Emerging Markers and Technologies in Urine Sample Validity: A Brief Review of Detection Methods and Applications

Abstract

Urine sample validity testing is critical in medical diagnostics, forensic investigations, and workplace drug screening to ensure accurate and reliable results. The increasing sophistication of tampering methods, such as adulteration and substitution, necessitates the development of advanced testing techniques. This review explores the latest advancements in urine validity testing, including the integration of machine learning (ML) and artificial intelligence (AI) with high-resolution mass spectrometry (HRMS) and liquid chromatography-tandem mass spectrometry (LC-MS/MS). These technologies enhance the detection of novel chemical and biological markers, such as unique metabolite profiles, polyglycole patterns, and DNA methylation markers (e.g., TWIST1 and NID2). The identification of new biomarkers and the application of multi-modal analytical approaches provide comprehensive and sensitive detection of tampering. Additionally, the development of non-invasive and point-of-care testing methods offers immediate and accurate results, making these techniques more accessible and practical. Future directions in the field focus on refining these technologies, ensuring ethical data handling, and expanding regulatory frameworks to protect privacy and enhance the reliability of testing protocols. The advancements discussed promise significant improvements in the detection and prevention of urine sample tampering, ensuring the integrity of testing processes across various applications.

Keywords: Urine Sample Validity**,** Adulteration Detection**,** High-Resolution Mass Spectrometry (HRMS)**,** Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS)

1. INTRODUCTION

Urine sample validity is crucial in medical diagnostics, workplace drug testing, and forensic investigations. The accuracy of these tests relies on ensuring the sample's integrity, which can be compromised by adulteration, substitution, or dilution.

Historically, urine validity has been determined using basic parameters like temperature, pH, specific gravity, and creatinine levels. However, with the increasing sophistication of adulteration methods, there is a need for more advanced markers and technologies to accurately assess sample validity. This review explores both traditional and emerging methods for detecting urine sample tampering, focusing on chemical and biological markers, advanced analytical techniques, and practical applications.

2. Traditional Methods for Validating Urine Samples

A freshly collected urine sample typically has a temperature between 32°C to 38°C. Deviations from this range can suggest tampering, such as the use of synthetic urine. The normal pH range for urine is 4.5 to 8.0. Significant deviations from this range can indicate adulteration, such as the addition of acids or bases to alter the chemical composition of the sample [1].

Specific gravity measures the concentration of solutes in urine, with normal values ranging from 1.002 to 1.030. Abnormally low specific gravity can indicate dilution [2].

Creatinine is a metabolic byproduct found in urine, and levels below 20 mg/dL may suggest dilution, whether by water or other substances [3].

While these traditional markers are useful, they have limitations in detecting sophisticated adulteration methods, such as the use of synthetic urine products designed to mimic these parameters (Table 1) [4].

Table 1: Dilution, Adulteration, Substitution of Urine Specimen [4]

Urine States	Description
Diluted	– Urine creatinine ≥ 2 mg/dL but < 20 mg/dL – Specific gravity > 1.001 but < 1.003
Substituted	– Urine creatinine < 2 mg/dL – Specific gravity < 1.001 or > 1.020
Adulterated	– pH < 3 or > 11 – Nitrite concentration > 500 mcg/mL – Chromium concentration > 50 mcg/mL – Presence of: Halogen (bleach, iodine, fluoride), glutaraldehyde, pyridine, surfactant

3. Emerging Markers and Technologies

The field of urine sample validity testing has seen significant advancements with the development of new chemical and biological markers, as well as sophisticated analytical technologies. These innovations enhance the ability to detect tampering, such as adulteration, dilution, or substitution, which may not be identifiable using traditional methods.

3.1. Chemical Markers

3.1.1. Metabolites and Biomarkers:

Recent studies have leveraged metabolomics—a comprehensive study of metabolites within biological specimens—to identify markers indicative of urine adulteration. These markers are often metabolites whose levels can vary significantly due to the addition of adulterants or changes in the urine's composition:

- **Amino Acids and Purines**: For instance, the presence and levels of certain amino acids (e.g., phenylalanine, tryptophan) and purines (e.g., uric acid) can signal adulteration. An increase in amino acids such as histidine and a decrease in metabolites like uric acid have been associated with specific adulterants like potassium nitrite [5].
- **5-HO-isourate**: This compound is a breakdown product of uric acid, and its presence in unusually high concentrations may indicate chemical adulteration. This marker,

among others, is detected using high-resolution mass spectrometry (HRMS), which can identify even minute changes in metabolite concentrations [6].

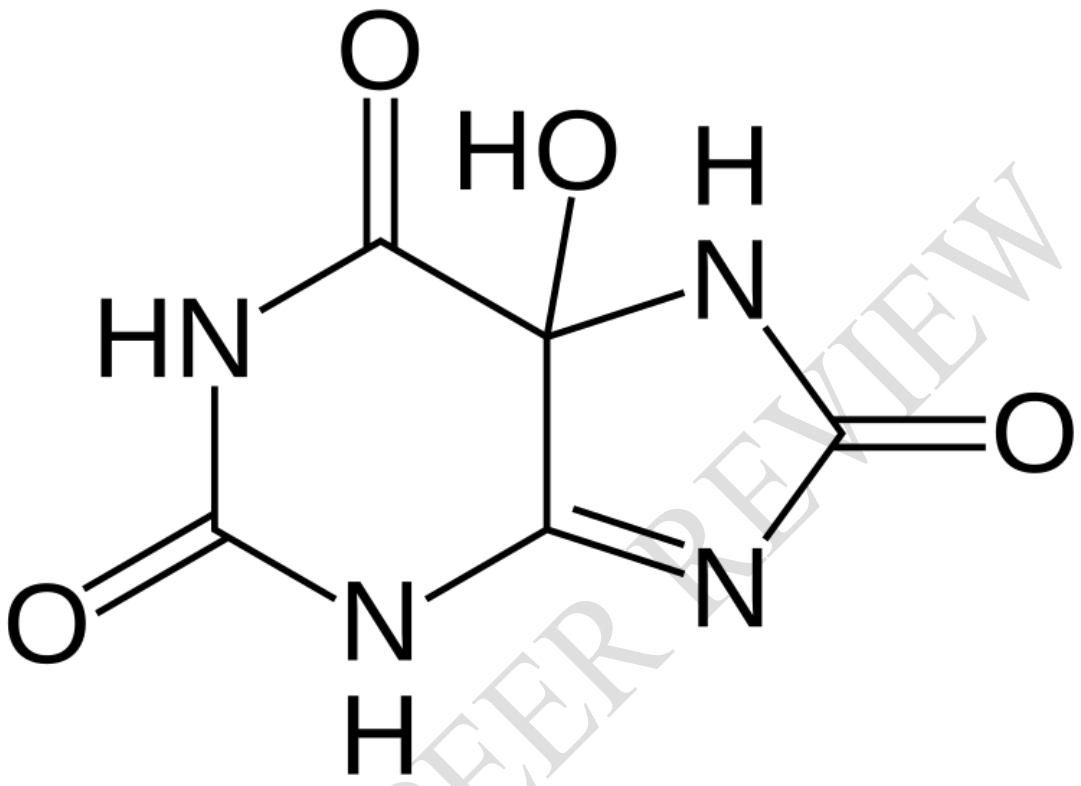

Figure 1: 5-Hydroxyisourate chemical formula [6].

3.1.2. Polyglycole Patterns:

Polyglycoles are synthetic compounds that can be present in commercial synthetic urine products. These compounds, often added to mimic the physical and chemical properties of natural urine, can be detected using advanced techniques such as HRMS. The unique patterns of polyglycoles are not typically found in authentic urine, making them reliable markers for identifying synthetic urine [7].

3.2. Biological Markers

3.2.1. Endogenous Compounds:

Endogenous compounds, naturally occurring substances in the body, serve as critical indicators of urine authenticity:

- **Carnitines and Phenylacetylglutamine**: The presence and ratio of various carnitines (such as propionyl-carnitine, butyryl-carnitine) and phenylacetylglutamine are stable in natural urine. Discrepancies in these levels can indicate adulteration or dilution, as synthetic or diluted samples often lack these biomarkers in expected concentrations [8].

3.2.2. DNA Methylation Markers:

DNA methylation markers, typically used in cancer diagnostics, are now being explored for urine sample validity testing:

- **TWIST1 and NID2**: These genes are commonly methylated in bladder cancer tissues. The detection of methylated TWIST1 and NID2 in urine sediments using methylation-specific PCR (MSP) can differentiate between normal and cancerous samples. This application not only aids in cancer detection but also ensures that the sample is derived from a human source, not synthetic [9].

4. Advanced Analytical Techniques in Urine Sample Validity Testing

Advanced analytical techniques are revolutionizing the field of urine sample validity testing by providing highly sensitive, specific, and comprehensive methods for detecting sample adulteration, substitution, and other forms of tampering. The primary advanced techniques include various forms of mass spectrometry (MS) and chromatography, often augmented with machine learning (ML) and artificial intelligence (AI). These techniques offer a detailed molecular analysis, allowing for the identification of both known and novel adulterants, as well as the differentiation between authentic and synthetic urine samples.

4.1. Mass Spectrometry (MS)

Mass spectrometry is a critical tool in the analysis of urine samples due to its ability to accurately measure the mass-to-charge ratio of ions. This capability enables the detection and quantification of a wide range of substances, from small metabolites to larger biomolecules [10].

4.2. High-Resolution Mass Spectrometry (HRMS)

HRMS provides an exceptionally high level of accuracy in determining the exact mass of ions, making it invaluable for identifying subtle changes in urine composition that may indicate adulteration. This technique is capable of detecting low-abundance metabolites,

which are often used as biomarkers of tampering [11]. HRMS has been used to detect the presence of specific chemical adulterants such as potassium nitrite by identifying characteristic metabolic byproducts like 5-HO-isourate, a breakdown product of uric acid. This level of detail is crucial for identifying adulteration that might go undetected by traditional methods [12].

4.3. Quadrupole Time-of-Flight (QTOF) MS

QTOF MS combines quadrupole mass spectrometry with time-of-flight analysis, providing both high resolution and mass accuracy. It is particularly useful for untargeted metabolomics studies, where the goal is to profile all measurable metabolites in a sample [13]. QTOF MS has been utilized in the detection of synthetic cannabinoids in urine. This technique allows for the identification of both the parent compounds and their metabolites, facilitating the differentiation between synthetic cannabinoids and naturally occurring substances in the body [14].

4.4. Chromatography Techniques

Chromatography, often used in conjunction with MS, enhances the separation of complex mixtures into individual components, enabling more precise analysis.

4.4.1. Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS)

LC-MS/MS is one of the most powerful techniques in analytical chemistry, combining liquid chromatography for separation with tandem mass spectrometry for identification and quantification. This method provides high specificity and sensitivity, making it ideal for detecting low concentrations of substances in complex biological matrices [15]. LC-MS/MS has been instrumental in distinguishing between authentic and synthetic urine. The technique can identify specific biomarkers, such as polyglycoles and other exogenous compounds, that are typically absent in natural urine. This method is also used to detect a wide range of drugs and their metabolites, making it essential for forensic and clinical toxicology [16].

4.4.2. Gas Chromatography-Mass Spectrometry (GC-MS)

GC-MS combines gas chromatography with mass spectrometry and is highly effective for the analysis of volatile and semi-volatile compounds. This technique is particularly useful

in the identification of synthetic substances that may be added to urine samples [17]. GC-MS has been used to detect synthetic cannabinoids, which are often volatile and can be easily separated using gas chromatography. The subsequent mass spectrometry analysis provides detailed information on the molecular structure, aiding in the identification of these compounds [18].

5. Machine Learning and Artificial Intelligence

The integration of machine learning (ML) and artificial intelligence (AI) with advanced analytical techniques enhances the analysis of complex datasets. These technologies can identify patterns and correlations that may not be immediately apparent, providing deeper insights into the data.

5.1. Applications in Urine Sample Testing

- **Pattern Recognition and Classification**: ML algorithms, such as artificial neural networks (ANNs) and random forests, can classify urine samples based on their chemical profiles. These models are trained on large datasets and can accurately predict the authenticity of a sample by recognizing patterns associated with tampering [19].
- **Predictive Modeling**: AI models can predict the likelihood of a sample being adulterated based on the presence of specific markers. For instance, a study employed a machine learning model that analyzed features extracted from HRMS data to detect chemically adulterated urine samples with high accuracy [20].

6. Combined Approaches and Multimodal Analysis

The most robust approaches to urine sample validity testing often involve combining multiple analytical techniques. By integrating different methods, such as LC-MS/MS and HRMS, researchers can cross-verify results and ensure comprehensive coverage of potential adulterants. In one study, the combination of enzymatic detection of uric acid, LC-MS/MS analysis, and specific commercial tests like the Axiom Test True Synthetic Urine, provided a multifaceted approach to identifying synthetic urine samples. This multi-modal strategy ensured high sensitivity and specificity, covering both direct and indirect markers of urine substitution [21].

7. Case Studies and Application

A study by Vikingsson et al. [22] investigated the use of synthetic urine to evade drug testing. The researchers analyzed samples using traditional tests, which failed to detect the synthetic nature of the urine. However, advanced techniques like LC-MS/MS profiling and the detection of specific biomarkers, such as polyglycole patterns, successfully identified synthetic samples. This study underscores the limitations of traditional validity tests and the need for advanced methodologies.

Steuer et al. [5] conducted a proof-of-concept study using high-resolution mass spectrometry (MS) to detect chemical adulteration in urine samples. By analyzing metabolite changes, they identified specific markers, such as amino acids and purines, indicative of adulteration with potassium nitrite. This study demonstrated the potential of metabolomics in identifying a broad range of adulterants, paving the way for routine MS screening procedures.

Renard et al. [23] explored the use of DNA methylation markers for detecting bladder cancer in urine samples. They identified the methylation of TWIST1 and NID2 genes as highly sensitive and specific markers. The study showed that these markers could detect early-stage and low-grade bladder cancer, illustrating the broader application of urine biomarkers in both clinical and forensic settings.

Franke et al. [16] compared three methods for distinguishing authentic urine from synthetic urine, including enzymatic detection of uric acid and LC-MS/MS analysis. The study found that LC-MS/MS provided the highest sensitivity and specificity, accurately identifying synthetic samples that traditional methods could not detect. This study highlights the importance of combining different analytical techniques for comprehensive testing.

Streun et al. [20] developed a machine learning model using high-resolution MS data to detect chemically adulterated urine samples. The model achieved high accuracy, sensitivity, and specificity, demonstrating the potential of combining advanced analytical techniques with machine learning for effective adulteration detection.

Mogler et al. [14] focused on the detection of synthetic cannabinoids (SCs) in urine samples. They utilized LC-MS/MS to identify specific metabolites, demonstrating the

method's effectiveness in detecting recent SC use. This study is crucial for forensic toxicology, where detecting emerging drugs of abuse is a continuous challenge.

Li et al. [24] developed a urine preservative kit to maintain the integrity of circulating cell-free DNA (cfDNA) in urine, which can be used for detecting genomic alterations in cancer. The kit demonstrated excellent preservation of cfDNA, enabling accurate genomic testing from urine samples even after prolonged storage under various conditions. This study highlights the potential of non-invasive urine testing for cancer diagnostics.

Lam et al. [25] evaluated urinary 3-methoxytyramine as a biomarker for neuroblastoma, comparing its diagnostic performance with other established catecholamine-related biomarkers. The study found that urinary 3-methoxytyramine was a reliable marker, correlating well with disease activity and offering a non-invasive method for monitoring neuroblastoma.

Gauchel et al. [26] explored the use of low-molecular-mass polyethylene glycols (PEGs) as enteral labeling markers for detecting urine adulteration. They developed an isocratic reversed-phase high-performance liquid chromatographic method to monitor the renal excretion of PEGs, providing a novel approach to detecting sample substitution.

Aldubayyan et al. [27] developed an LC-MS/MS method for detecting synthetic cathinones and their metabolites in urine. This method was particularly useful for identifying cases of polydrug use, where synthetic cathinones were present alongside other stimulant drugs. The study highlights the need for comprehensive screening to detect a wide range of substances in forensic and clinical toxicology.

8. Challenges and Limitations

The adoption of these new markers and technologies faces several challenges:

Advanced analytical techniques like MS and LC-MS/MS require specialized equipment and trained personnel, potentially limiting their routine use in some settings.

The collection and analysis of biological samples, especially in forensic and workplace settings, raise ethical questions about privacy and consent.

Despite their high specificity, advanced markers can still yield false results if not applied and interpreted correctly. This underscores the need for stringent validation and standardization of testing protocols.

9. Future Directions in Urine Sample Validity Testing

The field of urine sample validity testing is evolving rapidly, driven by advances in technology and a deeper understanding of biochemical markers. Future directions in this field focus on improving the accuracy, efficiency, and comprehensiveness of testing methods. This involves the integration of novel biomarkers, advanced analytical techniques, ML and AI, and innovative testing methodologies. These advancements aim to address the current limitations and anticipate emerging challenges in detecting urine sample tampering, ensuring more reliable results in medical, forensic, and workplace contexts.

The development of new biomarkers is essential for enhancing the accuracy of urine validity testing, focusing on differentiating between natural and adulterated samples. Key areas include identifying unique markers in synthetic urine, such as specific chemical additives and stabilizers, as well as changes in metabolite ratios that indicate dilution or tampering. DNA methylation patterns, like those in TWIST1 and NID2 genes, offer potential for highly specific verification of urine's biological origin. Future research will likely uncover more metabolites and biochemical pathways uniquely affected by tampering, expanding the range of detectable adulteration methods.

Advancements in analytical techniques, particularly HRMS and enhanced chromatography methods, aim to improve the detection of low-abundance metabolites and synthetic compounds. These improvements, along with the development of tandem techniques like LC-QTOF-MS, promise quicker and more detailed analyses. There is also a move towards more comprehensive, multi-modal testing protocols and non-invasive, point-of-care testing methods, which provide immediate results without extensive lab processing.

10. CONCLUSION

Urine sample validity testing is crucial for maintaining the integrity of medical diagnostics, forensic investigations, and workplace testing. The evolution from traditional methods to advanced chemical and biological markers, supported by sophisticated analytical

techniques, represents a significant advancement in this field. As research continues to uncover new markers and refine existing technologies, these innovations promise to enhance the accuracy, reliability, and comprehensiveness of urine sample validity testing.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies suchas Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

CONSENT AND ETHICAL APPROVAL

It is not applicable.

REFERENCES

1. Martínez-Castrejón M, López-Díaz JA, Solorza-Feria O, Talavera-Mendoza O, Rodríguez-Herrera AL, Alcaraz-Morales O, Hernández-Flores G. Environmental, economic, and social aspects of human urine valorization through microbial fuel cells from the circular economy perspective. Micromachines. 2022 Dec 16;13(12):2239.
2. Meister I, Zhang P, Sinha A, Skold CM, Wheelock ÅM, Izumi T, Chaleckis R, Wheelock CE. High-precision automated workflow for urinary untargeted metabolomic epidemiology. Anal Chem. 2021 Mar 19;93(12):5248-58.
3. Goggin MM, Nguyen TT, Inoue H, Hand CJ. Synthetic urine: Implications for workplace drug testing. Drug Test Anal. 2017;9(6):844-9.
4. Raouf M, Bettinger JJ, Fudin J. A Practical Guide to Urine Drug Monitoring. Fed Pract. 2018 Apr;35(4):38-44.
5. Steuer A, Arnold K, Schneider TD, Poetzsch M, Kraemer T. A new metabolomics-based strategy for identification of endogenous markers of urine adulteration attempts exemplified for potassium nitrite. Anal Bioanal Chem. 2017;409(26):6235-44.
6. Oksanen E, Blakeley MP, El-Hajji M, Ryde U, Budayova-Spano M. The neutron structure of urate oxidase resolves a long-standing mechanistic conundrum and reveals unexpected changes in protonation. PLoS One. 2014 Jan 23;9(1):e86651.

7. Kluge J, Rentzsch L, Remane D, Peters F, Wissenbach D. Systematic investigations of novel validity parameters in urine drug testing and prevalence of urine adulteration in a two-year cohort. Drug Test Anal. 2018;10(10):1536-42.

8. Wissenbach DK, Steuer AE. Advances in testing for sample manipulation in clinical and forensic toxicology-Part A: urine samples. Anal Bioanal Chem. 2023 Sep;415(21):5101-15.

9. Ng K, Stenzl A, Sharma A, Vasdev N. Urinary biomarkers in bladder cancer: A review of the current landscape and future directions. Urol Oncol. 2021 Jan 1;39(1):41-51.

10. Borden SA, Palaty J, Termopoli V, Famiglini G, Cappiello A, Gill CG, Palma P. Mass spectrometry analysis of drugs of abuse: challenges and emerging strategies. Mass Spectrom Rev. 2020 Sep;39(5-6):703-44.

11. Bergström MA, Lövgren H, Abrahamsson A, Eriksson EK, Andersson ML, Komorowska M, Axelsson MA. Rethinking Drug Analysis in Health Care: High-Throughput Analysis of 71 Drugs of Abuse in Oral Fluid Using Ion Mobility--High-Resolution Mass Spectrometry. J Anal Toxicol. 2022 Sep 1;46(7):765-75.

12. Rampler E, Abiead YE, Schoeny H, Rusz M, Hildebrand F, Fitz V, Koellensperger G. Recurrent topics in mass spectrometry-based metabolomics and lipidomics—standardization, coverage, and throughput. Anal Chem. 2020 Nov 28;93(1):519-45.

13. Liying Z, Min S, Baohua S, Hang C, Xin W, Hongxiao D, Ping X, Yan S. Application of a UPLC-MS/MS method for quantitative analysis of 29 synthetic cannabinoids and their metabolites, such as ADB-BUTINACA and MDMB-4en-PINACA in human hair in real cases. Forensic Sci Int. 2022 Feb 1;331:111139.

14. Mogler L, Franz F, Rentsch D, et al. Detection of the recently emerged synthetic cannabinoid 5F-MDMB-PICA in 'legal high' products and human urine samples. Drug Test Anal. 2018;10(1):196-205. doi:10.1002/dta.2201.

15. Mina A, McNeice L, Rennie M, Banukumar S, Vazquez S. How to screen for adulterated and synthetic urine samples when testing for drugs of abuse? A study to evaluate and Integrate axiom assay in specimen validity Testing protocol. EC Pharmacol Toxicol. 2022;10:33-40.

16. Franke L, Fuczik C, Hubig M, Peters FT, Wissenbach DK. Evaluation of biochemical assays and optimization of LC-MS/MS analysis for the detection of synthetic urine. J Anal Toxicol. 2023.

17. Krotulski AJ, Mohr AL, Kacinko SL, Fogarty MF, Shuda SA, Diamond FX, Kinney WA, Menendez MJ, Logan BK. 4F-MDMB-BINACA: a new synthetic cannabinoid widely implicated in forensic casework. J Forensic Sci. 2019 Sep;64(5):1451-61.

18. Haschimi B, Mogler L, Halter S, Giorgetti A, Schwarze B, Westphal F, Fischmann S, Auwärter V. Detection of the recently emerged synthetic cannabinoid 4F-MDMB-BINACA in "legal high" products and human urine specimens. Drug Test Anal. 2019 Sep;11(9):1377-86.

19. Wang MW, Goodman JM, Allen TE. Machine learning in predictive toxicology: recent applications and future directions for classification models. Chem Res Toxicol. 2020 Dec 23;34(2):217-39.

20. Streun GL, Steuer A, Ebert L, Dobay A, Kraemer T. Interpretable machine learning model to detect chemically adulterated urine samples analyzed by high-resolution mass spectrometry. Clin Chem Lab Med. 2021;59(8):1392-9. doi:10.1515/cclm-2021-0010.

21. Kahl KW, Seither JZ, Reidy LJ. LC-MS-MS vs ELISA: validation of a comprehensive urine toxicology screen by LC-MS-MS and a comparison of 100 forensic specimens. J Anal Toxicol. 2019 Nov;43(9):734-45.

22. Vikingsson S, Krauss ST, Winecker R, Flegel R, Hayes ED. Update on urine adulterants and synthetic urine samples to subvert urine drug testing. J Anal Toxicol. 2022. doi:10.1093/jat/bkac029.

23. Renard I, Joniau S, van Cleynenbreugel B, Collette C, Naome C, Vlassenbroeck I, et al. Identification and validation of the methylated TWIST1 and NID2 genes through real-time methylation-specific polymerase chain reaction assays for the noninvasive detection of primary bladder cancer in urine samples. Eur Urol. 2010;58(1):96-104.

24. Li Z, Tang H, Zhang T, Liu C, Zhu S, Zhang Y, Xiang B, Zhao Z. Development and validation of urine cfDNA preservative kit for detection of genomic alterations in cancer. Cancer Res. 2019 Jul 1;79(13):2236-.

25. Lam L, Woollard G, Teague L, Davidson J. Clinical validation of urine 3-methoxytyramine as a biomarker of neuroblastoma and comparison with other catecholamine-related biomarkers. Ann Clin Biochem. 2017;54(2):264-72.

26. Gauchel G, Huppertz B, Feiertag H, Keller R. Clinical use of polyethylene glycols as marker substances and determination in urine by liquid chromatography. J Chromatogr B Analyt Technol Biomed Life Sci. 2003;787(2):271-9.

27. Aldubayyan NA, Castrignanò E, Humphries MA, Dennis I, Archer JRH, Wood DM, et al. A Quantitative LC–MS/MS Method for the Detection of 16 Synthetic Cathinones and 10 Metabolites and Its Application to Suspicious Clinical and Forensic Urine Samples. J Anal Toxicol. 2022;46(2):134-46.