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Failure Analysis of an Artificial Pancreas – Double Subcutaneous vs. Double Intraperitoneal Approach

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Motivation

Aim: Artificial pancreas (AP)

- Continuous glucose monitoring
- Fully automated insulin infusion
- No user input

Safety requirements

Increased degree of automation
-> Increased safety and reliability needs
-> Need for automatic fault detection

Particular challenges

- Simultaneous failures, disturbances and physiological changes
- Time delays and slow dynamics of insulin infusion and glucose sensing with subcutaneous (SC) approach
- Intraperitoneal (IP) approach as promising alternative with more physiological insulin levels [1] and faster glucose response [2]

System

General assumptions

- No hardware failures due to manufacturing process
- No software failures

Insulin infusion

- Off-the-shelf insulin pump
- Off-the-shelf consumables

Controller

- Capable of keeping nominal blood glucose level under normal circumstances
- No safety features implemented

Glucose sensing

- Enzyme-based amperometric sensors

FMEA

Failure Modes and Effects Analysis (FMEA) [3]

- Conducted by the authors with competence in cybernetics, control engineering, sensor technology, endocrinology, and medical care for patients with diabetes mellitus type 1
- Limited quantitative failure data accessible [4] and up to date [5]
- Qualitative estimations
- Selection focuses on site related effects, i.e. differences between SC and IP approach

Description of unit	Description of failure			Particularly fault prone sensing/infusion site or technology	Expected likelihood of occurrence O 1) (SC/IP)	Severity S 2) (SC/IP)	Likelihood of detection D 3)	Risk priority number RPN = O x S x D
	Failure mode	Failure cause	Circumstances/operation mode of occurrence					
Sensor unit and sensing site • Measures glucose concentration at sensing site • Determines blood glucose concentration based on that	Positively biased signal	Miscalibration	Calibration during changing blood glucose level	SC (physiological time lag)	5/3	4	2	40/24
			Too infrequent calibration	Enzymatic sensors	5	3	1	15
		Sensor degradation	End of lifetime causes fluctuating sensitivity, and calibration during a period of low sensitivity	Enzymatic sensors	5	4	4	80
		Interference with other analytes	Medication (e.g. pain reliever like acetaminophen)	Enzymatic sensor	3	4	8	96
	Negatively biased signal	Loss of sensitivity	Transient pressure induced sensor attenuation due to posture (particularly during night) or tight clothing compressing the sensor, etc.	SC	7/3	2	5	70/30
			Isolated non-physiological spikes caused by motion of the patient	SC	5/3	2	2	20/12
			Lack of oxygen at the electrode after long period with high glucose (assumes period of poor control)	Glucose-oxidase sensors	3	3-4	7	84
		Lowered local glucose concentration	Incomplete insertion	SC	3-4/1	3	2	24/6
			Insertion into area with local fibrous tissue	SC	3-4/0	3	8	84/0
			Bleeding caused by mechanical forces during physical activity (wound healing after insertion completed)	SC	4-5/0	3-4	7	140/0
			Bleeding caused during insertion	SC	3-4/2	3-4	6	96/48
			Sensor dislodgement by motion of the patient (particularly during physical activity)	SC	4-5/1	3-4	4	80/16
			Sensor enclosed by peritoneal wall rather than by circulating peritoneal fluid	IP	0/4	3-4	8	0/160
			Glucose sensing close to insulin infusion	-	4/4	4	8	128/128
		Miscalibration	Calibration during changing blood glucose level	SC (physiological time lag)	5/3	3	2	30/18
			Too infrequent calibration	Enzymatic sensors	5	3	1	15
		Sensor degradation	End of lifetime	Enzymatic sensors	5	3	4	60
	Delayed signal	Foreign body response	Long-term use	SC	5/4	3/2	9	135/72
		Fibrosis, lipohypertrophy	Insertion into chronically changed tissue after long term use of CGM and insulin pumps	SC	5/4	3/2	7	105/56
		Biocontamination	Inappropriate injection (non-sterile equipment)	IP	3/4	3	9	81/108
	Unknown disturbances	Intraabdominal pressure changes	Intestinal and respiratory movements, heart beat	IP	0/7	1	5	0/35
Insulin infusion unit • Delivers insulin according to the insulin infusion rate received from the control unit	Under-delivery	Insulin leakage from injection site	Swollen/contorted skin after long term use	SC	3/0	3	4	36/0
			Accidental catheter dislodgement	SC	4/3	3	4	48/36
			Incomplete insertion	IP	4/2	2	4	32/16
		Foreign body response	Foreign objects inside the body	Teflon cannulas, SC	5/4	2	8	80/64
		Tip of cannula blocked	Tip of cannula sticks in peritoneal wall or is blocked by foreign tissue response	IP	0/5	2	8	0/80

1) 1 < Once in a lifetime, 2 Once in a lifetime, 3 Once a year, 4 Once a month, 5 Once a week, 6 Once a day, 7 > Once a day

2) 1 Light or negligible hyperglycaemia, 2 Moderate hyperglycaemia or light hypoglycaemia, 3 Severe hyperglycaemia or moderate hypoglycaemia, 4 Diabetic ketoacidosis (DKA) or severe hypoglycaemia, 5 Unconsciousness due to DKA or severe hypoglycaemia

3) Probability of detection before severe glycaemic excursion: 1-2 Very high, 3-4 High, 5-7 Moderate, 8-9 Low, 10 Very low (or zero)

Conclusion

Site and sensor related complications

- Risks of many well-known SC complications are lower with IP approach
- New and unknown failures with IP approach
- Some failures are explicitly associated with enzymatic sensors

Fault detection and diagnosis

Faster dynamics at both ends of IP approach implies

- Potential for faster fault detection
- Potential for more successful fault diagnosis
- Improved fault detection and diagnosis reduce risks even more

References

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