	.	.	1	35*	Yes	.	.	.	.	.	Terminal ileum	3	Enterotomy	Recovery
Al-Saied	3	7	M	7	.	Yes	Yes	Yes	.	.	Yes	.	Yes	.	.	1	40*	Yes	.	Yes	.	.	.	Terminal ileum	7	Enterotomy	Recovery
et al. [16]		9	F	7	.	.	Yes	.	.	.	.	.	.	.	.	1	30*	Yes	.	Yes	Yes	Yes	Yes	Duodenum	7	Enterotomy	Recovery
		12	F	30	.	.	Yes	Yes	.	.	Yes	.	Yes	.	.	1	40*	Yes	.	Yes	Yes	.	.	Ileum	30	Enterotomy	Recovery
Faizah	2	17	F	3	.	.	Yes	.	.	.	.	.	Yes	.	.	1	Unknown	Yes	.	Yes	Yes	.	.	Terminal ileum	3	Enterotomy	Recovery
et al. [15]		18	F	2	.	.	Yes	.	.	.	.	.	.	.	.	1	Unknown	Yes	.	Yes	Yes	.	.	Jejunum	2	Enterotomy	Recovery
Singh et al. [18]	1	9	F	30	.	.	Yes	.	.	.	.	.	.	.	.	1	Unknown	Yes	.	Yes	Yes	Yes	Yes	Duodenum	30	Enterotomy	Recovery
Bradford et al. [28]	1	10	F	3	Yes	Yes	Yes	Yes	.	.	.	.	.	.	.	1	25*	Yes	.	.	.	Yes	.	Jejunum	5	Enterotomy	Recovery
Lip et al. [24]	1	22	F	4	.	Yes	Yes	.	.	.	.	.	Yes	.	.	1	30*	Yes	.	.	.	.	.	Terminal ileum	4	Enterotomy	Recovery
Zaitseva et al. [33]	1	17	M	4	.	.	Yes	Yes	.	.	Yes	.	Yes	.	.	1	25	Yes	.	Yes	Yes	.	.	Terminal ileum	4	Resection	Recovery
Fuger et al. [27]	1	14	F	1	.	.	Yes	.	.	.	Yes	.	.	.	.	1	30	Yes	.	Yes	Yes	.	.	Jejunum	1	Enterotomy	Recovery
Yang et al. [17]	1	18	M	3	.	Yes	Yes	.	.	.	Yes	.	Yes	.	.	4	28	Yes	.	Yes	Yes	Yes	.	Proximal ileum	3	Enterotomy	Recovery
Arshad et al. [35]	1	19	F	1	.	.	Yes	.	.	.	.	.	.	.	.	Multiple	Unknown	.	.	.	.	Yes	.	Duodenum	1	Endoscopy	Recovery
Lee et al. [34]	1	12	F	1	.	Yes	Yes	.	.	.	Yes	.	Yes	Yes	.	2	30*	Yes	.	Yes	.	Yes	Yes	Proximal Ileum	4	Enterotomy	Recovery
Mohamed	2	15	M	2	.	Yes	Yes	.	.	.	.	.	.	.	.	3	30*	.	.	Yes	Yes	.	.	Duodenum	2	Enterotomy	Recovery
et al. [14]		18	M	3	.	Yes	Yes	.	.	.	.	.	.	.	Yes	3	37*	.	.	Yes	Yes	.	.	Terminal ileum	3	Enterotomy	Recovery
Ramos-Mercado et al. [19]	1	11	F	3	.	.	Yes	.	.	.	.	.	.	.	.	1	Unknown	Yes	.	.	.	Yes	.	Terminal ileum	3	Resection	Recovery
Shangareeva et al. [32]	1	10	M	1	.	Yes	Yes	Yes	.	.	.	Yes	Yes	Yes	.	2	40*	.	.	Yes	Yes	.	.	Jejunum	9	Enterotomy	Recovery
Liang et al. [31]	15	6–36	M = 9 F = 6	Unknown	.	n = 2	Yes	.	.	.	.	.	Yes	.	n = 6	Unknown	Unknown	Yes	.	n = 15	n = 13	.	.	Small bowel	2–4 days	Enterotomy	Recovery
Care et al. [5]	1	18	F	3	.	Yes	Yes	.	Yes	.	.	.	.	.	.	3	30*	Yes	.	Yes	Yes	.	.	Ileum	10	Resection	Death
Khan et al. [26]	1	12	F	8	.	.	Yes	Yes	.	Yes	Yes	.	Yes	.	.	1	27	Yes	.	Yes	Yes	.	.	Terminal ileum	9	Enterotomy	Recovery
Michelakos et al. [23]	1	19	F	Unknown	.	.	Yes	.	.	.	.	.	.	.	Yes	1	30*	.	.	.	.	.	.	Jejunum	Unknown	Enterotomy	Recovery

*Case where the diameter of the SAPs beads was measured after removal. (Nb: number, SAPs: superabsorbent polymers; F: female; M: male; .: not reported/not performed).

abdominal magnetic resonance imaging (MRI) [16]. Superabsorbent polymer-made beads were always located in the small bowel (from the duodenum to the terminal ileum) [3,5,10,14–35].

Removal of beads

The removal of superabsorbent polymer-made beads required endoscopy in two cases (beads located in the duodenum) [25,35] and surgery in 41/43 cases [3,5,10,14–24,26–34] (Table 1). Enterotomy was performed in 36/43 cases [3,5,10,14–24,26–34], and bowel resection in 5/43 cases [5,19,20,22,33] (multiple perforations were found in one case [22]). In 3/36 cases, additional enterotomy was performed to remove beads that had not been found during the first surgery [14,32,34]. In 2/36 cases, revision surgery was required due to a leak of the bowel suture [21,24]. Endoscopy or surgery procedure was performed within the 24 h following admission in 21/43 cases [3,14–22,24–27,29,33,35]. In 6/43 cases, surgery was performed within 2.5 [2.0;7.3] days (from 2 to 8 days) [5,10,28,30,32,34]. In 16/43 cases, this delay was unknown [23,31]. The median delay between the onset of gastrointestinal symptoms and removal procedures was individually provided in 23/25 reports and was 3 [2.0;7;0] days [3,5,10,14–22,24–30,32–35]. In another report reporting 15 cases, the mean delay was 1.5 days [31]. Overall, except for one case for which no data was provided, this delay ranged from 1 to 7 days [3,5,10,14–22,24–35]. In three cases, an histological study of the extracted bead was performed, which showed "multiple gelatinous materials with numerous fungal hyphae" [16]. In one case, the histological study of the ileal resection showed necrotic lesions with the presence of birefringent fragments indicating the presence of the foreign body [5].

Outcome

Two fatalities were reported (Table 1). The first case was a 6-month-old boy with a 25 days delay between the onset of gastrointestinal symptoms and surgical management [21]. After the first surgery (enterotomy), a leak led to peritonitis and fatal sepsis. The second case was an 18-month-old girl with a 7 days delay between the onset of gastrointestinal symptoms and surgical management [5]. Before surgery, she developed multi-organ failure resulting in her death despite surgery. This patient had a concomitant *Salmonella* infection with diarrhea which may have may have promoted the swelling of the beads and the necrosis of the bowel wall.

Discussion

Compared to the increasing number of cases of ingestion of superabsorbent polymer-made beads reported to Poison Control Centers worldwide, mainly in children, bowel obstruction following bead ingestion is a rare but serious, even fatal complication [4–6,21]. All cases reported in this review involved children under 4 years of age who had ingested at least one bead. The diameter of the beads in their hydrated state was greater or equal to 25 mm.

These data raise several questions. Cases of bowel obstruction have been reported only in young children, whereas the increase in the ingestion of these beads concerns children of all ages [4–6]. Furthermore, the location of the obstruction, i.e., in the small bowel, is rather unusual after ingestion of a foreign body [37]. Areas of anatomical and physiological narrowing along the gastrointestinal tract (pylorus, duodenal C-loop, Treitz ligament, and ileocecal valve) are the common locations of obstruction; location in or beyond the jejunum is observed rarely [37–39].

The mechanism of bowel obstruction observed after ingestion of superabsorbent polymer-made beads is probably similar to that observed after ingestion of dried fruits or mushrooms, which also cause small bowel obstructions in both humans and animals [40–47] (Figure 2). These foods share the same characteristic as superabsorbent polymer-made beads: they swell in contact with digestive secretions as they move through the gastrointestinal tract. This suggests that superabsorbent polymer-made beads were probably ingested in their dried (or not fully hydrated) state, when their diameter was of the order of a few millimeters, as rounded objects larger than 25 mm in diameter are generally less likely to pass the pylorus, especially in young children [48,49].

In vitro evaluation of the swelling capacity of superabsorbent polymer-made beads in liquids showed that the volume gain was greatest during the first 12 h, while maximum swelling was reached after 96 h [10,50]. Assuming an average emptying gastric time of 45 min for liquids and 98 min for solids, and that foreign bodies that pass beyond the pylorus usually passed in feces within four to six days, maximal swelling of these beads is therefore expected in the small bowel [51–53]. As small bowel diameter increases with age (newborn: 5.1 mm; 6 months: 12 mm; 8 years: 21 mm; >15 years: 23 mm), children under 4 years of age are probably at higher risk to develop bowel obstruction after ingestion of superabsorbent polymer-made beads [51].

In addition to the obstruction of the intestinal lumen due to the increase in the size of the beads, the hygroscopic properties of superabsorbent polymer-made beads could promote obstruction due to adhesion to the intestinal mucosa [1]. In one case, the histological study of the resected intestine showed the presence of bead fragments in the area of necrosis [5]. Finally, although beads cannot clump together, we cannot rule out that higher numbers of ingested beads could be associated with a higher risk of bowel obstruction [50].

Three children developed seizures related to hyponatremia caused by vomiting [25,32,34]. There is no evidence to suggest that SAPs could be responsible for neurological toxicity. The onset of neurological toxicity (decreased consciousness or even coma) following the ingestion of colored *Bindeez*™ beads (Moose Enterprise Pty Ltd., Victoria, Australia) and *Aqua Dots*™ (Spin Master Ltd., Toronto, Canada) has been reported [54]. However, these beads are not a superabsorbent polymer-made product. They were sold as toys that allow the creation of multi-dimensional

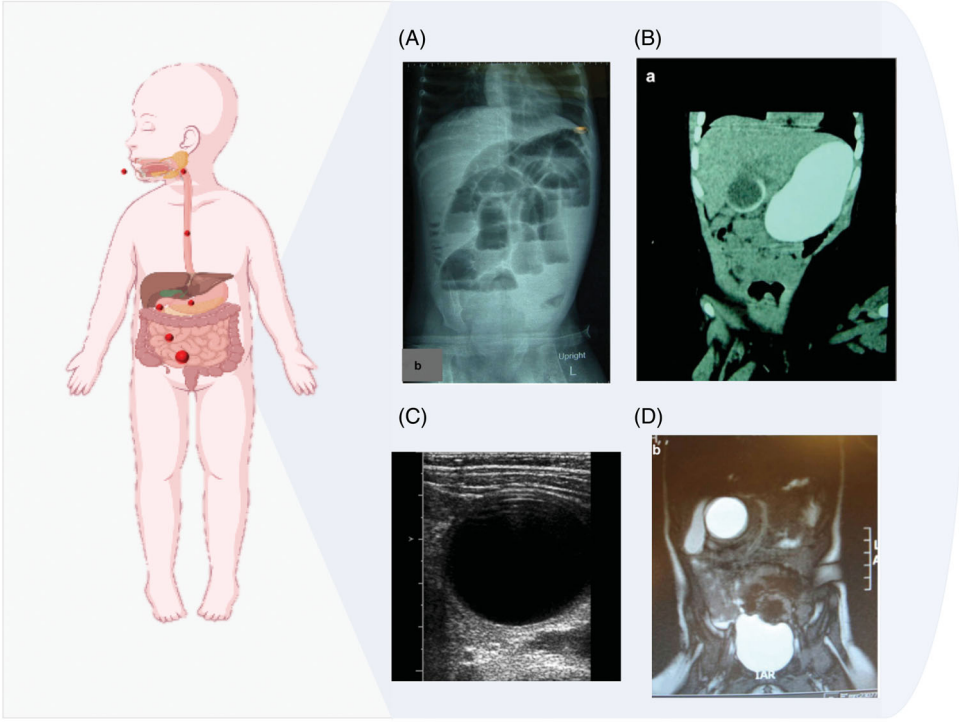

Figure 2. Proposed mechanism of SAPs bead-induced bowel obstruction in children (created with Biorender.com). Young children ingest the SAPs beads in their dried (or not fully hydrated) state – i.e., when their diameter is of the order of a few millimeters, assuming that rounded objects larger than 25 mm in diameter are generally less likely to pass the pylorus, especially in young children [48, 49]. Then, the SAPs beads gradually swell in the small bowel and cause the obstruction. (A) Abdominal X-ray (erect) showed multiple air-fluid levels [16], (B) Abdominal CT scan with IV and oral water-soluble contrast revealed cystic structure in the 1st and 2nd part of the duodenum with surround contrast widening the lumen indicating intraluminal lesion (duplication cyst) [16], (C) Abdominal MRI revealed large well-defined fluid intensity signal cystic lesion in the right upper abdomen $3 \times 3 \times 3.3$ cm located in the right subhepatic region [16], (D) Ultrasound image revealing the fluid-filled bead, measured at $3.8 \times 3.1 \times 3.1$ cm. Dilated loops of the small bowel were identified proximal to this structure [3]. (All these images have been reproduced with permission of the publisher through the Copyright Clearance Center's RightsLink® service. (A) refers to the 1-year-old child from the report by Al Saied et al. and corresponds to part b of Figure 2, the caption has not been modified [16]; (B) and (D) refers to the 9-month-old child from the report by Al Saied et al. and corresponds to parts a and b of Figure 1 [16], the captions have not been modified; (C) refers to the case reported by Moon et al. and corresponds to Figure 2, the caption has not been modified [3]).

shapes after melting the beads in contact with water. Toxicological analysis showed γ-hydroxybutyric acid in the poisoned children's urine, leading to the discovery that the manufacturer had substituted 1,5-pentandiol with 1,4-butanediol (a precursor of γ-hydroxybutyric acid) for cost reasons [55].

As mentioned in the introduction section, superabsorbent polymer-made beads-induced systemic toxicity is unexpected. In rats, radiolabeled polyacrylate is poorly absorbed by the gastrointestinal tract (∼3%) and mainly excreted in the feces (∼90%) while a minor part is excreted in urine (<1%) or exhaled in carbon dioxide (<1%), suggesting very poor metabolism [7]. Moreover, the chronic oral administration of superabsorbent polymers of up to 3000 mg/kg/day for 93 days in rats did not result in histological, hematological or clinical chemistry changes [7]. Finally, the oral median lethal dose (LD_{50}) in rats is >40,000 mg/kg [56].

There is a discrepancy between the steady increase in the number of reported cases of beads ingestions in children and the low number of cases of bowel obstruction following these exposures. We found four Poison Control Center's series reporting suspected ingestions of superabsorbent polymer-made bead [4–6,9]. On the 487 suspected ingestions reported to Poison Control Centers, we found only one case of bowel obstruction [5]. This suggests that not all superabsorbent polymer-made beads have the capacity to cause bowel obstruction, even in infants. Darracq et al. [50] showed that superabsorbent polymer-made beads described as "*Orbeez*" (dried diameter: ∼2 mm) never exceeded 11.5 mm in diameter *in vitro* in water. Forrester et al. [6] did not report a case of bowel obstruction after ingestion of beads assumed to be *Orbeez*™ (The Maya Group Inc., Torrance, California, USA). Other researchers studied another type of bead (unspecified brand – dried diameter: 2 mm) *in vitro* in water. They reported an increase in the volume of ∼260 times, but superabsorbent polymer-made beads in their fully hydrated state never exceeded 13 mm in diameter [57]. Moreover, these experiments, carried out with water at room temperature, do not reflect the real characteristics of intestinal fluid where lower pH, higher ion content, and temperature could decrease the swelling capacity of superabsorbent polymer-made beads [50,58,59]. The swelling capacity of superabsorbent polymer-made beads is therefore highly variable and have a predefined size beyond which they cannot swell. In reality, most marketed beads could never reach the critical size to induce small bowel obstruction.

Diagnosis of bowel obstruction following ingestion of superabsorbent polymer-made beads remains very difficult. In three-quarters of cases, bead ingestion was unwitnessed. Forrester et al. [6] reported the onset of minor symptoms (vomiting, abdominal pain, constipation, diarrhea, fever) in less than 5% of children in a series of 110 children (range:

<1–15 years) who ingested beads assumed to be *Orbeez*™, but none developed bowel obstruction. These data suggest that not all symptomatic patients develop bowel obstruction. The most common sign of bowel obstruction observed in all children in this review was repeated vomiting.

The contribution of imaging to diagnosis is variable. Superabsorbent polymer-made beads are radiolucent, and no abdominal radiograph showed evidence of foreign body ingestion [57]. Abdominal CT was more helpful in visualizing beads but in only 50% of cases [16,18,21,25,34]. The most useful imaging modality was an abdominal ultrasound, which visualized beads in 82% of cases, even though the diagnosis of bowel obstruction due to a foreign body was made on ultrasound in less than half of those patients. On ultrasound, beads appear as round liquid masses since the density of superabsorbent polymer-made beads is identical to water [3,17,29,57]. The round echoless areas in the intestine can mimic a duplication cyst, even if the wall of the cyst is thicker than that of the beads [15,18,26,57]. The use of abdominal MRI is rarely reported, but this technique seems helpful as it provides a well-defined fluid intensity signal (high T2-signal intensity) [16]. Moreover, the advantage of this imaging technique has already been reported in cases of liquid-filled packets ingested by body packers [60].

Management of bead ingestion remains unclear. Due to the limited number of cases of bowel obstruction, the development of guidelines based on the results of prospective studies is unlikely. As reported in this review, most superabsorbent polymer-made bead ingestions causing bowel obstruction are unwitnessed. Therefore, all children with repetitive vomiting should have a medical evaluation and foreign body ingestion should be considered in the differential diagnosis. In case of witnessed ingestion of superabsorbent polymer-made beads, considering that the number of reported cases of bowel obstruction seems small compared to the number of reported ingestions [4–6,9], non-symptomatic children could probably be safely monitored at home for 6 days, i.e., the expected time for a foreign body passing the pylorus to be eliminated in the stool [51–53]. The time between the ingestion of the beads and the onset of symptoms was reported in very few patients (less than or equal to 48 h), making it impossible to draw any conclusions [3,10,14,22]. Conversely, based on this review, all children under 4 years of age with witnessed ingestion of superabsorbent polymer-made beads who present with vomiting, should have a prompt medical examination. In all cases, if the clinical examination points to the diagnosis of bowel obstruction, an abdominal ultrasound should be performed if no obstacle is visualized on an abdominal X-ray. Although intestinal decontamination with polyethylene glycol (PEG) has been proposed for documented ingestion of superabsorbent polymer-made beads, it cannot be recommended as beads are capable of swelling after immersion in PEG [50,58,61]. Similarly, the early endoscopic extraction of beads in the stomach could be proposed [62] but is probably inappropriate considering the probable unfavorable benefit/risk ratio given the risks associated with anesthesia and the low risk of developing a bowel obstruction after bead ingestion [63].

In case of small bowel obstruction, urgent surgical removal by enteromy is probably the treatment of choice as impacted beads no longer have the possibility to progress through the gastrointestinal lumen, especially as their diameter may still increase [3]. As described in this review, endoscopy can be used successfully for cases where the bead is located in the duodenum [25,35]. However, the procedure seems challenging to carry out with the need to fragment the beads [25,35]. After surgery/endoscopy, close clinical monitoring should be maintained as persistent intestinal beads may not be detected by imaging or during surgery in case of multiple ingestion as described in three patients who had to have a second surgery a few days after the first [14,32,34].

Finally, this review focused on the bowel obstruction induced by the ingestion of superabsorbent polymer-made beads. However, other complications may arise after ingestion of superabsorbent polymer-made products. In 2019, the United Kingdom National Health Service (UK-NHS) issued an alert about the use of *Vernagel*™ (Vernacare Limited, Chorley, United Kingdom), a sodium polyacrylate powder used in vulnerable elderly to prevent their bedding or clothes from becoming soiled with urine and to prevent them from falling if their urine spills on the floor [64]. UK-NHS reported the ingestion of *Vernagel*™ in an elderly and confused patient that resulted in death from asphyxiation after the granules swelled in the upper airway. Alharbi et al. [65] also reported aspiration of a superabsorbent polymer-made product into the airways of a child after ingestion, causing recurrent lung infections. Finally, during the review process, we found two reports reporting two cases of ear canal obstruction by superabsorbent polymer-containing products resulting in tympanic or inner ear damage [66,67].

Conclusions

Although increasing, ingestions of superabsorbent polymers or superabsorbent polymer-made products by children, including superabsorbent polymer beads marketed as ornamental objects or toys, rarely seem to be associated with severe complications. Due to their physical and chemical properties, there is a risk of small bowel obstruction as a result of an increase in bead size within the gastrointestinal tract, which can be fatal if management is delayed. Small bowel obstruction usually occurs in children <4 years who have ingested beads whose diameter in the hydrated state can reach more than 25 mm in diameter. Diagnosis is made difficult by the radiolucent nature of superabsorbent polymers. If symptoms of bowel obstruction appear in the hours or days following bead ingestion, prompt medical care in the hospital is necessary, and surgery is frequently required.

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