FAILURE MODES AND EFFECTS ANALYSIS (FMEA) – AN ASSESSMENT TOOL FOR RISK MANAGEMENT IN CLINICAL LABORATORIES

REMONA ELIZA DAVID[1], MINODORA DOBREANU[2]

[1,2]*University of Medicine and Pharmacy Tîrgu-Mureș*

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Abstract: *The present paper aims to be an example of the clinical laboratory risk assessment, though it does not include all the possible risks. This paper presents the evaluation technique FMEA (failure modes and effects analysis) as a tool for risk management and quality improvement of the clinical laboratory analyses. The purpose of FMEA is to aid the clinical laboratory in raising awareness and in identification of the possible hazardous situations of a testing system. Once the hazardous event has been identified, the risk can be estimated, analyzed and treated. Using the standard CLSI EP18-A guidelines, the table FMEA has been laid and, thus the errors from the pre-analytical process, especially, have been ranked according to criticality.*

This paper aims to be an example of risk assessment in a clinical laboratory, but without the inclusion of all possible risks. This example does not apply to all proceedings encountered in a clinical laboratory and should not be confused with a customized quality control plan of a laboratory, which is the next step of risk assessment.

For risk assessment, the laboratory collects information from several different sources:

- *accreditation requirements;*
- *information about the measurement system provided by the manufacturer;*
- *information about the laboratory's particular environment;*
- *information about health and clinical applications of test results*.(1)

Accreditation requirements

Laboratories purchase standards that provide guidelines to be followed: [1] SR EN ISO 15189: 2013, "Medical Laboratories - Particular requirements for quality and competence"; [2] ISO / TS 22367: 2008 "Medical laboratories - Reduction of error through risk management and continual improvement"; [3] Clinical and Laboratory Standards Institute (CLSI). "EP18-A2: Risk Management Techniques to Identify and Control Laboratory Error Sources".

SR EN ISO 15189: 2013, section 4.14.6: "The laboratory must evaluate the impact of work processes and potential failures on examination results as they affect patient safety, and must modify processes to reduce or eliminate the identified risks, with records to be kept of decisions and action taken".(2)

SR EN ISO 15189: 2013, section 4.14.7: "The laboratory must establish, monitor and periodically review quality indicators for critical aspects of pre-examination, examination, and post-examination processes. The monitoring processes of indicators will be planned, which include setting objectives, methodology, interpretation, limits, plan of action and duration of the measurements. The laboratory must periodically evaluate whether or not the indicators meet their effectiveness."(2)

ISO/TS 22367:2008 characterizes the application of ISO 15189 as a system for reducing laboratory errors and improving patient safety by applying the principles of risk management, with reference to pre-examination, examination and post-examination processes. ISO/TS 22367:2008 proposes a methodology for identifying clinical laboratory errors that would be avoided with the application of ISO 15189.(3)

EP18-A2 is used as a guideline for risk management activities describing different techniques to identify and control laboratory errors.(4)

Information about the measurement system provided by the manufacturer

A clinical laboratory has the manual of the equipment available, which contains a number of requirements referring to conditions and environmental precautions established by the manufacturer (e.g. the storage conditions should be between 2 – 8° C). The users' guide comprises a section with possible error messages that provides information about the equipment or the testing process that can be affected or involved.(5) Manufacturers determine and describe hemolysis, jaundice, lipemia (HIL) indices and alert indices for clinical laboratory equipment, which use an automatic system for the detection of HIL.(6)

Reagent product inserts can include sections such as: "Limitations", "Warnings and precautions", with reference to certain drugs, food or chemicals that can influence test results.(1)

Information about the laboratory's particular environment

The clinical laboratory establishes training programmes for staff members by covering different aspects of the system.

Information about health and clinical applications of test results

Information regarding the usefulness of a test is provided by physicians, which is very important for the clinical laboratory. Thus, feedback is provided about the performance limits of the test based on the clinical experience.

All this information can be used to create a map of the process or a "fishbone diagram". A map of the process classifies

[1]Corresponding author: Remona Eliza David, Str. Păltiniș, Nr. 21-23, Cod 540520, Tîrgu-Mureș, România, E-mail: elizaremona@yahoo.com, Phone: +40740 168508
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the measurement process in several stages/ components, thus facilitating the identification of errors which may present the source of major risks to patients.(1,5)

Aspects that should be considered when mapping a process for an automatic measuring system:

- training and competence of the operator;
- shipment and storage of reagents and calibrators;
- assessment of the acceptability of specimens;
- initiation of equipment;
- calibration of equipment;
- operation of equipment;
- review and validation of test results.(1,5,7)

Pursuing the process map we can identify possible errors which belong to different phases/ components of the process. It is practical to group possible errors into five major categories (samples, operators, reagents, environmental conditions and measuring system), and then represent these in a "fishbone diagram" (a great visual tool that conveys several information subsequently used in a FMEA table).(8) The list of possible errors will be represented in one of the columns of the FMEA table. It is important to take into account that errors can also occur in the pre-examination, examination and post-examination process.(3)

Risk evaluation is a comprehensive process of risk identification, analysis and assessment. ER EN 31010: 2011; "Risk management - Risk assessment techniques" provides guidance on selection and application of systematic techniques for risk assessment.

The first step in risk assessment is to identify possible errors and their causes. Risk management aims at preventing situations in which errors may occur, so that incorrect results are not reported to clinicians, thus, preventing to cause harm to patients. Based on identified errors, a personalized quality control plan (QCP) is compiled by using the process map or "fishbone diagram".(5)

The purpose of this paper is to present the FMEA evaluation technique as a tool for risk management and quality improvement in a clinical laboratory. CLSI EP18-A2; "Risk Management Techniques to Identify and Control Laboratory Error Sources; Approved Guideline - Second Edition"; 2009 describes the elements of FMEA (Failure Modes and Effects Analysis)/ FTA (Fault Tree Analysis) and FRACAS (Failure Reporting and Corrective Action System) risk assessment techniques.(4)

FMEA aims at helping equipment and reagents manufacturers, as well as clinical laboratories to raise awareness and identify possible hazardous situations associated to a testing system. Once a hazard situation is identified, the risk can be evaluated. In case of critical errors, control measures are implemented to reduce risks.

FMEA is used and applied in the following situations:

- to increase customer satisfaction (physicians and/or patients);
- to identify human errors and their effects;
- when the decision to introduce a new product or process in the clinical laboratory is taken;
- to establish methods of control for newly introduced processes;
- for existing processes when their goals of improvement is modified in order to ensure greater safety for patients;
- in case of error analysis in existing processes for continuous quality improvement.(8)

FMEA analyzes the situation of a clinical laboratory before a measurement system is acquired and subsequently implemented. This allows users to check whether potential errors identified by the manufacturer may affect the clinical laboratory. Laboratory staff examine whether there are other possible errors, and whether the existing control measures are adequate.(9) In cases where control measures do not reduce the risk to a clinically acceptable level, additional control measures are sought that will be implemented later. It is important to include pre-analytical and post-analytical processes in FMEA. A clinical laboratory may show reluctance to apply FMEA, because the staff responsible for the development and implementation of this technique requires experience, and this also imposes multidisciplinary teamwork.

FMEA needs detailed information for each phase/component of the system, thus making possible to analyze the modalities in which each phase/component can fail. The required information is not always readily available.

The followings should be identified for each phase/component of the process:

- the manner how failure/errors can occur;
- mechanisms that can produce these errors;
- effects that can occur after the error is produced;
- the severity of effects by deciding if the error is acceptable or unacceptable from the clinical point of view;
- methods to detect failures/errors.(8)

FMEA is a process that is finalized under the form of a table containing the list of possible errors that can occur during the pre-analytical, analytical and post-analytical processes. The table can contain information provided by both the manufacturer and clinical laboratory describing the importance of each error, which could be the source of incorrect results or delays in turnaround time.

FMEA working teams should be as conservative as possible in deciding what is and what is not an error, as a way of prioritizing errors. CLSI EP18-A2 uses numerical quantification called "criticality" (called "risk" in SR EN ISO 14971:2011). According to the ISO/IEC GUIDE 51:2014, "risk is a combination of the probability of occurrence of harm/error and the severity of that harm".

Table no. 1. The definition of risk (9,10,11)

Risk is the combination of	**the probability of occurrence**	**of harm and**	**the severity of that harm.**
	The probability of occurrence includes exposure to a hazardous situation, the occurrence of a hazardous event and the possibility to prevent or limit damage.	"Harm is injury or damage to the health of people, or damage to property or the environment. "	According to SR EN ISO 14971: 2011, severity is the measure of possible consequences of a hazard.
		CLSI EP23-A:2011 says that damage to property or the environment is not considered harmful unless directly harm people.	

How to compile a FMEA table:

The columns have been suggested by CLSI E18-A2. For each of them it has been described the way to fill it in and its specific characteristics.

The FMEA table comprises the following columns:(12)

1. Column "phase/component of the process"

The "phase/ component of the process" column is useful in identifying the phase/component of the process to which most of the errors/failures correspond. In order to maintain the phase/ component of the process a flow diagram of the process should be compiled (e.g. "fishbone diagram" where errors/failures are grouped into five major categories - samples, operators, reagents, laboratory environment and measuring system).

2. Column "the main sources of errors/failure"

The "main sources of errors/failure" column is used to list the potential failure modes.

3. Column "the main causes of potential errors/failure modes"

Using a list of causes of errors, it should be mentioned which errors will be monitored.

4. Column "the consequence of errors"

Any error can possibly trigger a cascade of events. For example: concerning the consequence of incorrect laboratory results on the health care of a patient, it should be taken into consideration what happens after the clinician receives the report of the medical analysis. The clinical laboratory ought to evaluate the severity of the error. For our laboratory it has been decided to use a scale from 1-5.

Regarding the health care of the patient, two outcomes are possible for the above example:

- an incorrect result that may or may not lead to an incorrect medical decision;
- delayed test result, which may or may not affect a patient's health care.

5. Column "evaluated" (yes/no)

When the FMEA table presents a generic list of possible errors, the laboratory should select the errors that correspond to the analyzed testing system by adding new issued errors or marking with "No" those errors which are not evaluated.

6. Column "the severity of harm"

In a clinical laboratory, the consequences of errors can be as follows: an incorrect test result, a result received late by the clinician or lack of the requested test result. These situations can influence the health care of a patient as a test result can lead to misdiagnosis which subsequently may be followed by inadequate treatment or lack of appropriate treatment. For each possible error, the laboratory must evaluate the severity of harm, which can be the consequence of this, using a scale with a number of levels necessary to cover the range of possible degrees of severity. Too many levels may not result in an accurate and objective assessment of the severity of harm. This estimation requires the decision of the medical laboratory in collaboration with clinicians who use these test results. CLSI EP23-A, Section 6.3.2.2, describes the severity of harm using semi quantitative scale levels of severity of 1 to 5, as suggested in SR EN ISO 14971: 2011.(5,9)

Table no. 2. Scale of severity (1 – 5)

Terms	Evaluation	Description of SR EN ISO 14971:2011
Catastrophic	5	Deceased patient
Critic	4	Life threatening, permanent harm/ injuries
Severe	3	Injuries that require medical intervention
Minor	2	Temporary lesion which does not require medical intervention
Negligible	1	Temporary discomfort

7. Column "likelihood of occurrence"

After errors are identified in a clinical laboratory, it is necessary to establish the probability of occurrence for each of them. The clinical laboratory should establish a scale for assessing the probability of occurrence of the cause. The scale that is used by our laboratory has been 1 to 5 (5 is more likely than 1) and the correlation between the probability of occurrence and each number on the scale will be established. Alternatively, one of the scales of SR EN ISO 14971: 2011, Annex D can be used.(9)

Table no. 3. Probability of harm (1 – 5) example from our laboratory and example according to SR EN ISO 14971: 2011, Annex D

Terms	Evaluation	Practical example from our laboratory	Example according to SR EN ISO 14971: 2011, Annex D
Frequent	5	Once a day	$\geq 10^{-3}$
Probable	4	2 – 10 a week	$<10^{-3}$ and $\geq 10^{-4}$
Occasionally	3	Every week	$<10^{-4}$ and $\geq 10^{-5}$
Isolated	2	Once a month	$<10^{-5}$ and $\geq 10^{-6}$
Improbable	1	Once a year	$<10^{-6}$

Note: the clinical laboratory must determine the significance of each term on the scale, this may vary for different tests.

8. Column "detection methods"

Detection methods do not prevent errors but the occurrence of their effects. It is necessary to raise awareness of the importance of the detection phase because this is similar to the accuracy of the diagnosis of a medical test. Detectability is expressed as the probability of the implemented control process by the laboratory to detect or prevent an error and can be quantified by using a scale of 1 to 5. The clinical laboratory will decide whether detectability is taken into account to estimate criticality.

Table no. 4. Scale of detectability (1 – 5)

Evaluation	Practical example
5	Ineffective control
4	It is unlikely that control measures detect errors
3	Control measures may or may not detect errors
2	Control measures almost always detected errors
1	Control measures can detect errors

9. Column "criticality"

For FMEA, criticality is the process of severity referring to the probability of occurrence of errors. Criticality is synonymous with risk. The probability of occurrence of an error and the severity of harm are both descriptive criteria, therefore it is difficult to draw up a procedure that combines both of them. EN ISO 14971: 2011 proposes the outline of risk matrix as follows: the probability levels of error occurrence are represented on the Y axis, while the severity levels of harm are represented on X axis. Each cell in the table indicates whether the risk of the evaluated error is acceptable or unacceptable from the clinical point of view.(4,5) The clinical laboratory should correlate the scale levels with the numerical value of criticality obtained by multiplying the probability level of the occurrence of the error, the level of the severity of harm and /or detectability. High criticality numbers must be followed by specific quality control, and then the assessment of residual risk of harm to decide whether this is clinically acceptable. If the residual risk is still not clinically acceptable, the laboratory must identify additional measures to reduce the risk. This process is repeated until the residual risk has been reduced to the clinically acceptable level. In case the risk was considered "unacceptable" this means that, the adopted control measures are not adequate to keep the risk at a low level. The interpretation of the results of the risk matrix should be performed by both clinical laboratory and clinicians to determine if they are applicable. For example,

in a large laboratory, a frequent minor error can be considered acceptable, because in the context of thousands of results this is admissible. But a serious error that occurs occasionally cannot be accepted.

10. Column "prevention"

Preventive measures involve modifying a phase/component of the process. If the error is prevented, the consequence of the error is eliminated.

11. Column "measures of continuous improvement"

Control measures (prevention, detection or improvement) implemented by the laboratory to minimize the risk usually cannot change the severity of the errors, they can only reduce the probability of occurrence of errors.

12. Column "evaluation - Six Sigma indicator"

SR EN ISO 15189: 2013N, Section 4.14.7, says that "a clinical laboratory should establish quality indicators for systematically monitoring and evaluating the centre's contribution to patient care". According to the same standard, Section 3.19, the quality indicator is defined as "the degree to which a set of inherent characteristics fulfils particular requirements". Measurements could be expressed as percentage, number of defects per million opportunities (DPM) or on the Six Sigma scale. For the selected indicators, the Six Sigma value 4 – 5 shows that the assessed laboratory processes are well supervised and stable over time. Developing measurement principles is a strategic point of a clinical laboratory. Without measurement performance cannot be evaluated objectively. The performance of the process should be an important part of the program of continuous improvement in the laboratory (CLSI QMS06-A3: Quality Management System: Continual Improvement; Approved Guideline-Third Edition, 2011).(13) The laboratory should not choose only those quality indicators that are aimed for laboratory processes but also for the processes that extend beyond the laboratory and those that they encounter.(14)

Various organizations, regulations, standards and/or contracts may influence the laboratory's choice of quality indicators. The laboratory shall monitor all aspects of the testing process (pre-examination, examination and post-examination) in addition to the general administrative processes. The indicators are defined by each laboratory, but it needs to cover all aspects mentioned.(14) It would be ideal to be able to monitor all laboratory processes, but it is not practical too. Risk management tools can be used to select specific indicators of certain critical components that can be effectively implemented and monitored by a medical laboratory (CLSI EP18-A2).(4) Laboratory management should be sure that the selected indicators allow to measure a wide variety of non-conformity. In order to assess the quality of each indicator selected by the laboratory, a worksheet can be compiled in which the recommended actions, the limitations of these actions as well as the activities of the quality control plan are mentioned.(14)

Table no. 5 is an example of the proposed FMEA to our laboratory, which was outlined by taking into account the indications of the CLSI EP18-A2 standard, and where probable errors from pre-analytical process were described according to the internal and external context of the laboratory.

Table no. 5. Example of FMEA

Phase/ component of the process	Main sources of error	Main causes of potential failure mode	Effect of error	Evaluated (yes/no)	Severity of harm	Probability of occurrence	Measures of detection	Criticality	Prevention	Measures of continuous improvement	Evaluation Six Sigma quality indicator
Sample	Sampling	Incorrect results due to incorrect identification data	Results from another patient	Yes	2	4	The operator must confirm the patient (ID and name) by inserting his/her birthday or personal ID number in the device before testing is initiated. 3	24	Revision of the tagging process. Retraining staff	Staff training	---
		Lack of request or incorrect interpretation of the request for laboratory analysis	The results are useless for patient care	Yes	3	4	Staff with experience and appropriate training can confirm two IDs for a patient before testing. 3	24	The barcode system ensures the proper registration of requests. Errors due to barcodes are rare but due to manual registration of requests, errors are more common.	Limiting the access of specialized personnel to file registration by using password to enter the computer system.	5.2
	Presentation of samples	Sample collected in unsuitable vacutainer/ additives	Sampling must be repeated	Yes	1	2	5	10	Retraining staff	Staff training	4.7
		Inadequate volume	Delayed diagnosis and treatment waiting for a second sampling with adequate volume.	Yes	2	4	The detector identifies the samples with low volume. The sensor detects a meniscus generating electricity, thus ensuring that the volume is at an appropriate level. Otherwise, a system error occurs and the result will not be released. 2	16	Retraining staff involved in sampling (recommendation for coagulation and hematology tests, where volume is a criterion for rejecting the sample). Visual examination can identify low volume samples before they are placed in the analyzer (recommendation for biochemical tests).	Monitoring the tendency of accepting samples with low volume by tracking the frequency of error messages of the measurement system and personnel training.	4.4
	Conformity of samples	Hemolysis	Delayed diagnosis and treatment waiting for a second sampling.	Yes	3	4	1	12	Personnel training on sampling techniques, respectively, on the interference of hemolysis with some biochemical parameters.	HIL Automatic detection system. The development of a study to establish the limits of interference of HIL on quantitative determinations.	4

		Lipemia	Delayed diagnosis and treatment waiting for a second sampling.	Yes	3	4	1	12	Training personnel and informing patients about the importance of blood collection for medical analysis in the morning, after fasting for 8-10 hours.	HIL Automatic detection system. The development of a study to establish the limits of interference of HIL on quantitative determinations.	3.9
		Icterus	Interference on the determination of certain analytes	Yes	3	4	1	12	---	HIL Automatic detection system. The development of a study to establish the limits of interference of HIL on quantitative determinations.	4.5
		Blood coagulation	Incorrect results	Yes	4	2	Micro-clots cannot be detected 2	16	Implementation of a pre-examination procedure, which assumes the assessment of quality sampling and personnel training for this procedure. The assessment of the frequency of system errors caused by the presence of blood clots and retraining staff responsible for blood sampling. Testing staff responsible for sampling and processing of samples.	Staff training	4.5
Reagents/ calibrators / controls	Reagents	Incorrect results due to damage to reagents during transport	Incorrect results	Yes	3	3	Testing QC samples that were received by the laboratory on the occasion of another transport than reagent transport. Damaged QC samples can lead to the incorrect assessment of the integrity of the reagent. 3	27	Reagent storage condition recommended by the manufacturer is between 2˚C - 8˚C. There is no certainty that these conditions were maintained during transportation. It is recommended to check the temperature for cool boxes during transportation (thermogram).	Continuous monitoring of temperature by using alarm systems for refrigerators in the laboratory.	---
	Calibrators	Incorrect results due to damaged calibration materials	Incorrect results	No	1	1	The user's manual released by the manufacturer describes a process of internal control that monitors calibrator absorbance values, ensuring that the value of the measurement for calibration is between predefined acceptable limits. 1	1	The manufacturer recommends the verification of the calibration performance by analysing the control samples. More frequent analysis of controls can provide the laboratory assurance that the system is stable and calibration is not diverted.	Continuous monitoring of temperature by using alarm systems for refrigerators in the laboratory.	---

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