A Hazard Analysis of Class I Recalls of Infusion Pump

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Abstract

Background: The adverse event report of medical devices is one of the post-market surveillance tools for regulators to monitor device performance, detect potential device-related safety issues, and contribute to benefit-risk assessments of these products. Along with the development of the related technologies and market, the amount of adverse events keeps increasing, which results in the need for efficient tools that help to analyze the adverse events monitoring data and to identify the risk signals.

Objective: To establish a hazard classification framework of the medical devices, and to apply it over practical adverse event data regarding infusion pumps. Subsequently, to analyze the risks of infusion pumps, and to provide reference for the risk management of this type of device.

Methods: The authors defines a general hierarchical classification of medical device hazards. This classification is combined with the Trace Intersecting Theory to form a human-machine-environment interaction model. Such model is applied to the dataset of 2001?2017 class ? infusion pump recalls extracted from FDA website. This dataset does not include the cases caused by illegal factors, in order to reflect the risk signals of this type of device.

Results: The proposed model is leveraged in the hazard analysis over 70 cases of class I infusion pump recalls by FDA. According to the analytical results, the “infusion pump dose not infuse accurate dosage (over or under delivery of fluid)” is identified to be an important source of product technical risk. The Energy hazard is the major hazard form for infusion pumps. The product component failure is the main direct cause for the studied cases.

Conclusions: The proposed human-machine-environment interaction model, when applied to adverse event data, can help to identify the hazard forms and direct causes of medical device adverse events.

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KEYWORDS
adverse events analysis; infusion pump; risk management; hazard classification; human-machine-environment interaction model

Introduction

Infusion pump

Continuous intravenous delivery of drugs with short half-lives such as inotropic agents and vasodilators is a recommended technique in acute care [1]. A syringe pump is a device that intravenously infuses fluids, drugs, or nutrients in the patient [2]. The application of infusion pump is helpful for lightening nurses' work strength, improving the accuracy and efficiency. The purpose of using a syringe pump in clinical settings is to administer an accurate amount of drug or fluid over a relatively long duration, and it can be especially favorable for continuous infusion of very small amounts such as 0.1 ml/h [3]. Transfusion pump and syringe pump (hereinafter referred to as "infusion pump").

The infusion pump system is mainly composed of the following parts: the microcomputer system, the pump component, the detection system, the alarm device and the input and display device. The microcomputer system controls and manages the whole system intelligently, prevents the occurrence of the wrong infusion, and sends the alarm signal to the alarm device for sound and light alarm. The pump component is the power source of the liquid injection. The detection system is used to detect the working state of the infusion pump in order to detect all kinds of abnormality in time, which is usually made up of different kinds of sensors in different parts. The alarm device is used to inform the medical and nursing staff of the normal and abnormal state. The input part is used to set the parameters of the infusion, such as the amount of infusion and the speed of the infusion. The display section is responsible for displaying the parameters and current state of work.
The use of infusion pumps was identified as the area with highest risk, based on incident report data [4]. A higher median MAE rate was observed for the intravenous route (53.3% excluding timing errors (IQR 26.6-57.9%)) compared to when all administration routes were studied (20.1%; 9.0-24.6%), where each dose could accumulate more than one error [5]. Intravenous infusion may present the greatest preventable medication administration error risk to hospitalized patients [6]. At present, usage of infusion pumps are very high in clinic, but there are many problems existing in the clinic application such as discontinued infusion, leakage, inaccuracy of infusion dose, too fast or too slow infusion speed, etc. According to the clinical needs, analyzing the failure and mode-effect of infusion pumps was useful for evaluating the ease of use and ergonomics and evidence-based procurement [7].

The failure modes and infusion errors of infusion pump is always the top ten hazards on ECRI Institute's annual list. ECRI Institute announce 2017's top-ranked hazard focuses on infusion errors that can occur when using large-volume infusion pumps [8]. On August 23, 2013, ECRI Institute PSO clinical engineering staff spotted the risk of infusion pump during regular review of device-related events submitted to the PSO. The team saw multiple events at one hospital in which an infusion pump had stopped working with no apparent cause. Investigation revealed that a disconnection between the pump module and the PC unit had caused unexpected cessations of infusion therapy for several patients. The problem resulted from corroded or damaged interunit interface (IUI) connectors [9]. ECRI Institute's PSO Monthly Brief February 2015, ECRI Institute PSO patient safety analyst Stephanie Uses, PharmD, MJ, JD, emphasized the potential risk on each phase of the medication use process. There is a risk of confusion among look-alike/sound-alike injection drugs formations, concentrations, and dosages when prescribing the proper one for the patient during the Prescribing stage, he said. And risks during

Monitoring phase include inadequate monitoring—when patients' response to the insulin is not observed to see if an adjustment in dose is necessary [10].

Thus, it will be critical for improving the success rate for emergency treatment of patients to be able to effectively decrease risks of infusion pump in clinical. In 2010, Yi Zhang et al. introduced a generic insulin pump model and a preliminary hazard analysis based on this model [11], they divided the hazardous situations into five categories associated with generic insulin infusion pump, including therapeutic, energetic, chemical/biological, mechanical and environmental. Paul Curzon et al. established a tool focused on understanding how the design of interactive medical devices (such as infusion pumps, monitors and diagnostic devices help save lives) can support safety [12]. Paolo Masci presented a hazards analysis identified a substantial set of root causes of use hazards in software design, which is general in the sense that the problematic functionalities are common in broad classes of infusion pumps [13]. He and his partners established a model-based risk analysis methodology that helps manufacturers identify and mitigate use hazards in their products at early stages of the development life-cycle [14]. They also presented a generic user interface architecture, GIP-UI, to facilitate the identification and reasoning of use hazards in infusion pumps [14].

Medical device adverse events

The medical devices, due to their natural characteristics, may bring safety risks, together with health benefits, to the users. The medical device adverse events refer to the qualified post-market medical devices cause a variety of harms (or potential harms) to the human body under normal operation. These adverse events (including any symptoms, signs, diseases, or the events could result in significant injury or death) do not necessarily have a direct causal relationship with medical devices, can only be temporarily associated with medical devices. The monitoring work of medical device adverse events can be useful in warning healthcare institution and regulatory bodies on how to use medical device safely and effectively. All national regulators have established the corresponding data reporting system to actively collect the medical device adverse events.

In order to reduce or avoid the possible risks and damage to human health caused by medical devices, recalling the post-market defective medical devices is an internationally accepted method for safety management of post-market medical devices. As one of the active practitioners of medical device recall, the U.S. Food and Drug Administration (FDA) categorizes all recalls into three classes according to the level of hazard caused by medical devices. The class I is defined as dangerous or defective products that predictably could cause serious health problems or death [15].The recalls is available in the Medical Devices/Safety/List of Recalls on the FDA's official website, http://www.fda.gov.

In 1972, Professor Elwyn Edwards first proposed the principle of "human" as the center of a particular system interface in security work, elements including software, hardware, environment, and liveware. The acronym SHEL stands for these four elements, these factors constitute the SHEL model. The human error should be analyzed because of the mismatch between interfacial elements. In the use of medical device risk analysis, in 2011, Liu long et al. has established a "medical personnel" centric medical device risk analysis model based on the SHEL model, called DELPS (Device, Environment, Liveware, Patient, Software) [16]. Masci

P et al. presented a hazard analysis method that extends Leveson's System Theoretic Process Analysis (STPA) with a comprehensive set of causal factor categories, so as to provide developers with clear guidelines for systematic identification of use-related hazards associated with medical devices, their causes embedded in UI software design, and safety requirements for mitigating such hazards [17]. Michael D. Harrison et al. concerned with how to demonstrate that a user interface software design is compliant with use-related safety requirements, and they established a methodology aims to demonstrate how to achieve the FDA's agenda of using formal methods to support the approval process for medical devices [18]. Paolo Masci et al. established a technique integrates human cognitive process models and general interaction design principles, and uses a model-based approach for systematic exploration of potential hazards [19].

However, from the perspective of medical device supervision, the goal of post-market medical device risk management is to further discover the unacceptable risks and causes of medical device products through production and post-production safety data (including medical device adverse events), such as : product design, production process, specifications and other issues, and then take appropriate risk control measures, that is, "product" as the center of the risk analysis, evaluation and control process, its starting point and foothold are "products".

Therefore, based on the above research results, this paper presents a hazard classification framework of the medical devices and human-machine-environment interaction model, and use it to analyze 70 cases of FDA class I infusion pump recalls, in order to identify the direct cause of all risks, then putting forward some advices for the lifecycle management of infusion pumps.

Methods

Adverse event reports are the main source of data of this research. Our mission here is to find out key hazard risk factors and direct causes through the analysis of adverse events reports. Analyzing the hidden risk of medical device based on adverse event report is generally considered as a complicated job. The risk factors cannot be directly extracted if we don't have appropriate tool to structuralize the content in those reports. Taken the infusion pump as an example, its application environment of is a complex system of human-machine-environment interaction. It's almost impossible for us to identify the hidden risk factors without thoroughly understanding this complex system. Therefore, in this research, we developed a tool to allowing modeling of such complex system, and then use this tool to analyze the hazard of infusion pump.

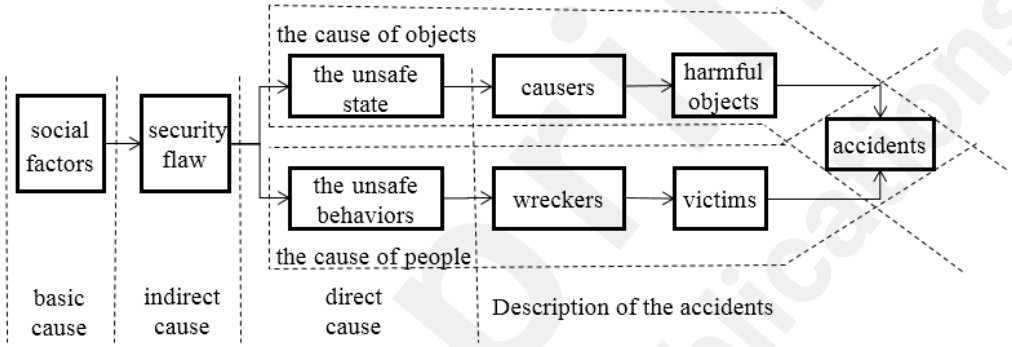
This tool is developed based on the Trace Intersecting Theory, which is a widely used generic tool for analysis of complex system. But it is too general to be directly applied to our target – Infusion pumps. In order to better adapt to the characteristics of medical device products, we extend this theory with five new types, so that the model can now be applied to the risk analysis of medical devices, and then use it to analysis infusion pump recalls.

In terms of the evolution process of safety theory, the early theories of "Accident proneness" emphasized the influence of people's personality characteristics on accidents. Later, Heinrich put forward the "Accident causation theory", emphasizing that accidents are the result of the interaction of various factors. In 1961 and 1966, Gibson and Haddon introduced a new concept: accidents are incorrect or undesirable energy transfers or releases. At this time, it was

discovered that injury accidents could be prevented by controlling energy. In 1969, J.Surry suggested that people's mishandling of information might lead to accidents. After the inheritance and development of these ideas by many people, it is found that the unsafe behavior of people or the unsafe state of things is the direct cause of industrial accidents.

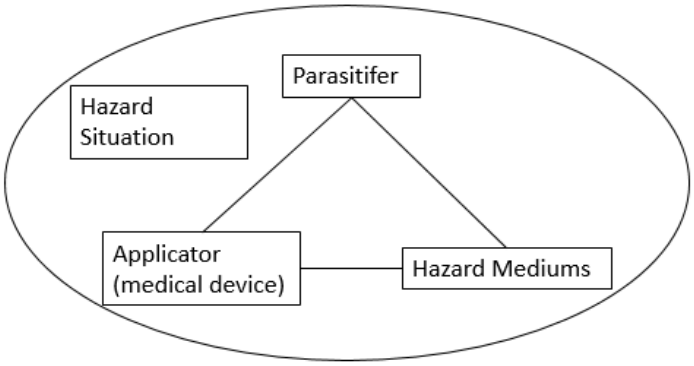
The Trace Intersecting Theory focuses on the cause of the accident. Such causes can be summarized as equipment's faults (or defects) and human errors. The intersection of the two event chains indicates an accident. The basic idea is that the injury accidents are the result of the development of two series of interrelated people and things (including the environment). As a result of a variety of factors, the unsafe behaviors of people and the unsafe state of the objects will keep on evolving in their respective trajectories, and the accidents will happen at a later point when they meet or interact at a certain time and space (see Figure1).

Figure1. The schematic diagram of the Trace Intersecting Theory



The occurrence mechanism of medical device adverse events consists of four types of interactive factors (see figure 2). Among them, the "parasitifer" is an individual who may be injured, including the patient and/or medical personnel. The "applicator" is the medical device that generates force, transmits or prevents energy. And a "human-machine" relationship is formed between the "applicator" and the "parasitifer". For the purpose of diagnosis and treatment, the exchange or transmission of material, energy and information between the human body system and the medical device system will continue. When the material, energy and information involved in the exchange/transmission exceed the limit tolerance of the human body, a certain type of harm will be shown, and we call it "hazard mediums". The "hazard situation" focuses on the conditions or environment in which the injury occurs, i.e. the condition and degree of the human body in various hazardous environments.

Figure 2. The mechanism of medical device adverse events



Modern physics considers that material and energy are the elements of the objective world, but a closer look will find that information is another attribute of the objective world, in addition to the material and energy [20]. Therefore, we use the material, energy and information as the three fundamental elements to model the objective world, for the purpose of hazard analysis. But it's difficult to separate material from energy because energy exists in any type of material, and energy cannot live alone without the material being its host. Thus in the following analysis, the material and energy are merged together and is analyzed as "energy".

As a result, the medical device adverse events can be divided into three types based on different hazard mediums, respectively are: (1) Energy hazard; (2) Information hazard; (3) Energy and Information hazard (see Table 1).

Table 1. The hazard classification framework of the medical devices

Hazard classification	Subtype
TypeⅠ Energy hazard	Subtype Ⅰa (Excessed Energy)
	Subtype Ⅰb (Insufficient Energy)
Type Ⅱ Information hazard	Subtype Ⅱa (Incorrect Information)
	Subtype Ⅱb (Insufficient Information)
	Subtype Ⅱc (Overloaded Information)
Type Ⅲ Energy and Information hazard	Subtype Ⅲa (Energy-dominant)
	Subtype Ⅲb (Information-dominant)
	Subtype Ⅲc (Dual-culprit)

The Energy hazard medium is called type Ⅰ medical device adverse event. It refers to the event th at medical devices may directly cause human injury in the form of energy under the application e nvironment [21]. The Energy hazard can be further divided into two subtypes: the Excessed Energy and the Insufficient Energy. Among them, the Excessed Energy refers to the scenario

when certain kind of energy exceeds the threshold that the humans can bear, which may directly or directly lead to the damage of human body. The form of such Excessed Energy can be: mechanical energy (Ia-01), radiant energy (Ia-02), thermal energy (Ia-03), electricity (Ia-04), biological and chemical energy (Ia-05), etc (Ia-06). The Insufficient Energy refers to an event that may cause human injury directly because the normal life energy and material exchange, between the human body and the surrounding environment, is interfered. These cases are in the form of hypoxia, hypothermia and hydropenia which can cause exchange impairment between the human body and the surrounding environment (Ib-01) or the failure of life support or first-aid in critically ill patients (Ib-02), etc (Ib-03).

The Information hazard is called type Ⅱ medical device adverse event. It refers to events that may directly cause human injury in the form of information under the application environment. This type of hazard can be further divided into three types: Incorrect Information, Insufficient Information and Overloaded Information, what are in the form of data, text, sound and image, etc.

The Energy and Information hazard has the characteristics of both the Type I and Type II hazard at the same time, called type Ⅲ medical device adverse event. According to the weight of each constitutional hazard, the Type III hazard can be divided into three subtypes: the Energy-dominant, Information-dominant and Dual-culprit. The Dual-culprit subtype means the Energy and Information both contribute to the hazard, and their contributions are both significant.

From the point of system security, the risk factors of "human-machine-environment" system come from three interrelated aspects: “human”, “machine”, “environment”. In a specific environment, the user has acquired recognition, perception of different information of medical devices, and repeated the actual operation. Through this process, medical devices can be controlled and used to diagnose and treat patients. To describe how a hazard was caused by such interaction between human, medical device and environment, the authors define a human-machine-environment interaction model (see Figure 3)that contains five kinds of direct causes (O-D□P-D□E-D□D and U). Each direct cause (see Table 2) represents a set of direct causes of certain group of adverse events.

Figure3. The schematic diagram of the human-machine-environment interaction model

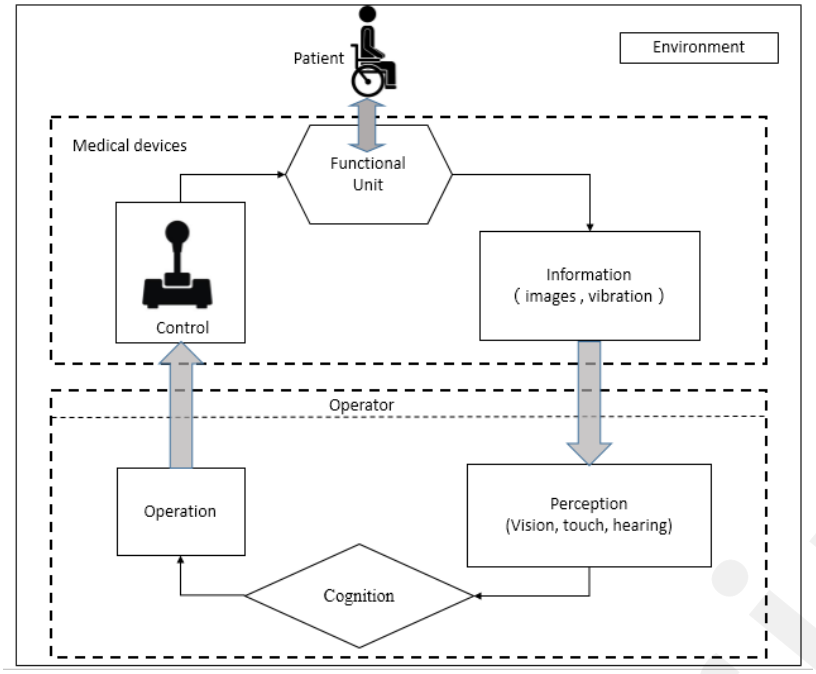


Table 2. The type of direct causes

Direct cause	Description	Main forms	
O-D	A safety accident that may be caused by the interaction problem of the operator and the device	Usability problems	Display interface
			Control interface
			Human Machine Interface(HMI) matching (space□seat□workspace)
			Label / Specification
			Other
P-D	A safety accident that may be caused by the interaction problem of the patient and the device	P-D-1 Usability problems	Display interface
			Control interface
			Human Machine Interface(HMI) matching (space□seat□workspace)
			Label / Specification
			Other
		P-D-2 Internal risk	Biocompatibility (blood□tissue□immunoreaction)
			Tissue/organ infection
			Tissue/organ damage
			Other
E-D	A safety accident that may be caused by the interaction effect of the environment and the device	Effect on the environment or be disturbed by other devices	Pollution (eg: air pollution)
			Be disturbed (eg: electromagnetic interference)
			Other
D	A safety accident that	D-1 (Hardware failure)	

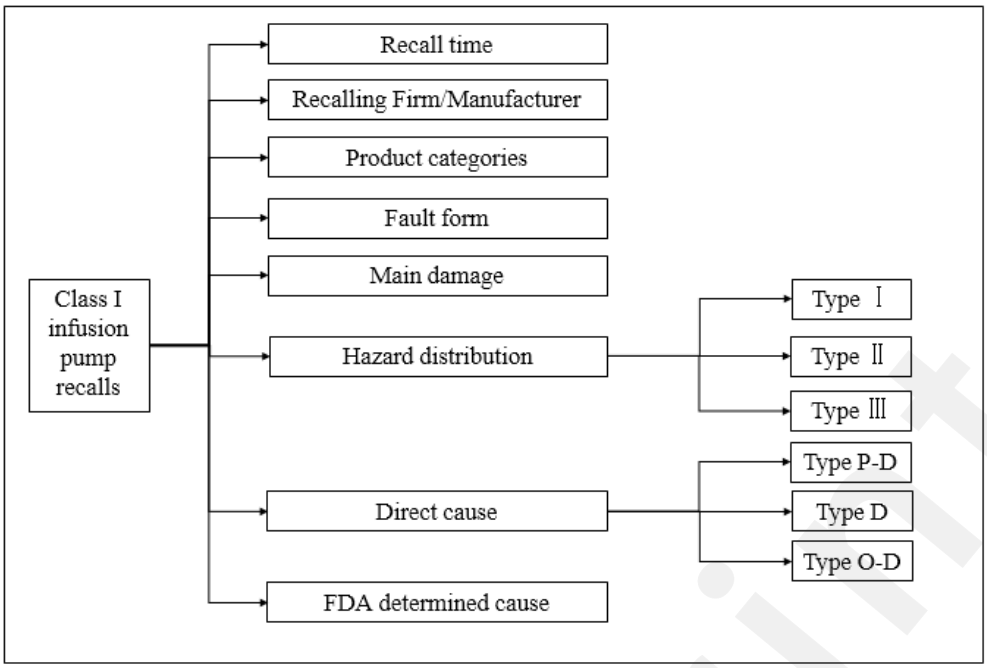
	may be caused by the component failure of the device	D-2 (Software failure)
U	Unknown causes or unexpected injuries	Unknown scientific principle, involve multiple chaotic factors, unexpected events

The O-D type direct cause refers to the safety events caused by the interaction problem between the operator and the device, which is mainly expressed as the availability problems，including display interface, control interface, label / specification, etc. The P-D type direct cause refers to the safety events caused by the interaction problem between the patient and the device, which is mainly expressed as the availability problems and the internal risk. And the interpretation of the availability problems is the same as above. The internal risks include biocompatibility (blood, tissue, immune response), tissue or organ infection and tissue or organ injury. The E-D type direct cause refers to the safety events caused by the interaction of the environment and the device, which is mainly expressed as the equipment affects the work environment or is affected by other facilities. The D type direct cause refers to the safety events caused by the failure of the device component, which is mainly expressed as hardware failure and/or software failure. The U type direct cause refers to the safety events caused by unknown causes or unexpected injuries. Among them, O refers to operator, P refers to patient, D refers to device, E refers to environment, U refers to unknown.

To help readers to better understand the use of the hazard classification framework established in this paper，the following example (from Multimedia Appendix 1: ID 17) provides detailed instructions. Manufacturer Reason for Recall: Package labeled as an insulin syringe for use with U-100 insulin contains an insulin syringe for use with U-40 insulin. Risk of overdose of insulin. The incident involving two aspects of the hazard, including overdose of insulin (Ⅰa–05) and Mislabeled (Ⅱa), which caused by the interaction problem of the operator and the device (the O-D type direct cause).

Figure 3 illustrates the pathway of performing statistical analysis over infusion pump recall by leveraging the above human-machine-environment interaction model and the hazard classification framework (see figure 4).

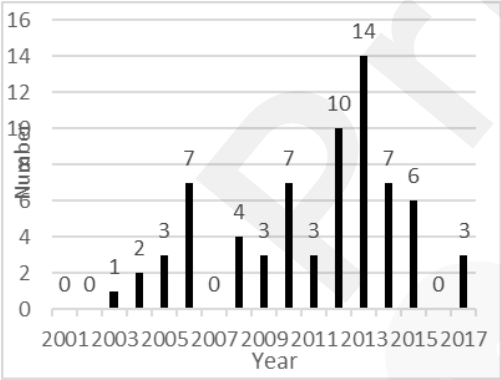
Figure4. The train of thought to statistical analysis



Results

From 2001 to 2017, the amount of class I infusion pump recalls released by FDA in different year is shown in Figure 5. We found that the largest amount of recalls occurred in 2013, which accounted for 20% of the total. The amount of recalls in the period from 2001 to 2006 shows a rising trend, but keep in their downward tendency after five years of 2006. The total number of recalls for 2012~2015 accounted for 53%, and there is a gradual decline trend after 2013.

Figure 5. The distribution of recall time



Recalling Firm/Manufacturer consist mainly of Medtronic Inc, Hospira Inc, Baxter Healthcare Corp, and CareFusion 303, Inc (see Table 3). The total number of recalls for the four companies accounted for 57%. However, the largest number of recalls of a company's products does not indicate that the company's products are more risky, because a bigger market share is likely to increase the amount of recalls.

Table 3. The distribution of Recalling Firm/Manufacturer

Recalling Firm/Manufacturer	Count of recalls
Medtronic Inc	14
Hospira Inc	11
Baxter Healthcare Corp	8

CareFusion 303, Inc	7
Disetronic Medical Systems, Inc	3
Animas Corporation	2
B. Braun Medical, Inc	2
Cardinal Health	2
Covidien	2
Insulet Corporation	2
Sigma International General Medical Apparatus, LLC	2
Codman & Shurtleff, Inc.	1
Elite Biomedical Solutions LLC	1
First Medical Source LLC	1
ICU Medical, Inc.	1
I-Flow Corporation	1
Iradimed Corporation	1
Manufacturer Codman & Shurtleff, Inc.	1
Micromedics, Inc.	1
MOOG Medical Devices Group	1
Nurse Assist, Inc	1
Roche Insulin Delivery Systems Inc.	1
Smiths Medical ASD, Inc.	1
Symbios Medical Products, LLC	1
Tandem Diabetes Care Inc	1
Walkmed Infusion LLC	1
In total	70

The infusion pump can be divided into the following subtypes: injection pump, elastic pump and peristaltic pump [22-23]. The most common injection pump is the insulin pump. The nutrition pump is a representative of peristaltic pump, and the disposable infusion pump is an example of elastic pump [22]. Another classification method is divided into an epidural pump and an intravenous pump. The epidural pump is a topical medication, and the intravenous pump is a systemic medication, so the epidural pump can achieve a good analgesic effect with very few drugs, but the catheter is easy to fall off when the patient moves.

There are 12 out of 70 cases (17%) are passive devices, including 6 cases of disposable medical equipment and 6 cases of infusion pump components. Obviously, there are 58 out of 70 cases (83%) are active equipment. It is shown that the infusion pumps make the maximum proportion, and insulin infusion pumps have the second largest amount. There are also seven cases of recalls related to infusion pump applications (see Table 4).

Table 4. The list of product categories

Product categories	Number	Percentage
Intravenous injection transfusion system	4	6%(4 out of 70)
Infusion pump applications	7	10%(7 out of 70)
Insulin infusion pump	12	17%(12 out of 70)
Infusion pump	47	67%(47 out of

		70)
In total	70	100%

There were 17 cases of adverse events caused by ‘software failures' (see Table 5). The main outcome of equipment faults is the product component failures, characterized by sensor failure, the pump door breakdown, flow restrictor failure, keypad failure, infusion tube bending or occlusion, the Catheter Access Port (CAP) may detach from the main body of the pump, etc. As shown in Table 4, there are many occurrences of power failures and alarm failures (no alarm, false alarm). Furthermore, there can be other problems such as: mislabeled, back flow or free flow, unintended higher flow rate, etc.

Table 5. The list of the fault form

Equipment faults	Count
Electrical shorting	1
Failure to detect air-in-line conditions	1
Weak seals of the sterile pouches	1
Cartridges leaking	1
Mislabeled	2
Unexpected shutdown	2
Higher flow rate	3
Back flow or free flow	3
Power failure	9
Alarm failures	15
Software failures	17
Component failure	22

Note: a case of a recall may have multiple equipment failure.

Table 6 shows the 66 out of 70 cases caused the patient, which manifests as infection, overdose, underdose, and incorrect treatment. It is known that under-infusion can result in delay or interruption of infusion therapy, serious injury or death. Moreover, a drug overdose can lead to serious adverse clinical consequences such as respiratory depression, coma or death.

Table 6. The list of the main damage

Hazard	Number	Percentage
Infection	3	5%(3 out of 66)
Incorrect treatment	9	14%(9 out of 66)
Overdose	18	27%(18 out of 66)
Underdose	36	55%(36 out of 66)
In total	66	100%

Next, we examined the effect of the hazard classification framework. These data suggest that the Energy hazard was the major form of expression (see Table 7).

Table 7. The distribution list of hazard distribution

Hazard classification	Number	Percentage
Ⅰ	47	67%(47 out of 70)
Ⅱ	4	6%(4 out of 70)
Ⅲ	19	27%(19 out of 70)
In total	70	100%

Certain case of subtype Ⅰ hazard may correspond to multiple harmful mediums form, thus it is recognized as the both the Excessed Energy case and Insufficient Energy case. Because of this,

the
47 cases of typeⅠhazard in Table 7 actually contain 27 cases of Excessed Energy and 32 cases of Insufficient Energy (Table 8 shows the corresponding detailed distributions).
The results shows that the subtype Ⅱ hazard(Information hazard) includes one case of Incorrect Information and three cases of Insufficient Information. Moreover, 19 cases of subtype Ⅲ hazard (Energy and Information hazard) include 14 cases of Energy-dominant and 5 cases of Information-dominant.

Table 8. The distribution list of typeⅠ

Subtype	Energy medium	Number	In total	
Ⅰa	Ⅰa-01	1	27	59
	Ⅰa-03	1		
	Ⅰa-05	25		
Ⅰb	Ⅰb-02	25	32	
	Ⅰb-03	7		

Lastly, we statistical analysis the direct cause. There are 72 cases by reason of a case of a recall may have multiple direct causes. As shown in Table 9, the D type direct cause make the maximum proportion.

Table 9. The distribution list of direct cause

Direct cause	Number	Percentage
P-D	2	3%(2 out of 72)
O-D	6	8%(6 out of 72)
D	64	89%(64 out of 72)
In total	72	100%

The availability issues can be observed from the O-D type direct cause, including two cases of mislabeled and four cases of control interface problems. The D type direct cause include 17 cases of software failures and 45 cases of hardware failures (see Table 10).

Table 10. The distribution list of the D type direct cause

The D type direct cause	Number	Event manifestations
Software failures	17	Unexpected shutdown，communications errors
Hardware failures	45	Component failure，material fracture
Invalid information	3	——
In total	65	

We have noticed that FDA website published the FDA determined cause. Its statistics analysis reveals that the main cause is device design (see Table 11).

Table 11. The distribution list of FDA determined cause

FDA Determined Cause	Number
Equipment maintenance	1
Labeling design	1
Mixed-up of materials/components	1
Packaging process control	1
Pending	1
Process change control	1
Software Manufacturing/Software Deployment	1
Use error	1
Component change control	2
Under Investigation by firm	2
Component design/selection	3
Process control	3
Process design	4
Nonconforming Material/Component	6
Software design	6
Other	7
Device Design	28
In total	69

Discussion

Overall, our study establishes a hazard classification framework of the medical devices. Through the statistical analysis on the above 70 cases of FDA class I infusion pump recalls, our results confirm that the 'infusion pump does not infuse accurate dosage (over or under delivery of fluid)' is a key contributor to the product technical risk.

Product component failures

Most product component failures are caused by device design. Below are most popular case within this type of failure:

- The 'sensor failure' may generate a false alarm or an undetected fluid build-up within the distal line, resulting in delay/interruption of therapy or over-infusion.
- The 'full or partial occlusion of the infusion tube' may prevent fluid from reaching the patient, causing an interruption of delivery.
- The normal closure of the 'pump door' is closely related to the dosage delivered, which helps the patient to ensure proper treatment process. If the door assembly breaks, it may prevent the door from closing properly, thus unrestricted flow may occur. If the door cannot be closed, the pump cannot be used and this will lead to a delay in therapy.
- The 'Flow restrictor bead became displaced' may be the root cause of fast flow of contents.
- The 'Luer tube may break at the connection to the pump' and, if this is not noticed by the patient, the patient may receive an under delivery of drug. A delay/interruption in therapy

has the worst-case potential to result in significant injury or death. Depending on the drug and the dosage delivered, over-infusion has the worst-case potential to result in significant injury or death.

- Also one fact that may explain these defects is the fact that some pumps are still in R&D when the companies start to sell these ones. Typically that was the case of Hospira with the Symbiq pump.

Software failure

There were 17 out of 70 cases (Table 10) of adverse events caused by 'software failures'. Such failures are usually characterized by following adverse event contents: 'wrong instruction', 'error codes', or 'communication errors'. The operator may execute the wrong operation according to the wrong instruction, resulting in overdose or underdose.

Alarm failures

There were 15 out of 70 cases of adverse events caused by alarm failures, including 5 cases of 'false alarm' and 10 cases of 'no alarm'. The main forms include: (1) Pump shutting off during use without warning. (2) 'A false visual or audible alarms' causes the infusion pump to stop supplying the fluids to the patient. The fault alarm system may be due to the failure of 'internal detector, unable to trigger the alarm', or 'the fault of software', or 'lack of regular maintenance'. The alarm hazards is among the top five hazards on ECRI Institute's 2011 list [24]. These studies could help hospitals to enhance their management system, for example, to improve the existing nurse training system thus to better educate nurses about their shared responsibilities. At the same time, these studies also provide a new strategy to ensure the safe usage of medical devices. Nurses should not only pay attention to the operation procedures, but also to focus on maintenance. In fact, the shortage of nurses is another possible reason for the failure to maintain the medical devices. More importantly, manufacturers can also strengthen post-market maintenance.

Power failure

Power failure can result in the situation that the device ceases operation without warning and also losses the data. An incorrect voltage could potentially lead to a loss of communication between the PC unit main processor and the keyboard processor that can lead to unexpected loss of therapy. Excessive battery discharge can damage the batteries and may further interrupt the therapy. Therefore, we recommend manufacturers to consider designing other backup power and to simplify the operation of replacing batteries.

Taken together, the product component failure is the main direct cause of infusion pump. The Energy hazard, containing the Excess Energy subtype and Insufficient Energy subtype, is the major form of the hazard of infusion pump. Among the Excess Energy-type of hazards, the 'infection' and 'overdose' occur most frequently, but the 'interruption of infusion therapy' is the hazard which causes most serious injury. A big portion of the hazard of Insufficient Energy is the 'interruption of therapy', which was mainly caused by 'unexpected shutdown', 'power failure', or 'component failures'.

Limitations of this research

The biggest problem is that manufacturers, distributors, medical institutions and device users fail to actively cooperate with the supervision department. Also, many steps should be performed

by the healthcare institution before to implement a pump, which can avoid some of the problem encountered with the infusion pumps. In particular, many defects are not reported to the FDA or other agencies (e.g. Health Canada) but directly to the providers of infusion pumps. As a consequence, many other types of events are not reported: free flow, valve dysfunction, foam in the product due to the mechanism of the pump, haemolysis, and so on. Therefore, there is a lack of sufficient data to further optimize the model in the research work. In addition, influential factors such as the service life of medical devices do not appear in the report, which increases the difficulty of the research.

Conclusions

With social progress and development of technology, the infusion pumps are widely used in clinical settings. There is a potential safety risk while alleviating the patient' s suffering, so it is of great significance to ensure proper usage and safe usage of infusion pumps. This paper is meant to investigate the direct cause of occurrence of infusion pump risks. This may helps to provide reference for the infusion pump risk management and to provide effective information for safe usage of infusion pump safety in clinical environments. To this end, we propose a new data analysis method that can help revealing single variety of medical devices adverse events' risk characteristics and common problems based on the Trace Intersecting Theory. It can be used to guide the specific quality monitoring work for the FDA and national authorities to form a complete regulatory system of post-marketing medical devices.

We believe that carrying out risk assessment and analysis work for the post-market medical devices is of great significance, which can optimize the product risk control solutions and have a positive effect on the development of public health. If any materials are required or further suggestions on this subject, please feel free to contact the author.

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Conflicts of Interest

None declared.

Abbreviations

None.

Multimedia Appendix 1:

[The hazard classification of 2001 □ 2017 class Ⅰ infusion pump recalls extracted from FDA website.]

References

1. Weiss, M., Bänziger, O., Neff, T. et al. Influence of infusion line compliance on drug delivery rate during acute line loop formation. Intensive Care Med (2000) 26: 776. doi:10.1007/s001340051246.

2. Bongsu Jung, Kwang-Suk Seo, Suk Jin Kwon, Kiyoung Lee, Suyong Hong, et al. Efficacy evaluation of syringe pump developed for continuous drug infusion. J Dent Anesth Pain Med 2016;16(4):303-307.https://doi.org/10.17245/jdapm.2016.16.4.303. URL http://www.webcitation.org/6xojIx4p3

3. Jacobs B. Using an infusion pump safely. Nursing 2006; 36: 24.

4. Fechter, RJ (Fechter, RJ); Barba, JJ (Barba, JJ). Failure mode effect analysis applied to the use of infusion pumps. IEEE, 345 E 47TH ST, NEW YORK, NY 10017 USA

5. Keers RN1, Williams SD, Cooke J, Ashcroft DM. Prevalence and nature of medication administration errors in health care settings: a systematic review of direct observational evidence. Ann Pharmacother. 2013 Feb;47(2):237-56. doi: 10.1345/aph.1R147. Epub 2013 Feb 5.

6. Elias, Beth L, and J. A. Moss. "Smart Pump Technology." *Computers Informatics Nursing Cin* 29.4 Suppl(2011):TC61-67.

7. Poder TG. USING THE HEALTH TECHNOLOGY ASSESSMENT TOOLBOX TO FACILITATE PROCUREMENT: THE CASE OF SMART PUMPS IN A CANADIAN HOSPITAL. Int J Technol Assess Health Care. 2017 Jan;33(1):54-62. doi: 10.1017/S0266462317000125. Epub 2017 Jun 5.

8. https://www.ecri.org/EmailResources/PSO_Monthly_Brief/2017/PSO_Brief_0117.pdf.

9. https://www.ecri.org/Pages/PSO-Prevents-Safety-Risk-with-Infusion-Pumps.aspx. URL http://www.webcitation.org/6xoj1TUvu

10. https://www.ecri.org/EmailResources/PSO_Monthly_Brief/2015/PSO_Brief_0215.pdf.

11. Yi Zhang, Paul L Jones, Raoul Jetley. A Hazard Analysis for a Generic Insulin Infusin Infusion Pump. Journal of diabetes science and technology, 2010,4(2):262-283.

12. Paul Curzon and Ann Blandford and Cox, A. and Harold Thimbleby (2015) Safer Interactive Medical Device Design: Insights from the CHI+MED Project. Proceedings of the 5th EAI International Conference on Wireless Mobile Communication and Healthcare, October, London, UK. ACM.

13. Masci, P. (2014). A preliminary hazard analysis for the GIP number entry software. Technical report.

14. Masci, P., Zhang, Y., Jones, P., Thimbleby, H., & Curzon, P. (2014). A generic user interface architecture for analyzing use hazards in infusion pump software. Proceedings of the 5th Workshop on Medical Cyber-Physical Systems (MCPS 2014), 1–14. OASIcs: Open Access Series in Informatics, vol. 36.

15. FDA Product Recalls-From First Alert to Effectiveness Checks [EB/OL].(2013-12-7)[2013-12-10].http://www.fda.gov/ForConsumers/ConsumerUpdates/ucm049070.htm#top#top. URL http://www.webcitation.org/6xoj8FjhU

16. LIU Long, WANG Zhu, LI Ping. Methods for Analysis of Medical Devices Use-related Risk: Comperison, Improvement and Application. Industrial Engineering and Management, 2011, 16(6):133-138.

17. Masci P, Zhang Y, Jones P, Campos JC. 2017. A Hazard Analysis Method for Systematic Identification of Safety Requirements for User Interface Software in Medical Devices. 15th International Conference on Software Engineering and Formal Methods (SEFM 2017). LNCS, volume 10469, Springer copy at http://www.tinyurl.com/ybqe4rpk

18. Michael D. Harrison, Paulo Masci, José Creissac Campos and Paul Curzon (2017) Verification of User Interface Software: the Example of Use-Related Safety Requirements and Programmable Medical Devices, IEEE Transactions on Human-Machine Systems 47(6), July, IEEE. DOI: 10.1109/THMS.2017.2717910

19. Paolo Masci, Paul Curzon and Harold Thimbleby (2015) Early identification of software causes of use-related hazards in medical devices. Proceedings of the 5th EAI International Conference on Wireless Mobile Communication and Healthcare, October, London, UK. ACM.

20. https://tieba.baidu.com/p/4210902827. URL http://www.webcitation.org/6xoXhKTmE

21. Wen Qiang, Tang Xiao-hong, Liu Xiao-lan, et al. The Study on Classification of Medical Device Adverse Events Based on Epidemiological Model of Injure. Chinese Journal of Pharmacovigilance□2011,8(11):658-661.

22. Dong Fang, Cheng Yun-zhang. Active medical device products and adverse events monitoring. Beijing: China Medical Science Press, 2013:66-73. ISBN: 9787506763080

23. Wang Chen, Liu Zhi-cheng. An overview of the harm of FDA in the risk management of infusion pumps in the United States. Capital Medicine,2012,4:6-7.

24. https://www.ecri.org/EmailResources/PSO_Monthly_Brief/2011/PSO_Brief_Jan11.pdf.

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