Cyber-Physical System for Donor Organs' Rejection Risks Prevention Based on Donor and Recipient Health Monitoring

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Abstract

Today in Ukraine the problem of transplantation of organs and other anatomical materials to humans is very acute. Among the reasons hindering the development of transplantation of anatomical materials to humans in Ukraine is the rejection of donor organs by the recipient's body. The dependences of the process of rejection of donor organs by the recipient's body on the different surface structures of cells in the recipient and donor, on the incompatibility of recipient and donor on HLA antigens, on the level of dangerous antibodies in the recipient's body, on consideration of only the waiting time for the distribution of donor organs, on the origin of the donor organ (cadaveric organ or organ from a living donor), on the general health of the recipient, on the age of the donor, on the gender of the recipient, on the recipient's disease and its phase, which required transplantation, on the chosen type of immunosuppressive therapy, and on the presence of progressive chronic dysfunction of the transplanted organ. The established dependencies are useful in the selection of donor organs - in order to minimize the risk of rejection of organs by the recipient. Rules and method for supporting the decision on the possibility or undesirableness of donation and transplantation, taking into account the risks of rejection of donor organs, have been developed. The architecture of the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is developed, aimed at verifying the existing list of factors of donor organ rejection. Based on this test, the developed cyber-physical system offers a conclusion on the possibility (if all donor organ rejection factors are eliminated or minimized) or undesirableness (if one or a group of donor organ rejection factors cannot be eliminated) of donation and transplantation in a given case.

Keywords

Cyber-physical system, Unified State Information System on Organ and Tissue Transplantation, donor, recipient, rejection of donor organs.

1. Introduction

Today in Ukraine the problem of transplantation of organs and other anatomical materials to humans is very acute. Every year, thousands of Ukrainians need organ transplants to save their lives, but there are only a few transplant surgeries. In total, today there are more than 1 million people with transplanted organs who lead an active lifestyle and even play sports [1, 2]. In developed countries, organ transplantation is the standard of care for many diseases of the kidneys, heart, liver, lungs, and others. Ukraine lags behind by 20-25 years in the development of organ transplantation due to lack of

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funding for transplantation, lack of a single register of donors, the ratio of presumption of consent and disagreement, prospects for the development of transplant coordination services, problems of education and training of doctors, lack of a single electronic register, etc.[3].

According to the Law of Ukraine "On the use of transplantation of anatomical materials to humans" [4], transplantation activities should be based solely on the Unified State Information System on Organ and Tissue Transplantation (USIST). In general, the productivity of health workers increases with the use of decision support systems and information technology, as they provide doctors with relevant information, increase the efficiency of modern medical resources, promote the integration of Ukrainian medicine into the global medical space [5-7].

Among the reasons hindering the development of transplantation of anatomical materials to humans in Ukraine is the rejection of donor organs by the recipient's body, despite careful verification of the compatibility of organs or other anatomical materials of the donor and recipient. Serious adverse events and the continuing risk of chronic transplant rejection continue to be a problem for transplantation [8].

Thus, a successfully developed and implemented the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring may be *relevant and important* for USIST, because it will help decide on the possibility or undesirableness of donation and transplantation in a given case, taking into account factors of the donor organs' rejection.

2. Literature Review

Let's review the known cyber-physical systems for health status monitoring.

The lifestyle changes of people have been resulting in increase in their health problems. This demands a need for cyber-physical systems involving ubiquitous healthcare system. Cyber-physical systems have a large potential in healthcare for improving the treatment quality and increasing the patients' assistance speed. Cyber-physical systems help automatizing the treatment process and using multiple medical devices simultaneously. These systems allow gathering information about patient's health that provide reducing the progressions of a disease and improving the patient's healing process. Cyber physical systems have behaviour, which emergent from the interactions of physical systems with software systems. The medical cyber-physical system is a unique cyber-physical system, which combines networking capabilities, embedded software control devices and complex physiological dynamics of patients in the modern medical field. Medical cyber-physical systems are the interconnected, dependable and intelligent system of embedded medical devices used to monitor and control multiple aspects of the patients’ physiological state [9-18].

Paper [9] develops module for data analysis of the architecture of centralized healthcare cyber-physical system, which identifying the causes of diseases, researching the new diseases, automatizing the health monitoring of patients and remote treatment, providing the actual information about disease and treatment methods for clinics of the centralized healthcare cyber-physical system.

Paper [10] develops a framework for health's calculating and monitoring in cyber-physical systems using data driven techniques. The framework consists of four components: data acquisition and feature extraction, state identification and real time state estimation, cyber-physical health calculation, operator warning generation.

In the paper [11] the independent health monitoring mechanism as a human-recognizable measure of system's trustworthiness is proposed. This mechanism detects actual violations of constraints and calculates the possibility to violate the constraints. The proposed health monitor consists of two components: health measurement functions, which are tailored to each component of the cyber-physical system; the probabilistic health-state determination, which is directly derived from Bayesian estimation methods.

Security of the data in the cyber-physical systems is key concern when it is accessed from remote location. Because medical practitioners use this data for making the health related decisions, risk of intrusion is present. The main objective of the paper [12] is presenting the state-of-the-art review on security challenges, security requirements and current authentication schemes of cyber-physical systems for health monitoring.

The overview [13] presents architectures and frameworks of the medical cyber-physical system from different perspectives, modeling and verification methods, identification and sign sensing technologies, key communications' technologies, data storage and analysis technologies, monitoring systems, data security and privacy protection technologies, and key research perspectives and directions.

The paper [14] studies the perspective of interoperability of health data (different type of data based on different types of sensors and other medical devices) on cloud-based medical cyber-physical systems, and proposes a conceptual framework to support healthcare professional with an integrated view of the heterogeneous data for analysing, sharing, and decision making.

The authors of [15] review the state-of-the-art in enabling quality of service (QoS) for remote health care applications using technological advancements in the area of Internet of things. In particular, they investigate the QoS challenges required to meet the analysis and inferencing needs of such applications and to overcome the limitations of existing big data processing tools.

The development of medical devices connected to Internet of things has been alleviating the strain on the modern healthcare system by giving users the opportunity to reside in the home during treatment or rehabilitation. The paper [16] studies recent state-of-the-art research on the field of Internet of things for health monitoring, examines several potential use cases of blending the technology.

Authors of [17] propose a reliability/availability quantification methodology for the Internet-of-Medical Things infrastructure using a hierarchical model of three levels: fault tree of overall infrastructure consisting of CFE member systems; fault tree of subsystems; continuous-time Markov chain models of components/devices in the subsystems. Five case-studies of configuration alternation and four operational scenarios of the Internet-of-Medical Things infrastructure are considered in [17] to comprehend the dependability characteristics of the Internet-of-Medical Things physical infrastructure.

The paper [18] focuses on discussing core technologies that are shaping Internet of Things-based healthcare. Further, the paper provides challenges that must be addressed so that the Internet of Things-based healthcare system becomes robust.

A review of known cyber-physical systems for health status monitoring showed that, despite a large number of different solutions, a cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is currently lacking, and existing cyber-physical systems cannot be used as a subsystem (module) of USIST for deciding on the possibility or undesirableness of donation and transplantation in a given case, taking into account the factors of rejection of donor organs. Therefore, *the aim of this study* is to develop a cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring, and the method on which it will be based.

Such a system, like any decision support system, should be represented as a tuple of several sets - in particular, a set of basic elements (based on subject area analysis), a set of rules, and a set of methods used to process information. Therefore, in order to develop a cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring, *the following tasks* should be solved:

1. conducting the analysis of the subject area for determining the factors of rejection of donor organs
2. development of rules for deciding on the possibility or undesirableness of donation and transplantation, taking into account the risks of rejection of donor organs
3. development of a method for supporting the decision on the possibility or undesirableness of donation and transplantation, taking into account the risks of rejection of donor organs
4. designing the architecture of the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring.

3. Determination of Donor Organs' Rejection Factors

The main problem with any transplant is the immune response of the recipient's body to the donor organ (transplant). Acute transplant rejection may occur days or weeks after transplantation. The immune system can perceive the grafted organ as foreign and attack it, destroying it and leading to failure.

The cause of rejection reactions is the different structures of the cell surface. This surface structure is determined genetically, so each person has their own cell surface structure [19]. For this reason, relatives are often the most suitable organ donors, as there is increased genetic similarity.

The donor and recipient must be similar in histocompatibility antigens, which are integrated into the HLA system (Human leukocyte antigens). The selection of the most compatible donor and the recipient is based on the results of such a test. Another cross-match test identifies potentially dangerous antibodies in the recipient that can damage the transplant and lead to donor organ rejection.

The transfer of donor tissue containing immune cells, especially bone marrow and liver tissue, often leads to a "reverse" immune response of cells against the host organism - the reaction of Graft-versus-Host-disease [20].

The current algorithm for the distribution of donor organs does not take into account differences in the potential survival of donor organs, focuses on waiting times and not on properly weighed medical factors, which is a major factor in the non-survival of donor organs [8].

Obtaining a cadaveric organ doubles the patient's chances of survival, but the organ from a living donor quadruples them. Thus, its initial state is of great importance for the fate of the donor organ. The corpse origin of the organ is a powerful risk factor for graft dysfunction and reduced survival, especially against the background of more active use of elderly donors in recent years [21]. For example, statistics from Catalonia, a world leader in organ donation, show that the average life expectancy of a patient who has had a cadaveric kidney transplant is 15 years; in the case of a kidney transplant from a living donor, this period is increased by 10 years.

The state of health of the recipient at the time of transplantation also programs the further functioning of the donor organ [21]. For example, active cytomegalovirus infection in the postoperative period may be the cause of chronic rejection.

Donor organs from donors under the age of 38 are characterized by better survival (for example, Figure 1 shows the 10-year survival rate of a transplant received from donors of different ages). The association between the age of the donor and the function and survival of the donor organ is due to the fact that the organ from an elderly donor is often characterized by dysfunction due to age-related diseases [22].

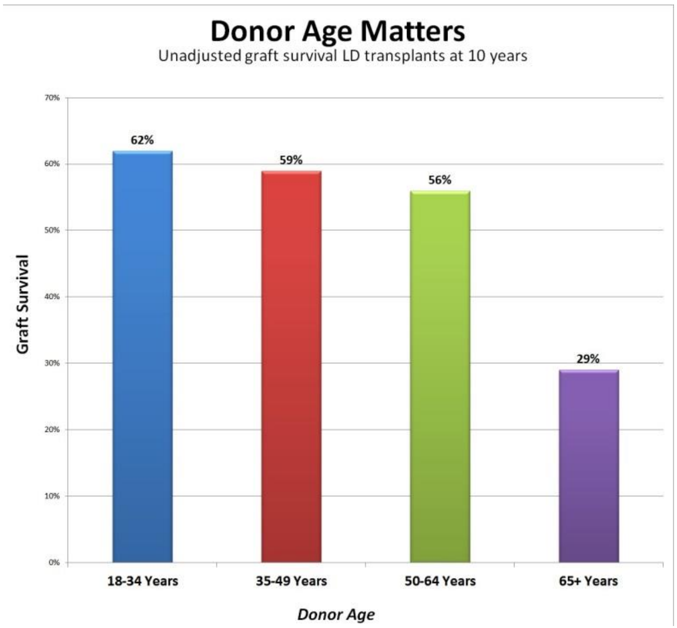

Figure 1: Survival rate for 10 years of transplant received from donors of different ages [22]

Donor organs transplanted to women are characterized by better survival [21].

The main reason for the "loss" of the donor organ after transplantation is the progressive chronic dysfunction of the transplanted organ. According to the literature, if by the end of the first year after transplantation, for example, kidney transplantation, the number of functioning grafts reaches 90% or more, then after 10-15 years the number of functioning grafts is only up to 50% [23].

Immunosuppressive therapy is used to preserve the graft by suppressing the body's immune response to a foreign organ. Immunosuppressive drugs (cyclosporine, tacrolimus, azathioprine or mycophenolate, glucocorticoids, antibodies to basiliximab, and anti-thymocyte globulins) are used for induction therapy - sometimes in high doses. The fixed long-term drug is prescribed as the main therapy; usually, a combination of steroids and calcineurin inhibitors (cyclosporine or tacrolimus) is required. Induction therapy with monoclonal antibodies against the interleukin-2 receptor (basiliximab) or polyclonal antibodies against T-lymphocytes or thymocyte antigens is used for all indications for transplantation. The analysis revealed a significant difference in graft survival depending on the type of immunosuppression - between group 1, which received cyclosporine A, azathioprine, and steroids, and group 3, which received cyclosporine A, mycophenolate mofetil, steroids, and antibodies to receptor II. In group 1, 5-year survival of renal allograft was 71%; in groups 2 and 3, the lifespan of renal allograft did not differ - 93% of grafts functioned for 5 years [24].

In addition, of great importance in the process of engraftment or rejection of the implant is the disease that has become an indication for transplantation, as well as its phase. For example, in bone marrow transplantation, the risk of bone marrow rejection is significantly higher for patients who were in the acute phase of leukaemia at the time of transplantation [25].

Therefore, as a result of the study it is possible to form a list of factors that cause the rejection of donor organs:

1. different surface structure of cells, different blood groups in the recipient and donor
2. incompatibility of the recipient and the donor for HLA antigens
3. high level of dangerous antibodies (cross-match) in the recipient
4. concentration of the used algorithm of distribution of donor organs on waiting time, instead of on medical factors
5. the origin of the donor organ (posthumous or in life donation)
6. general health of the recipient
7. age of the donor
8. gender of the recipient
9. progressive chronic dysfunction of the transplanted organ after transplantation
10. type of immunosuppressive therapy
11. the disease of the recipient, which became an indication for transplantation, and the phase of this disease

Thus, the study revealed the dependence of the process of rejection of donor organs by the recipient from different surface structures of cells in the recipient and donor, the incompatibility of recipient and donor for HLA antigens, the level of dangerous antibodies in the recipient, considering only waiting time in the distribution of donor organs, the origin of the donor organ (cadaveric organ or organ from a living donor), the general health of the recipient, the age of the donor, the gender of the recipient, the recipient's disease and its phase that required the transplant, the type of chosen immunosuppressive therapy, and also from the presence of progressive chronic dysfunction of the transplanted organ. The established dependencies are useful in the selection of donor organs, as well as in the appointment of supportive postoperative therapy to minimize the rejection of donor organs by the recipient.

Obviously, among the identified list of factors, there are many factors that can be identified by the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring, after processing data from sensors and donor’s and recipient’s tests – different cell surface structures (based on the processing of donor's and recipient's tests), different blood groups of the recipient and donor (based on the processing of donor's and recipient's tests), incompatibility of recipient and donor by HLA antigens (based on the processing of donor's and recipient's tests), high level of dangerous cross-match antibodies of the recipient (based on the processing of the results of the recipient's tests), the general state of health of the recipient (based on the processing of data obtained from sensors of the cyber-physical system, as well as the results of the recipient's tests). In addition, the cyber-physical system can be useful in identifying the following risk factors – the origin of the donor organ (posthumous or in life donation); the age of the donor; gender of the recipient.

4. Cyber-Physical System for Donor Organs' Rejection Risks Prevention Based on Donor and Recipient Health Monitoring

Taking into account the above factors that may be identified by the cyber-physical system for donor organs' rejection risks prevention, let's develop rules for deciding on the possibility or undesirableness of donation and transplantation, taking into account the risks of donor rejection.

Rules for deciding on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs:

1. if the surface structure of donor cells (set SSC_d) and recipient cells (set SSC_r) coincide, i. e. $SSC_d = SSC_r$, then $f=f+1$ and $b[1]=0$, else $b[1]=1$
2. if the blood groups of the recipient bt_r and donor bt_d coincide, i. e. $bt_r = bt_d$, then $f=f+1$ and $b[2]=0$, else $b[2]=1$
3. if the HLA antigens of the donor (set HLA_d) and the recipient (set HLA_r) are compatible, i. e. $HLA_d = HLA_r$, then $f=f+1$ and $b[3]=0$, else $b[3]=1$
4. if the level of dangerous antibodies (cross-match) in the recipient cm_r does not exceed the established threshold value cm_{th}, i. e. $cm_r \le cm_{th}$, then $f=f+1$ and $b[4]=0$, else $b[4]=1$
5. if all indicators of the recipient's health $HS_r = \{hs_r^1, hs_r^2, \ldots, hs_r^n\}$, obtained from the sensors, as well as from the results of the recipient's tests, are normal (do not exceed the reference values), i. e. if $hs_r^1 \le hs_{th}^1$ and $hs_r^2 \le hs_{th}^2$ and ... and $hs_r^n \le hs_{th}^n$, then $f=f+1$ and $b[5]=0$, else $b[5]=1$
6. if the donor organ has a lifetime origin, then $f=f+1$ and $b[6]=0$, else $b[6]=1$
7. if the age of the donor a_r does not exceed the established threshold value a_{th}, i. e. $a_r \le a_{th}$, then $f=f+1$ and $b[7]=0$, else $b[7]=1$
8. if the gender of the recipient is female, then $f=f+1$ and $b[8]=0$, else $b[8]=1$

Given the peculiarities of the formation of array *b*, *the rules for the formation of recommendations for the transplantologist on the available risk factors* are as follows:

1. if $b[1] = 1$, the transplantologist is advised to pay attention to the discrepancy between the surface structure of the donor and recipient cells
2. if $b[2] = 1$, the transplantologist is advised to pay attention to the differences in blood groups of the recipient and the donor
3. if $b[3] = 1$, the transplantologist is advised to pay attention to the incompatibility of HLA antigens of the donor and recipient
4. if $b[4] = 1$, the transplantologist is advised to pay attention to the high level of dangerous antibodies (cross-match) in the recipient
5. if $b[5] = 1$, the transplantologist is recommended to pay attention to the current state of health of the recipient (carefully analyze the indicators obtained from system sensors, as well as the results of tests of the recipient)
6. if $b[6] = 1$, the transplantologist is recommended to pay attention to the origin of the donor organ
7. if $b[7] = 1$, the transplantologist is advised to pay attention to the age of the donor
8. if $b[8] = 1$, the transplantologist is advised to pay attention to the gender of the recipient

Then *the method for supporting the decision on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs* consists of the following steps:

1. training of the system by practicing transplantologists – setting the threshold value cm_{th} of the level of dangerous antibodies (cross-match) in the recipient; setting a list of all important indicators of the recipient's health – the formation of the set $HS = \{hs^1, hs^2, \ldots, hs^n\}$; setting reference (threshold) values of all indicators of the health of the recipient $HS_{th} = \{hs_{th}^1, hs_{th}^2, \ldots, hs_{th}^n\}$; setting the threshold age of the donor a_{th}
2. formation of a set of indicators of the recipient's health $HS_r = \{hs_r^1, hs_r^2, \ldots, hs_r^n\}$ on the basis of data obtained from cyber-physical system sensors, as well as due to semantic analysis of recipient's tests results with selection of values of required indicators (elements of the set $HS = \{hs^1, hs^2, \ldots, hs^n\}$); formation of sets of surface structure of donor cells (set SSC_d) and recipient (set SSC_r) based on semantic analysis of donor's and recipient's tests results with selection of values of required indicators (elements of the sets *SSC)*; determination of the

blood group of the recipient bt_r and donor bt_d on the basis of semantic analysis of the results of tests of the recipient and donor with the selection of the values of the required indicators (elements *bt)*; formation of sets of HLA antigens of the donor (set HLA_d) and the recipient (set HLA_r) based on semantic analysis of donor's and recipient's tests results with a selection of values of required indicators (elements of the sets *HLA)*; determination of the level of dangerous antibodies (cross-match) in the recipient cm_r on the basis of semantic analysis of the results of the recipient's tests with the selection of the values of the required indicator (element *cm)*; formation of the questions to the transplantologist about the origin of the donor organ, the age of the donor, and the gender of the recipient

3. analysis of sets of the surface structure of donor cells (set SSC_d) and the recipient cells (set SSC_r); blood groups of recipient bt_r and donor bt_d; sets of HLA antigens of the donor (set HLA_d) and the recipient (set HLA_r); the level cm_r of dangerous antibodies (cross-match) in the recipient; set $HS_r = \{hs_r^1, hs_r^2,..., hs_r^n\}$ of all recipient's health indicators obtained from system's sensors, as well as from recipient's tests; the origin of the donor organ; age of the donor; the gender of the recipient – using each of the developed rules for deciding on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs – and counting the counter *f* and filling the array *b*
4. if $f = 8$, the conclusion is given on the possibility of donation and transplantation for this case, as all factors of rejection of donor organs are eliminated or minimized
5. if $f \neq 8$ $(f < 8)$, then: a conclusion is given on the undesirableness of donation and transplantation for this case, as one or a group of factors of rejection of donor organs are present; the transplantologist is provided with available risk factors that may lead to the rejection of the donor organ – in accordance with the developed rules for the formation of recommendations for the transplantologist on the available risk factors

The developed method for supporting the decision on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs provides: a conclusion on the possibility or undesirableness of donation and transplantation for a particular case; in the case of a conclusion on the undesirableness of donation and transplantation in a particular case - the formation of recommendations to the transplantologist on the available risk factor(s) in order to make a final informed decision on whether or not to perform transplant surgery.

The cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is aimed at verifying the list of factors that cause donor organ rejection. Based on this verification, the cyber-physical system for donor organs' rejection risks prevention offers a conclusion on the possibility (if all factors of rejection of donor organs processed by the system are eliminated or minimized) or undesirableness (if one or a group of rejection factors of donor organs processed by the system cannot be eliminated) of donations and transplants in one case or another. In addition, in the case of a decision on the undesirableness of donation and transplantation in some cases, the cyber-physical system for donor organs' rejection risks prevention provides the transplantologist with available risk factors that may lead to rejection of the donor organ, in order to analyse in detail these risk factors by the transplantologist and make a final informed decision on whether or not to perform transplant surgery.

The proposed cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is grounded on the developed method for supporting the decision on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs, and the rules for deciding on the possibility or undesirableness of donation and transplantation and the rules for the formation of recommendations for the transplantologist on the available risk factors.

The cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring includes a set of sensors to measure some indicators that characterize the current state of health of the recipient – sensors to measure temperature, heart rate, blood oxygen level (saturation), blood pressure, blood sugar level, skin conductivity and body composition, biopotential and bioimpedance of the recipient.

The architecture of the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is presented in Figure 2.

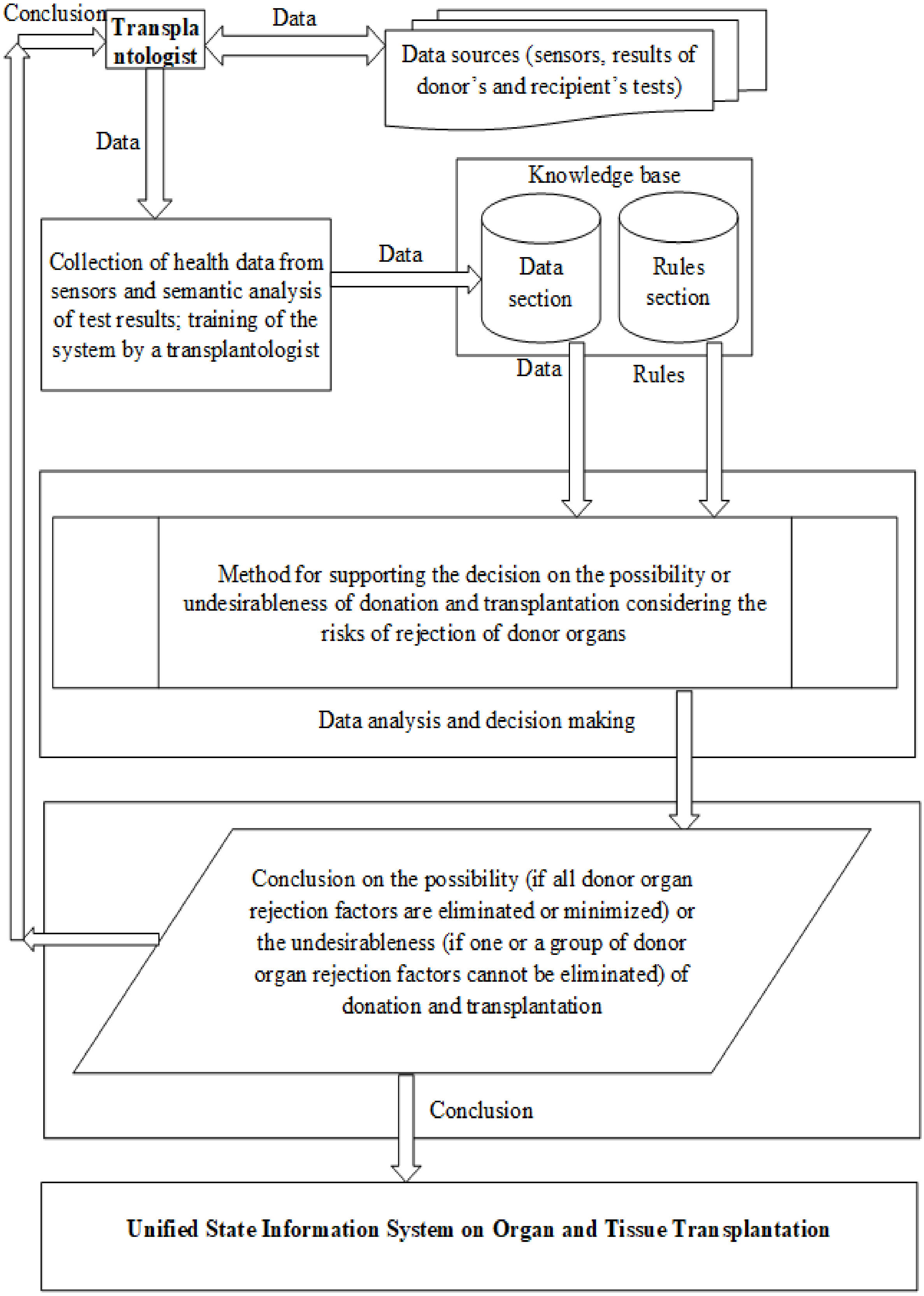

Figure 2: The architecture of the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring

5. Results & Discussion

Let's consider the functioning of the developed method for supporting the decision on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs and cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring.

Practicing transplantologists was conducted training of the cyber-physical system, in the result of which in the systems: setting the threshold value cm_{th} of the level of dangerous antibodies (cross-match) in the recipient; setting a list of all important indicators of the recipient's health – the set $HS = \{hs^1, hs^2, \ldots, hs^n\}$; setting reference (threshold) values of all indicators of the health of the recipient – the set $HS_{th} = \{hs_{th}^1, hs_{th}^2, \ldots, hs_{th}^n\}$; setting the threshold age of the donor a_{th}.

For example, let's consider a case of heart transplantation to a woman from a deceased donor aged 55 years. The recipient woman was connected to sensors of the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring, and a number of tests were performed on both the recipient and the donor. Indicators were taken from the sensors, as a result of which part of the elements of the set HS_r was filled. Semantic analysis of the results of donor's and recipient's tests was performed, as a result of which the other part of the elements of the set HS_r was filled in, the sets SSC_d and SSC_r were formed; elements bt_r and bt_d were determined; the sets HLA_d and HLA_r were formed; the element cm_r was determined; questions to the transplantologist about the origin of the donor organ, the age of the donor, and the gender of the recipient were formed and asked, as well as answers were received.

Analysis of the elements of the set HS_r, the sets SSC_d and SSC_r, elements bt_r and bt_d, the sets HLA_d and HLA_r, element cm_r, the results of the transplant doctor's answers to the system's questions regarding the origin of the donor organ, the age of the donor, and the gender of the recipient were conducted using each of the developed rules for deciding on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs; the counter f is counted ($f=5$) and the array b is filled (Table 1).

Table 1
Array *b,* which accumulates signs of the presence/absence of a risk factor for donor organ rejection (for this example)

b[1]	*b[2]*	*b[3]*	*b[4]*	*b[5]*	*b[6]*	*b[7]*	*b[8]*
0	1	0	0	0	1	1	0

Because $f \neq 8$ $(f < 8)$, then: a conclusion is given on the undesirableness of donation and transplantation for this case, because a group of factors of rejection of donor organs are present; the transplantologist is provided with available risk factors that may lead to the rejection of the donor organ – in accordance with the developed rules for the formation of recommendations for the transplantologist on the available risk factors, the transplantologist is advised to pay attention to the differences in blood groups of the recipient and the donor, to the origin of the donor organ and to the age of the donor. The transplantologist once again analysed these risk factors in detail and made the final decision not to perform the described transplant surgery.

6. Conclusions

Today in Ukraine the problem of transplantation of organs and other anatomical materials to humans is very acute. Among the reasons hindering the development of transplantation of anatomical materials to humans in Ukraine is the rejection of donor organs by the recipient's body. Transplantation activities should be based solely on the Unified State Information System on Organ and Tissue Transplantation (USIST). The successfully developed and implemented the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring may be relevant and important for USIST, because it will help decide on the possibility or undesirableness of donation and transplantation in a given case, taking into account factors of the donor organs' rejection.

The conducted review of known cyber-physical systems for health status monitoring showed that, despite a large number of different solutions, a cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is currently lacking, and existing cyber-physical systems cannot be used as a subsystem (module) of USIST for deciding on the possibility or undesirableness of donation and transplantation in a given case, taking into account the factors of rejection of donor organs. Therefore, the aim of this study is to develop a cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring, and the method on which it will be based.

The dependences of the process of rejection of donor organs by the recipient's body on one or another factor have been established. The established dependencies are useful in the selection of donor organs, as well as in the appointment of supportive postoperative therapy to minimize the rejection of donor organs by the recipient. Among the established list of factors, there are many factors that can be identified by the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring, after processing data from sensors and analysis of the donor's and recipient's tests results.

The developed method for supporting the decision on the possibility or undesirableness of donation and transplantation considering the risks of rejection of donor organs provides: a conclusion on the possibility or undesirableness of donation and transplantation for a particular case; in the case of a conclusion on the undesirableness of donation and transplantation in a particular case - the formation of recommendations to the transplantologist on the available risk factor(s) in order to make a final informed decision on whether or not to perform transplant surgery.

The architecture of the cyber-physical system for donor organs' rejection risks prevention based on donor and recipient health monitoring is developed. This system is aimed at verifying the list of factors that cause donor organ rejection. Based on this verification, the cyber-physical system for donor organs' rejection risks prevention offers a conclusion on the possibility (if all factors of rejection of donor organs processed by the system are eliminated or minimized) or undesirableness (if one or a group of rejection factors of donor organs processed by the system cannot be eliminated) of donations and transplants in one case or another. In addition, in the case of a decision on the undesirableness of donation and transplantation in some cases, the cyber-physical system for donor organs' rejection risks prevention provides the transplantologist with available risk factors that may lead to rejection of the donor organ, in order to analyse in detail these risk factors by the transplantologist and make a final informed decision on whether or not to perform transplant surgery.

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8. References

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