**НЕИНВАЗИВНАЯ ДИАГНОСТИКА ОТТОРЖЕНИЯ СЕРДЦА, КАК ПРЕДИКТОР ДОЛГОСРОЧНОЙ ВЫЖИВАЕМОСТИ ТРАНСПЛАНТАТА.**

**ТРАНСПЛАНТАТТЫҢ ҰЗАҚ МЕРЗІМДІ ӨМІР СҮРУІНІҢ ПРЕДИКТОРЫ РЕТІНДЕ ЖҮРЕКТЕН БАС ТАРТУДЫҢ ИНВАЗИВТІ ЕМЕС ДИАГНОСТИКАСЫ.**

**NONINVASIVE DIAGNOSIS OF HEART REJECTION AS A PREDICTOR OF LONG-TERM TRANSPLANT SURVIVAL.**

**Мырзахметова Г.Ш.1, Новикова С.П.2, Яхимович Я.С.3, Баянова М.Ф.4, Алтынова Ш.Х.5, Пя Ю.В.6**

1Мырзахметова Гульжан Шалатаевна - Заведующая отделением кардиологии 2, врач кардиолог, КФ “University Medical Center”, ул.Керей-Жанибек хандар 5/1, Астана, Казахстан. ORCID ID: 0000-0001-8325-1267, e-mail: mirzakhmetovaguljan@gmail.com.

2Новикова Светлана Петровна - Заведующая отделением кардиохирургии II, врач кардиохирург, КФ “University Medical Center”, ул.Керей-Жанибек хандар 5/1, Астана, Казахстан. ORCID ID: 0000-0001-8161-7712, e-mail: novikovas.ust@gmail.com

3Яхимович Яна Сергеевна - врач-резидент по специальности «Кардиология взрослая, детская», КФ "University Medical Center", ул.Керей-Жанибек хандар 5/1, Астана, Казахстан. ORCID ID: 0009-0003-5313-0378, e-mail: yana.yahim@mail.ru

4Баянова Миргуль Файзуллиновна - Заведующая Отделением клинико-генетической диагностики, КАД Лабораторной медицины, Патологии и Генетики, КФ “University Medical Center”,ул.Керей-Жанибек хандар 5/1, Астана, Казахстан. ORCID ID: 0000-0002-6167-5357, e-mail: mirgul.Bayanova@umc.org.kz

5Алтынова Шолпан Ханапина - Заместитель медицинского директора КФ “University Medical Center”, ул. Керей-Жанибек хандар 5/1, Астана, Казахстан. ORCID ID: 0009-0000-5592-0400, e-mail: Venera.Altynova@umc.org.kz

6Пя Юрий Владимирович - Председатель правления КФ “University Medical Center”, ул. Керей-Жанибек хандар 5/1, Астана, Казахстан. ORCID ID: 0000-0001-7249-0510, e-mail: yuriy.pya@umc.org.kz

**1Mirzakhmetova G.Sh., 2Novikova S. P., 3Yakhimovich Y.S., 4Bayanova M. F., 5Altynova Sh. Kh., 6Pya Y.V.**

1Mirzakhmetova Gulzhan Shalataevna - Head of Cardiology Department 2, Cardiologist, CF "University Medical Center," 5/1 Kerey-Zhanibek Kandar Street, Astana, Kazakhstan. ORCID ID: 0000-0001-8325-1267, Email: mirzakhmetovaguljan@gmail.com.

2Novikova Svetlana Petrovna - Head of Cardiac Surgery Department II, Cardiovascular Surgeon, CF "University Medical Center," 5/1 Kerey-Zhanibek Kandar Street, Astana, Kazakhstan. ORCID ID: 0000-0001-8161-7712, Email: novikovas.ust@gmail.com.

3Yakhimovich Yana Sergeevna - Resident in Adult and Pediatric Cardiology, CF "University Medical Center," 5/1 Kerey-Zhanibek Kandar Street, Astana, Kazakhstan. ORCID ID: 0009-0003-5313-0378, Email: yana.yahim@mail.ru.

4Bayanova Mirgul Faizullovna - Head of Clinical-Genetic Diagnostics Department, CAD Laboratory Medicine, Pathology, and Genetics, CF "University Medical Center," 5/1 Kerey-Zhanibek Kandar Street, Astana, Kazakhstan. ORCID ID: 0000-0002-6167-5357, Email: mirgul.Bayanova@umc.org.kz.

5Altynova Sholpan Khanapina - Deputy Medical Director CF "University Medical Center," 5/1 Kerey-Zhanibek Kandar Street, Astana, Kazakhstan. ORCID ID: 0009-0000-5592-0400, Email: Venera.Altynova@umc.org.kz.

6Pya Yuri Vladimirovich - Chairman of the Board CF "University Medical Center," 5/1 Kerey-Zhanibek Kandar Street, Astana, Kazakhstan. ORCID ID: 0000-0001-7249-0510, Email: yuriy.pya@umc.org.kz.

**Аңдатпа**

Бүгінгі таңда Қазақстанда созылмалы жүрек жеткіліксіздігі (СЖЖ) мәселесі барған сайын өзекті болып отыр. СЖЖ терминалдық сатысынан, әсіресе III-IV ФК пациенттерінде өлім-жітім жоғары. Жүрек трансплантациясы терминалды СЖЖ үшін хирургиялық емдеудің «алтын» стандартын білдіреді, бірақ трансплантацияланған жүректі бақылау үшін қолданылатын эндомиокард биопсиясы инвазивті және ыңғайсыз процедура болып табылады. Бұл мақалада айналымдағы бос донорлық ДНҚ (dd-cfDNA) көмегімен жедел трансплантациядан бас тартуды қауіпсіз және дәл бақылау мүмкіндігі қарастырылады. Зерттеу нысандары жүрек трансплантациясынан өткен 40 пациент болды. Нәтижелер олардың 60% - қайталама операция болғанын, ал 40% - бастапқы операция болғанын көрсетті. СЖЖ себебі әртүрлі, негізінен кеңею және ишемиялық кардиомиопатиялар болды. Dd-cfDNA әдісі dd-cfDNA жоғарылауының әртүрлі үлгілерімен Т-жасушалық және антидене арқылы бас тартуды саралау әлеуетін көрсетеді. Бұл айырмашылықтар диагностика мен емдеу тактикасында жоғары клиникалық маңыздылыққа ие. Дегенмен, dd-cfDNA қолдану мүмкіндіктеріне қарамастан, шекті мәндерді белгілеу және оның клиникалық тәжірибеде тиімділігін растау үшін қосымша зерттеулер қажет. Зерттеу сонымен қатар жүрек трансплантациясы саласындағы дәл медицина әдістерін әзірлеуде қосымша назар аударуды қажет ететін әдістің құны мен қолжетімділігі туралы маңызды сұрақтарды көтереді.

**Абстракт**

На сегодняшний день в Казахстане проблема хронической сердечной недостаточности (ХСН) становится все более актуальной, с высокой смертностью от терминальной стадии ХСН, особенно у пациентов III-IV ФК. Трансплантация сердца представляет собой "золотой" стандарт хирургического лечения терминальной ХСН, но эндомиокардиальная биопсия, используемая для мониторинга трансплантированного сердца, является инвазивной и неудобной процедурой. В данной статье исследуется потенциал безопасного и точного мониторинга острого отторжения трансплантата с использованием циркулирующей свободной ДНК донора (dd-cfDNA). Объектами исследования были 40 пациентов, перенесших трансплантацию сердца. Результаты показали, что у 60% из них операция была повторной, а у 40% - первичной. Причиной терминальной стадии ХСН были различные кардиомиопатии, преимущественно дилатационная и ишемическая. Метод dd-cfDNA демонстрирует потенциал в дифференциации Т-клеточно-опосредованного (ACR) и антитело-опосредованного (AMR) отторжения, с различными паттернами повышения dd-cfDNA. Эти различия имеют высокую клиническую значимость для диагностики и тактики лечения. Однако, несмотря на перспективы использования dd-cfDNA, требуются дополнительные исследования для установления пороговых значений и подтверждения его эффективности в клинической практике. Исследование также выдвигает важные вопросы о стоимости и доступности метода, которые требуют дополнительного внимания в разработке методов точной медицины в области трансплантации сердца.

**Abstract**

Currently, the issue of chronic heart failure (CHF) is increasingly relevant in Kazakhstan, with a significantly higher mortality rate from the terminal stage of CHF, especially among patients in FC III-IV. Heart transplantation is considered the "gold" standard for surgical treatment of terminal CHF; however, endomyocardial biopsy, used for monitoring the transplanted heart, is an invasive and inconvenient procedure. This study explores the potential of safe and accurate monitoring of acute transplant rejection using circulating donor-derived cell-free DNA (dd-cfDNA). The study involved 40 patients who had undergone heart transplantation. The results revealed that 60% of them had undergone repeat surgery, while 40% had undergone primary transplantation. The primary causes of terminal CHF included various cardiomyopathies, predominantly dilated and ischemic. The dd-cfDNA method shows promise in differentiating T-cell-mediated (ACR) and antibody-mediated (AMR) rejection, with distinct patterns of dd-cfDNA elevation. These differences have high clinical significance for diagnosis and treatment strategies. However, despite the prospects of using dd-cfDNA, further research is needed to establish threshold values and confirm its effectiveness in clinical practice. The study also raises important questions about the cost and accessibility of the method, requiring additional attention in the development of precision medicine methods in the field of heart transplantation.

**Ключевые слова:** ХСН, Трансплантация сердца, эндомиокардиальная биопсия, Метод dd-cfDNA.

**Keywords:** CHF, Heart Transplantation, Endomyocardial Biopsy, dd-cfDNA Method.

**Кілтті сөздер:** СЖЖ, Жүрек трансплантациясы, эндомиокардиалді биопсия, dd-cfDNA әдісі.

**Introduction**

As of today, the problem of chronic heart failure is highly relevant in Kazakhstan, with annual mortality from the terminal stage of chronic heart failure significantly higher than in the general population, reaching 12% among patients with heart failure in functional classes III-IV, even under treatment in a specialized hospital. The primary method of treating the terminal stage of heart failure, when optimal medical therapy is ineffective, is surgical treatment - heart transplantation.

According to the Republican Center for Coordination of Transplantation and High-Tech Medical Services of the Ministry of Health of Kazakhstan, more than 3 thousand Kazakhstanis are in need of organ transplantation, and 10 patients per 1 million population require heart transplantation. In recent years, not only has the number of transplantations worldwide increased significantly, but also the indicators of quality and duration of life for heart transplant recipients have improved.

Heart transplantation is considered the "gold" standard for the surgical treatment of terminal heart failure. According to the International Society for Heart and Lung Transplantation (ISHLT) data from 2019, the overall median survival is 12.5 years, and the conditional survival is 14.8 years for those who survive the first year. Successful heart transplantation improves the quality of life and increases the survival of patients.

One of the most serious complications, both in the early and late periods after transplantation, remains acute cellular and humoral (antibody-mediated) rejection. The probability of developing rejection of the heart transplant and coronary artery disease persists in patients after heart transplantation throughout their lives, necessitating continuous monitoring and correction of immunosuppressive therapy and early detection of signs of rejection.

Endomyocardial biopsy (EMB) is the standard for monitoring and assessing a transplanted heart. Despite its increasing prevalence and widespread recognition, EMB is an invasive procedure prone to errors and may be associated with both procedural complications and long-term consequences.

Furthermore, EMB, routinely used for monitoring during the first year after heart transplantation, is a costly medical procedure that is inconvenient for patients. Additionally, about 25% of biopsy samples are deemed unsuitable for use. In light of these limitations, extensive efforts have been made to develop non-invasive monitoring methods that could reduce the need for subsequent EMB. This emphasis is on monitoring the recipient's immune response to detect the onset of rejection. Currently, there is ongoing development of an analysis that directly assesses the health of the transplanted heart.

Considerable efforts have been made to develop non-invasive diagnostic biomarkers that could replace or reduce the need for endomyocardial biopsy.

Episodes of acute rejection are most common in the first weeks after transplantation and can be categorized into T-cell-mediated (ACR) and antibody-mediated (AMR) rejection.

During acute cellular rejection (ACR), lymphocytes infiltrate and proliferate in the interstitial space. The adaptive immune system plays a central role in ACR. Direct allorecognition involves the interaction between the T-cell receptor (TCR) on recipient T cells and mismatched human leukocyte antigens (HLA) on donor antigen-presenting cells [4,5,6,7]. Indirect allorecognition also plays a role. The interaction of HLA/peptide-TCR and co-stimulatory signals promotes the proliferation and differentiation of T cells. CD8+ T cells release perforin and granzyme B, inducing apoptosis of target cells. Monocytes and myeloid dendritic cells (DCs) also infiltrate the graft and contribute to acute rejection.

Antibody-mediated rejection (AMR) can occur within the first year after transplantation. AMR rejection is mediated by donor-specific antibodies targeting HLA or non-HLA antigens on the donor's endothelium. The antigen-antibody interaction leads to antibody-dependent cellular cytotoxicity and complement activation, causing lysis of target cells. Damage to endothelial cells results in platelet aggregation and recruitment of leukocytes through cytokines, chemokines, and chemoattractants, ultimately leading to acute rejection.

Дiagnostics of acute and chronic rejection of a cardiac allograft remains a challenging task, as rejection often occurs without symptoms, impacting both short-term and long-term transplantation outcomes. Significant progress has been made in molecular diagnostics for non-invasive monitoring of acute rejection after heart transplantation in the last decade. Alternative non-invasive biomarkers have the potential to replace or reduce the need for endomyocardial biopsy (EMB). These biomarkers are categorized into two groups: those reflecting allograft injury and those reflecting inflammatory and alloimmune processes underlying allograft rejection. Given the potential consequences of not diagnosing and treating acute rejection of a cardiac allograft, these biomarkers must be highly sensitive to rejection, even at the expense of low specificity [2,3].

Non-invasive methods include AlloMap, detection of donor-derived cell-free DNA (dd-cfDNA), microRNAs, extracellular vesicles, and donor-specific antibodies (DSA). Despite dozens of promising studies and potential biomarkers, only two have been approved by the Food and Drug Administration (FDA) and are used in everyday clinical practice: AlloMap and donor-derived cell-free DNA (dd-cfDNA) [11,12,13,14].

Cell-free DNA of donor origin (dd-cfDNA) is present ubiquitously in biological fluids and various environments, including soil and water biotopes. Recently, studies have shown that certain types of extracellular DNA can play a significant role in living organisms and indicate pathological conditions. Cell-free DNA refers to all non-encapsulated DNA in the bloodstream and was first detected in the blood plasma of healthy individuals in 1948. Cell-free DNA consists of approximately 150 base pairs of double-stranded DNA released from nucleosomes during apoptosis and necrosis. cf-DNA molecules exist as monomers, dimers, and trimers. Most cf-DNA circulates as nucleosomes or chromatosomes, as free DNA is vulnerable to rapid degradation by nucleases. An important characteristic of cf-DNA is its half-life in the bloodstream (30 minutes to 2 hours), indicating continuous release from apoptotic or necrotic cells.

There are various types of cf-DNA, with the most important being cell-free mitochondrial DNA, tumor DNA, and fetal DNA, all possessing similar properties. Concentrations of cfDNA vary under both normal physiological conditions (7-18 ng/ml in healthy individuals) and diagnosed diseases (800 ng/ml in patients with esophageal cancer). The initial discovery of cell-free DNA in 1948 by Mandel and Metais led to numerous studies assessing the role of cfDNA in various diseases. Initially used to study oncological markers in cancer patients, the most successful application of cf-DNA as a clinical biomarker is non-invasive prenatal testing (NIPT) for detecting fetal pathologies, showing higher accuracy compared to biochemical screening.

Recently, interest in cell-free DNA has increased in the field of transplantation. Determining the quantity of donor-derived cell-free DNA in a patient's blood plasma can aid in early detection of organ rejection after transplantation.

Cell-free DNA (cfDNA) is a widely used prognostic and predictive biomarker that enters the bloodstream as a result of cell death and is present in both healthy and sick individuals, but at much higher concentrations in the latter [15]. Each fragment of donor-derived cell-free DNA (dd-cfDNA) carries molecular characteristics of the cell from which it originated, such as DNA methylation status.

The detection of dd-cfDNA in the blood of transplant recipients has been proposed as a potential biomarker for organ rejection or damage to the transplanted cells. The initial method for detecting dd-cfDNA involved genetic differences, such as mismatched donor-recipient sex, where the presence of the Y-chromosome in a female recipient could indicate donor-derived DNA [17]. The data on dd-cfDNA were assessed based on HLA (human leukocyte antigen) mismatch between the donor and recipient in the HLA-DRB1 locus, using optimized droplet digital polymerase chain reaction (ddPCR) [18-19]. Another method for detecting dd-cfDNA includes a quantitative approach using polymerase chain reaction (PCR) and genomic sequencing.

According to De Vlaminck et al., comparing the results of endomyocardial biopsy (EMB) and the fraction of cell-free DNA, the latter was significantly increased five months after transplantation, while biopsy results were negative [20]. Their findings suggest that measuring dd-cfDNA levels can replace EMB and that these measurements can be used for other aspects of patient management, such as predicting rejection events and managing immunosuppressant dosage.

As explained by Zangwill, a higher overall level of dd-cfDNA in the early stages after transplantation predicted death [15].Начало формы

Cell-free DNA (cfDNA) also serves as a marker for graft survival. In cases of transplant rejection due to the destruction of its cells, donor-derived cfDNA (dd-cf-DNA) is released into the bloodstream, leading to an increase in its concentration in the recipient's body. Early elevation of dd-cfDNA levels is observed in patients during acute graft dysfunction, supporting the potential use of quantitative dd-cfDNA measurement as an alternative marker for organ rejection. Some studies report a temporary increase in dd-cfDNA levels in the early post-transplantation period, but in stable patients receiving immunosuppressive therapy, this indicator returns to baseline values around 7-10 days after transplantation.

Overall, research indicates that levels of donor cfDNA have high accuracy and can predict acute rejection of the transplanted organ, with predictive ability remaining consistent across all organ types. The highest cfDNA levels are observed in cases of acute antibody-mediated rejection (AMR). Several studies have compared dd-cfDNA with other markers of graft damage [7,8]. Methods used for quantitative determination of recipient dd-cfDNA in plasma include real-time polymerase chain reaction (PCR), droplet digital PCR (ddPCR), and next-generation sequencing (NGS). ddPCR and NGS require donor genotyping, evaluating the presence of a single nucleotide polymorphism where the recipient is homozygous for a specific allele, while the donor is not.

As a non-invasive quantitative marker of graft damage, dd-cfDNA promises to be a safe, accurate, and feasible method for monitoring acute rejection in heart transplant recipients. Although further research is needed to confirm specific threshold values for routine clinical use, dd-cfDNA currently demonstrates the greatest potential as a monitoring tool and screening method for patients who would benefit the most from preemptive biopsy. Advances in the use of dd-cfDNA monitoring further align with our efforts to develop precise medical methods for heart transplant recipients. Patterns of dd-cfDNA elevation also differ between AMR and acute cellular rejection (ACR), potentially aiding in diagnostics. The unique data obtained can facilitate a more precise diagnosis of AMR and ACR, helping determine the appropriate treatment strategy. The aim of this study is to explore the demographic indicators of heart transplant patients and identify immune tolerance and corrections in immunosuppressive therapy for recipients.

**Methods**

The study included 40 patients who had previously undergone orthotopic heart transplantation at the National Scientific Cardiac Surgery Center in the conditions of the Republic of Kazakhstan. Clinical material samples (venous blood) were collected from participants aged 18 and older who had undergone heart transplantation. Patients who refused to undergo diagnostic procedures specified in the study protocol were excluded from the research. Participants provided questionnaire data, and informed consents for study participation were obtained. Inclusion criteria for study participants were adults after heart or kidney transplantation:

* Age over 18 years
* Both male and female gender
* Presence of transplanted heart, kidney, or liver
* Patients who signed informed consent to participate in the study.
* Exclusion criteria for study participants were:
* Refusal to undergo diagnostic procedures as specified in the study protocol
* Participation in another study

Presence of anatomical or concomitant diseases, or other medical, social, or psychological conditions that, in the researcher's opinion, could limit the subject's ability to participate in the clinical study or meet the requirements of subsequent observation or affect the scientific validity of the results of the clinical study.

**Study Design**

The study design was a single-center, retrospective, observational clinical study. The diagnostic method involved genetic analysis, determining the percentage of donor-derived cell-free DNA (ddcfDNA) using allele-specific quantitative PCR. The assessment of the donor's cell-free DNA fraction (ddCF-DNA) relative to the total cell-free DNA in the recipients' blood is a non-invasive diagnostic method for acute rejection in patients after heart transplantation. Below are the interim results of the study, and all calculations were performed using Excel, presenting average statistical values.

**Ethics Approval**

This study was conducted in strict accordance with the principles outlined in the Helsinki Declaration. Before commencing the research, approval was obtained from the Local Bioethics Committee of the Corporate Fund "University Medical Center."

**Research Results**

A representative sample was collected based on the National Scientific Cardiac Surgery Center in Astana. The sample included 40 patients who had previously undergone orthotopic heart transplantation. The total sample size was 40 patients, including 8 females and 32 males. The age range was 17 to 59 years. Of the patients, 24 (60%) had undergone previous surgeries, and 16 (40%) had heart transplantation as their primary surgical intervention.

The terminal stage of heart failure was primarily caused by dilated cardiomyopathy in 19 cases (47.5%), ischemic cardiomyopathy in 7 cases (17.5%), hypertrophic cardiomyopathy in 4 cases (10%), non-compaction myocardium in 2 cases (5%), familial forms of cardiomyopathies in 4 cases (10%), and valvular cardiomyopathy in 4 cases (10%).

In the interim result of this clinical study, a positive cross-match reaction between the donor and the recipient was recorded in 5%. The average age of patients was 38.85±13.23 years, and dilated cardiomyopathy (47.5%) was the predominant cause of the terminal stage of heart failure in most cases.

**Discussion**

The effectiveness of this method for diagnosing donor heart rejection has been actively studied in the last 10 years. This method allows for the differentiation of acute cellular and antibody-mediated rejection, which have different therapeutic approaches, demonstrating high clinical significance. However, further research is required: firstly, new clinical trials are needed to obtain convincing evidence in favor of this method; secondly, to determine clinical effectiveness compared to invasive approaches (transplant biopsy); thirdly, by studying the sensitivity and specificity of the method, establish threshold values at which clinicians could diagnose acute rejection. Moreover, current approaches to ddCF-DNA determination have several limitations, including the labor-intensive and high cost of these methods.

**Conflict of Interest:** There are no conflicts of interest.

**Funding:** This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant title: Non-invasive methods for diagnosis of transplant rejection as a predictor of long-term graft survival, Grant No. BR21882206).

**Authors' Contributions:** All authors have equal contributions. All authors have approved the final version of the article.

**References**

1. Khush, K., Cherikh, W. S., Chambers, D. C., Harhay, M. O., Hayes, D., Hsich, E.,Stehlik, J. (2019). The International Thoracic Organ Transplant Registry of the International Society for Heart and Lung Transplantation: Thirty-sixth Adult Heart Transplantation Report — 2019; Focus Theme: Donor and Recipient Size Match. The Journal of Heart and Lung Transplantation. doi:10.1016/j.healun.2019.08.004
2. Mengel M, Sis B, Kim D, Chang J, Famulski KS, Hidalgo LG, Einecke G, de Freitas DG, Tymchak W, Burton J, Halloran PF. The molecular phenotype of heart transplant biopsies: relationship to histopathological and clinical variables. *Am J Transplant.*2010;10:2105–15. [[PubMed](https://pubmed.ncbi.nlm.nih.gov/20883545)] [[Google Scholar](https://scholar.google.com/scholar_lookup?journal=Am+J+Transplant&title=The+molecular+phenotype+of+heart+transplant+biopsies:+relationship+to+histopathological+and+clinical+variables&volume=10&publication_year=2010&pages=2105-15&pmid=20883545&)]
3. Saraiva F, Matos V, Gonçalves L, Antunes M, Providência LA. Complications of endomyocardial biopsy in heart transplant patients: a retrospective study of 2117 consecutive procedures. *Transplant Proc.*2011;43:1908–12. [[PubMed](https://pubmed.ncbi.nlm.nih.gov/21693299)] [[Google Scholar](https://scholar.google.com/scholar_lookup?journal=Transplant+Proc&title=Complications+of+endomyocardial+biopsy+in+heart+transplant+patients:+a+retrospective+study+of+2117+consecutive+procedures&volume=43&publication_year=2011&pages=1908-12&pmid=21693299&)]].
4. Snyder TM, Khush KK, Valantine HA, Quake SR. Universal noninvasive detection of solid organ transplant rejection. *Proc Natl Acad Sci U S A.*2011;108:6229–34. [[PMC free article](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3076856/)] [[PubMed](https://pubmed.ncbi.nlm.nih.gov/21444804)] [[Google Scholar](https://scholar.google.com/scholar_lookup?journal=Proc+Natl+Acad+Sci+U+S+A&title=Universal+noninvasive+detection+of+solid+organ+transplant+rejection&volume=108&publication_year=2011&pages=6229-34&pmid=21444804&)]
5. Austin BA, Taylor DO. Surrogate markers of rejection. *Curr Opin Organ Transplant.*2010;15:645–9. [[PubMed](https://pubmed.ncbi.nlm.nih.gov/20651597)] [[Google Scholar](https://scholar.google.com/scholar_lookup?journal=Curr+Opin+Organ+Transplant&title=Surrogate+markers+of+rejection&volume=15&publication_year=2010&pages=645-9&pmid=20651597&)]
6. Koestenbauer S, Stiegler P, Stadlbauer V, Mayrhauser U, Leber B, Schweiger M, Wasler A, Prenner G, Sereinigg M, Zelzer S, Stojakovic T, Scarpatetti M, Griesbacher A, Greilberger J, Tscheliessnigg K. Myeloperoxidase and carbonyl proteins: promising markers for non-invasive monitoring of graft rejection after heart transplantation. *J Heart Lung Transplant.*2010;29:1352–7. [[PubMed](https://pubmed.ncbi.nlm.nih.gov/20591692)] [[Google Scholar](https://scholar.google.com/scholar_lookup?journal=J+Heart+Lung+Transplant&title=Myeloperoxidase+and+carbonyl+proteins:+promising+markers+for+non-invasive+monitoring+of+graft+rejection+after+heart+transplantation&volume=29&publication_year=2010&pages=1352-7&pmid=20591692&)]
7. Morrow T. Blood test can replace invasive heart biopsy. *Manag Care.*2010;19:46–7. [[PubMed](https://pubmed.ncbi.nlm.nih.gov/20608409)] [[Google Scholar](https://scholar.google.com/scholar_lookup?journal=Manag+Care&title=Blood+test+can+replace+invasive+heart+biopsy&volume=19&publication_year=2010&pages=46-7&pmid=20608409&)]
8. Clerkin, K. J., Restaino, S. W., Zorn, E., Vasilescu, E. R., Marboe, C. C., & Mancini, D. M. (2016). The effect of timing and graft dysfunction on survival and cardiac allograft vasculopathy in antibody-mediated rejection. The Journal of Heart and Lung Transplantation, 35(9), 1059–1066. doi:10.1016/j.healun.2016.04.007
9. Patel JK, Kobashigawa JA. Should we be doing routine biopsy after heart transplantation in a new era of anti-rejection? Curr Opin Cardiol. 2006;21(2):127-131. doi:10.1097/01.hco.0000210309.71984.30
10. F. Saraiva, V. Matos, L. Gonçalves, M. Antunes, L. Providência, Complications of endomyocardial biopsy in heart transplant patients: A retrospective study of 2117 consecutive procedures. Transplant. Proc. 43, 1908–1912 (2011).

11. C. C. Marboe, M. Billingham, H. Eisen, M. C. Deng, H. Baron, M. Mehra, S. Hunt, J. Wohlgemuth, I. Mahmood, J. Prentice, G. Berry, Nodular endocardial infiltrates (Quilty lesions) cause significant variability in diagnosis of ISHLT grade 2 and 3A rejection in cardiac allograft recipients. J. Heart Lung Transplant. 24, S219–S226 (2005).

12. Heitzer, E., Auinger, L., & Speicher, M. R. (2020). Cell-Free DNA and Apoptosis: How Dead Cells Inform About the Living. Trends in Molecular Medicine. doi:10.1016/j.molmed.2020.01.012

13. Martuszewski, A., Paluszkiewicz, P., Król, M., Banasik, M., & Kepinska, M. (2021). Donor-Derived Cell-Free DNA in Kidney Transplantation as a Potential Rejection Biomarker: A Systematic Literature Review. Journal of Clinical Medicine, 10(2), 193. doi:10.3390/jcm10020193

14. Y M Dennis Lo, Diana S C Han, Peiyong Jiang, Rossa W K Chiu. (2021) Epigenetics, fragmentomics, and topology of cell-free DNA in liquid biopsies DOI: 10.1126/science.aaw3616

15. Sherwood K., Weimer E. T. (2018). Characteristics, properties, and potential applications of circulating cell-free DNA in clinical diagnostics: A focus on transplantation. J. Immunol. Methods 463, 27–38. doi: 10.1016/j.jim.2018.09.011

16. Hidestrand, M.; Tomita-Mitchell, A.; Hidestrand, P.M.; Oliphant, A.; Goetsch, M.; Stamm, K.; Liang, H.-L.; Castleberry, C.; Benson, D.W.; Stendahl, G.; et al. Highly Sensitive Noninvasive Cardiac Transplant Rejection Monitoring Using Targeted Quantification of Donor-Specific Cell-Free Deoxyribonucleic Acid. J. Am. Coll. Cardiol. 2014, 63, 1224–1226.

17. Lo, Y. D., Tein, M. S., Pang, C. C., Yeung, C. K., Tong, K.-L., & Hjelm, N. M. (1998). Presence of donor-specific DNA in plasma of kidney and liver-transplant recipients. The Lancet, 351(9112), 1329–1330. doi:10.1016/s0140-6736(05)79055-3

18. Xiaoxiao Qian1, Palak Shah2,3, Sean Agbor-Enoh (2022). Non-invasive Biomarkers in Heart Transplant: 2020-2021 Year in Review. DOI: 10.1097/MOT.0000000000000945

19. Sorbini M., Togliatto G. M., Simonato E., Boffini M., Cappuccio M., Gambella A., et al. (2021). HLA-DRB1 mismatch-based identification of donor-derived cell free DNA (dd-cfDNA) as a marker of rejection in heart transplant recipients: A single-institution pilot study. J. Heart Lung Transpl. 40, 794–804. 10.1016/j.healun.2021.05.001

20. De Vlaminck, I., Valantine, H. A., Snyder, T. M., Strehl, C., Cohen, G., Luikart, H., Khush, K. K. (2014). Circulating Cell-Free DNA Enables Noninvasive Diagnosis of Heart Transplant Rejection. Science Translational Medicine, 6(241), 241ra77–241ra77. doi:10.1126/scitranslmed.3007803