

## MODERN METHODS OF DRUG QUALITY CONTROL IN PHARMACEUTICS

<https://doi.org/10.5281/zenodo.20344570>

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### Abstract

This article provides a systematic analysis of modern analytical and instrumental methods used in pharmaceutical quality control. The quality of a medicinal product is directly linked to its safety and efficacy, and ensuring the unity of these three factors constitutes the primary objective of international pharmaceutical practice. Over the past decade, high-performance liquid chromatography (HPLC), mass spectrometry, near-infrared spectroscopy (NIR), nuclear magnetic resonance (NMR), and real-time monitoring technologies have been widely implemented in manufacturing processes. The article also discusses the regulatory foundations of quality control within the frameworks of ICH, USP, EP, and the State Pharmacopoeia, the concept of Process Analytical Technology (PAT), and the impact of digital transformation on quality control. The findings demonstrate that the optimal combination of analytical methods and continuous process monitoring represents the most effective approach to ensuring consistent drug quality.

### Keywords

quality control, HPLC, mass spectrometry, NIR spectroscopy, NMR, Process Analytical Technology (PAT), ICH guidelines, GMP, pharmacopoeial analysis, real-time monitoring, medicinal product, analytical validation.

### Introduction

Drug quality control is one of the most critical and responsible fields within the pharmaceutical industry. A series of tragic events throughout history the sulfanilamide elixir disaster of 1937 and the thalidomide scandal of the 1950s-1960s vividly demonstrated the severe consequences of the absence of a rigorous safety and quality control system for medicinal products. Following these incidents, national and international regulatory organizations the FDA (Food and Drug Administration) in the United States, the EMA (European Medicines Agency) in Europe, and the ICH (International Council for Harmonisation) at the global level undertook the development of robust legal and technical frameworks. Today, pharmaceutical manufacturing is conducted in accordance with Good Manufacturing Practice (GMP) requirements, and quality control encompasses all stages of production from raw materials through to the release of the finished product to market. Rapid advances in analytical chemistry and instrumentation have made it possible to obtain remarkably precise and rapid information

regarding the composition, purity, bioavailability, and stability of medicinal products to a degree previously unimaginable. This article provides a comprehensive examination of these modern methods and their role in pharmaceutical practice.

### **Main body**

Among the analytical methods that form the foundation of pharmaceutical quality control, high-performance liquid chromatography (HPLC) is currently recognized as the most widely used and versatile technique. HPLC enables the simultaneous determination of the quantitative composition of a drug substance, its impurities and degradation products, as well as the ratio between various chemical forms. The method is employed at an industrial scale due to its high sensitivity, reproducibility, and capacity for automation. In addition, liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) is capable of delivering accurate results at nanogram and picogram concentration levels, making it particularly valuable for measuring drug concentrations in biological matrices (blood, urine, tissues) and for the structural characterization of novel drug substances. The sensitivity of this method, situated at the intersection of analytical chemistry and pharmaceutical manufacturing, enables the detection of modern drug impurities at the nanomolar level a capability of great value in assessing impurity thresholds as defined by ICH Q3A/Q3B guidelines.

Gas chromatography (GC) and its combination with a mass spectrometric detector (GC-MS) are employed to monitor residual solvents, volatile organic impurities, and aromatic compounds in medicinal products. The ICH Q3C guideline defines the permissible limits for residual solvents, and GC-MS has become the standard tool for determining their compliance or non-compliance with pharmacopoeial norms. Infrared spectroscopy, and in particular its near-infrared variant (NIR Near-Infrared Spectroscopy), has attracted considerable attention in recent years as a technology that has effectively migrated "from the quality control laboratory to the production floor." The primary advantage of NIR spectroscopy lies in its ability to analyze samples without any prior preparation, directly through packaging that is, it can determine the composition, density, and moisture content of a tablet or capsule within seconds without destroying the sample. This characteristic makes it ideal for full in-line monitoring during manufacturing.

Nuclear magnetic resonance (NMR) spectroscopy occupies a unique position in the structural characterization of drug substances and, through solid-state NMR, in the identification of polymorphic forms. Since each polymorphic form of a drug molecule possesses distinct solubility and bioavailability characteristics, distinguishing between the various polymorphic forms of compounds such as carbamazepine, indinavir, or ranitidine may be of significant clinical importance. In this regard, NMR, alongside X-ray powder diffraction (XRPD), is considered one of the most reliable methods available. Various elemental analysis techniques are also applied in quality control: inductively coupled plasma mass spectrometry (ICP-MS)

enables the detection of heavy metal impurities lead, cadmium, mercury, arsenic in medicinal products at concentrations below 1 ppb. The ICH Q3D guideline establishes permitted daily exposure (PDE) limits for elemental impurities and has recognized ICP-MS as the primary method for their evaluation.

The Process Analytical Technology (PAT) concept was formally announced by the U.S. FDA in 2004 and is characterized as a technology that "controls" pharmaceutical manufacturing. PAT essentially encompasses a system for the real-time measurement, analysis, and control of the manufacturing process that is, analytical instruments are directly integrated with the production line. This approach signifies a shift from a finished-product testing strategy to a process control strategy. Raman spectroscopy, NIR sensors, or online HPLC modules embedded in the production line under a PAT framework continuously monitor product quality in each batch, with the capability to immediately alert the operator or automatically correct the process upon detection of any deviation. Leading pharmaceutical companies such as AstraZeneca, Novartis, and Pfizer are actively implementing PAT-based manufacturing, simultaneously achieving the goals of improving product quality, reducing waste, and increasing economic efficiency.

Quality control of biological products monoclonal antibodies, recombinant proteins, and gene therapy products requires considerably more complex procedures than those applicable to small-molecule chemical drugs. Specialized analytical methods are essential in this field: ELISA and surface plasmon resonance (SPR) for measuring biological activity; high-resolution mass spectrometry for characterizing protein glycosylation; and dynamic light scattering (DLS) for assessing nanostructures and aggregation. Both the EMA and FDA require proof of analytical similarity for biological products, making the conduct of an extensive array of analytical tests mandatory in the registration of biosimilars.

The integration of digital technologies and artificial intelligence into quality control is heralding the next wave of revolutionary change. Machine learning algorithms are being applied to analyze large-scale databases of spectroscopic and chromatographic data, enabling the early detection of quality-related deviations as well as the differentiation between authentic and counterfeit medicinal products. Computer vision technology is being implemented for the fully automated inspection of visual defects in tablets, capsules, and injectable dosage forms, proving to be considerably more reliable and faster than manual human inspection. The application of blockchain technology in the pharmaceutical supply chain serves to prevent counterfeit medicinal products from entering the market: the entire lifecycle of each product batch is recorded in a tamper-proof digital ledger.

### **Conclusion**

Quality control of medicinal products in pharmaceuticals is not merely a matter of compliance with strict regulatory requirements, but an ethical responsibility toward the protection of public health. Modern analytical methods HPLC, LC-MS/MS, NIR, NMR, ICP-MS, and others complement one another to provide a

comprehensive characterization of the chemical, physical, and biological properties of a medicinal product. Process analytics based on the PAT concept not only enables real-time quality monitoring during manufacturing but also enhances economic efficiency. The rapid development of biological products is placing new demands on analytical science, and scientific and technological progress in this area shows no signs of slowing. The integration of artificial intelligence, digital monitoring, and blockchain technologies into quality control will make the pharmaceutical industry increasingly transparent, efficient, and reliable in the years to come. The study and practical implementation of these modern approaches are likewise urgent and indispensable tasks for the development of Uzbekistan's pharmaceutical industry and its alignment with international standards.

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