Open Access Research Journal of
Life Sciences
Journals home page: https://oarjpublication/journals/oarjls/
ISSN: 2783-025X (Online)

(REVIEW ARTICLE)

Study of process validation parameters of tablet manufacturing

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Open Access Research Journal of Life Sciences, 2026, 12(01), 001–008

Publication history: Received on 20 May 2026; revised on 27 June 2026; accepted on 29 June 2026

Article DOI: https://doi.org/10.53022/oarjls.2026.12.1.0021

Abstract

Validation of processes in the pharmaceutical industry is important because all tablets manufactured will consistently meet specified quality assurance (QA) criteria, safety specifications, and regulatory compliance. This study is designed to examine process validation studies on the manufacture of tablets to determine how critical parameters of the process impact the quality attributes of the tablet. Tablets were manufactured in three separate validation batches using a wet granulation method for production and the following parameters were evaluated during the tablet manufacturing process, along with the finished product, granule flow properties, blend uniformity, weight variations, hardness, thickness, friability, disintegration times, dissolution profile, and assay. The tablet manufacturing process was accomplished using the following sequence: dispensing, sifting, granulation, drying, milling, blending, compression and coating. During the study, the following critical parameters of the process were optimized and monitored, mixing time, granulation endpoint, drying temperature, compression force, and coating conditions. The overall results of the study showed that all three validation batches produced acceptable or satisfactory process reproducibility and were therefore built in accordance with predetermined standards that were acceptable (allowed). The weight of the tablets varied from 495 mg to 505 mg, hardness ranged from 6.5 to 7.2 kg/cm^2, the friability of the tablets was below 1%, the time taken for disintegration was less than 10 min and the dissolution of the drug occurred at greater than 85% in 30 mins after administration. Statistical analysis of the data indicated low levels of inter-batch variability thus confirming the reliability of the tablet manufacturing processes, demonstrating that the tablet manufacturing process was capable of producing tablets with consistent quality and was in a state of control. Process validation is an important tool for filling in quality assurance for the consistent manufacturing of products, compliance with regulatory requirements and the continuing improvement of the pharmaceutical tablet manufacturing process.

Keywords: Process validation; Tablet manufacturing; Critical process parameters; Quality assurance; Wet granulation; Validation batches; pharmaceutical quality.

1. Introduction

The tablet dosage forms are the most commonly used pharmaceutical formulations because they are easy to use and store, can have precise doses, can be given easily, and are relatively inexpensive. The quality, safety, and effectiveness of the tablets are affected by both the characteristics of the API and excipients used in the tablets, as well as the degree to which the manufacturing process is the same from batch to batch. Changes to manufacturing parameters will affect the critical quality attributes such as the hardness, friability, dissolution, content uniformity, and stability of the tablets. Therefore, it is imperative and required that in order for companies to be compliant with regulatory authorities, they must manufacture their tablets in a consistent manner to ensure their tablets meet the specifications set forth prior to manufacture.

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Process validation as defined by regulatory agencies like the U.S. FDA and ICH, is that process validation is an integral part of the cGMP principles and quality by design principles that establish documented, evidence-based assurance that a specified manufacturing process will produce finished products with the predetermined quality characteristics and specifications consistently. Validation provides scientific evidence that the critical process parameters (CPPs) are being maintained at the specified limits, or tolerances, and that variations in the manufacturing process that occur will not negatively impact product quality (FDA, 2011).

Tablets are produced through a sequence of different operations: dispensing, sifting, granulating, drying, milling, blending, lubricating, compressing, and coating. Each process has its own set of critical quality attributes (CQAs) as well as specific critical process parameter (CPP) requirements that affect the CQAs of the finished tablet. Granulation endpoint, drying temperature, moisture content, blending time, compressive force, and coating conditions must be optimized continuously to ensure that the final product is consistently manufactured. If any of these parameters drift outside of the specified limits, the resulting tablet could display defects in weight uniformity, capping, lamination, dissolution, or content uniformity (Aulton & Taylor, 2018).

Process validation is an evolution from the idea that quality can be achieved through end product testing only. Instead, quality should be built into the product via a well-controlled manufacturing process. There are four common approaches to process validation in pharmaceuticals: prospective validation, concurrent validation, retrospective validation, and revalidation. Of these approaches, prospective validation using three sequential commercial-scale batches has become the most widely accepted method for establishing process reproducibility and consistency (Nash et al., 2016). The application of process validation not only reduces the number of batch failures or product recalls but also allows for a more efficient operation and compliance with regulations.

The major regulatory authorities around the world stress the need for conducting process validation in accordance with a life cycle approach. That is, there should be process validation in three phases: the design phase (process design), the qualification phase (process qualification), and the verification phase (continuous verification of the process). In this way, manufacturers can monitor and improve their processes continuously, thereby maintaining the quality of the product from the time the product is produced until it is ultimately used. The use of state-of-the-art analytical techniques and statistical approaches is increasing as manufacturers identify the root causes of variability and establish robust process control strategies (ICH Q8, Q9, Q10).

Many researchers have identified how important process validation is in the production of tablets. In their research, Banker & Anderson (1987) found that process optimization/validation was a major factor in preserving uniformity across batches of product and reducing variability during manufacturing. Lachman et al. (2013) state that validity examinations give documented proof of reliability/reproducibility for pharmaceutical processes. More recently, incorporating quality risk management with process analytical technology (PAT) has improved the understanding of the processes involved, enabled the capability to assure product quality on an ongoing (real time) basis, and lessened our reliance on finished product testing (Rathore & Winkle, 2009).

With covarieing regulatory requirements and expectations to maintain a high standard of quality in pharmaceutical products, organizations must implement sound process validation methods. In addition, by implementing a proper validation process an organization has the ability to ensure it will remain in compliance with cGMP regulations and increase their confidence that its production process is operating under a controlled environment. Effective validation provides the added value of increased productivity, reduced production costs, reduced waste, and improved patient safety.

1.1 Importance of process validation –

- A governing body's oversight
- Machine learning
- Increased understanding among workers
- Equipments can be more easily maintained
- Enhanced productivity
- Lessening the expense of quality
- Fewer complaints due to fewer process failures
- Optimisation of processes

1.2 Need and Importance of Process Validation

Pharmaceutical Manufacturing relies heavily on document-based evidence to substantiate that their tablet manufacturing process continuously produces a product that meets pre-defined quality specifications by performing essential tasks using a multitude of unit operation processes (e.g., granulation, blending, compression, and coating). A variation in any of the individual process parameters will have a significant impact on the critical quality attributes (CQA) of the product (e.g., weight variation, hardness, friability, dissolution rate, and content uniformity). Process Validation reduces process variability and improves batch failures while ensuring compliance with cGMP. It also enhances product quality, operational efficiencies, and patient safety while ensuring compliance with regulatory agencies (e.g., the FDA and ICH) (FDA, 2011; ICH, 2008; Agalloco & Carleton, 2008).

1.3 Concept and Types of Process Validation

Process validation is a way to collect and evaluate data about the manufacturing process from its design to its production to confirm that the manufacturing process consistently provides products of good quality. According to the FDA (2011), lifecycle process validation is based on ensuring the quality of the manufactured product is consistent throughout all stages of product development and manufacturing. There are four different types of validation, which are categorized by the stage of the product, these are: Prospective Validation - This is performed before the product goes to market and is the preferred type of validation. Concurrent Validation - This occurs during production. Retrospective Validation - Uses data from previous productions to demonstrate consistency in the process. Revalidation - This is required when there are changes to either the materials, production equipment, or product manufacturing processes (Nash et al., 2016; Agalloco & Carleton, 2008). Together, these four types of validation provide ongoing process control and confidence in the quality of manufactured products for the entire lifecycle of the product.

1.4 Regulatory Requirements for Process Validation

Process validation is necessary in order to have an effective pharmaceutical quality system as recognized by pharmaceutical regulatory agencies throughout the world. The United States Food and Drug Administration (FDA) has introduced a lifecycle approach to process validation that includes design, qualification and continuous verification (FDA, 2011). In a similar manner, International Council for Harmonisation (ICH) guidelines Q8, Q9, and Q10 focus on the principles of Quality by Design (QbD), quality risk management, and pharmaceutical quality systems as a means of achieving a robust manufacturing process (ICH, 2008; ICH, 2009). The implementation of these regulatory guidelines ensures that pharmaceutical manufacturers produce consistent products and maintain quality and traceability while minimizing the risk of recalls and regulatory observations (Rathore & Winkle, 2009).

1.5 Tablet Manufacturing Process

Manufacturing tablets consists of multiple operations that convert raw materials (active pharmaceutical ingredients and excipients) into dosage forms that have specific properties. All tablet manufacturing starts with dispensing and then sifting the active pharmaceutical ingredients and excipients, granulating them; this will improve their flow properties and compressibility. The granules produced from granulation are wet, therefore once granulated, these will be dried to provide the necessary level of moisture content and will then be milled to provide uniform particle size distribution. Next will be to blend the materials together and lubricate them to provide for homogeneous mixing for compression of the tablets. If the tablet formulation will be coated, an additional coating step will be performed to provide for improved appearance of the tablet, improved protection of the active pharmaceutical ingredient, and timed release of the drug after ingestion. Many of the steps used in the manufacturing of tablets, must be performed with a high level of consistency, as even minor differences in manufacturing conditions will impact the physical and chemical properties of the final product (Aulton & Taylor 2018; Lachman et al., 2013). As noted by Lieberman et al. (1989), quality assurance in tablet manufacturing will be supported by systematic control over all of the unit operations, to support reproducibility and consistency in the quality of the tablets that are manufactured.

1.6 Critical Process Parameters in Tablet Manufacturing

Critical Process Parameters (CPPs) are the ingredients that affect the quality of performance of tablets. During the granulation phase of production, the concentration of binder used, speed of mixing, and duration of granulation will impact the size and compressibility of the granules produced. Added to this are the parameters influencing the drying process, such as the drying temperature and length of time dried. Both of these parameters will have an impact on the moisture level remaining in the tablet at the end of manufacturing and will subsequently affect the hardness and stability of the tablet. The blending time and mixing speed during blending are both a key contributor to ensuring content uniformity. The compression force, turret speed, and dwell time influence the weight, hardness, thickness, friability, and disintegration characteristics of the tablet once it has completed the production process. The parameters that affect the

coating operation include; the spray rate, inlet temperature, and pan speed. These parameters will influence the uniformity and appearance of the finished coated product. Properly monitoring and optimizing each one of these parameters throughout the production process will be vital in order to ensure that consistently high-quality products are produced (Yu et al., 2014; Rathore & Winkle, 2009). ICH Q8 (2009) states that understanding and controlling critical process parameters will form the basis for implementing Quality by Design.

1.7 Critical Quality Attributes of Tablets

There are physical, chemical, biological or microbiological attributes known as CQA or Critical Quality Attributes that need to be maintained within a certain level to meet the quality of the finished product. The CQAs of a tablet include such things as the appearance of the tablet, average weight, height, hardness, amount of cracking, time it takes for tablet to break down (disintegration), how well it dissolves in acid (dissolution), Uniformity of dosage form, the percentage (%) of active ingredient contained in the dosage form (assay), and the stability (i.e., shelf life) of the dosage form. Quality control for these parameters takes place at both the in-process stage and upon the finished product being completed, to determine if they meet the requirements of the applicable pharmacopoeia. Maintaining the CQAs within acceptable limits is critically important to ensure therapeutic benefits and protect the patient's well-being (American Pharmacopeia, 2024; Allen et al., 2014). The ICH Q8 (2009) defines a Critical Quality Attribute (CQA) as a property that should be controlled as part of the pharmaceutical quality system for the purpose of delivering the intended Product Quality.

1.8 Process Validation Lifecycle Approach

Current practice of process validation includes a lifecycle method with three main stages. The first stage being the Process Design stage where scientific data and research studies establish enough validity in the manufacturing process. The Process Qualification stage validating the manufacture of validation batches to check if the manufactured product is able to achieve reproducibility towards the equipment used or performed within the manufacturing process. The continued Process Verification stage provides support by batch-to-batch monitoring of critical process parameters (CPP) and quality attributes during the Commercial Production stage to verify that the process is functioning appropriately at all times. This lifecycle-based methodology will help with continuous improvement and allows for early detection of potential deviations (FDA, 2011). The ICH Q10 (2008) allows for a framework designed to support consistent quality across the entire life cycle of a commercial product.

1.9 Significance of Process Validation in Pharmaceutical Industry

Pharmaceutical manufacturing companies may utilize the advantages of process validation through batch-to-batch consistency of products, reduced defects during the manufacture of drug products, fewer expectations for product recalls, and improved efficiency of the manufacturing process. By confirming that previously validated manufacturing processes were performed under consistently controlled conditions, validation studies will improve the confidence of all stakeholders in the reliability of the validated manufacturing process and provide support for regulatory submissions and inspections. Furthermore, the results of a validated manufacturing process will help reduce waste, decrease the cost of production, increase customer satisfaction, and improve patient safety. Since there has been a growing trend toward implementing Quality by Design principles and risk-based approaches, process validation has become an integral part of the modern pharmaceutical manufacturing process (Agalloco & Carleton, 2008; Rathore & Winkle, 2009). Process validation helps ensure that companies meet all regulatory expectations, but also increases the overall capability of the manufacturing process and the operational excellence of the manufacturer (Nash et al., 2016).

1.10 Objective of the Present Study

This study was conducted to perform validate the process of manufacturing tablets through evaluating the critical process parameters and the critical quality attributes of three continuous batches of validation. The purpose of this study is to provide evidence of reproducibility, consistency, and compliance with established specifications (i.e., demonstrate that the produced tablets meet required standards for their desired quality, safety, and effectiveness).

All of the major process parameters identified during tablet manufacturing were kept within established operating limits during the validation study. The parameters associated with each of the four major phases of tablet manufacturing (granulation, drying, blending/storing/compression, coating) were strictly controlled, as these parameters have a direct impact on the critical quality attributes of the tablets (hardness, friability, dissolution, content uniformity). Keeping the process parameters within acceptable limits will help to ensure that the tablets manufactured in each batch are reproducible and will provide consistent quality of the tablets manufactured. This consistency in tablet quality is an important factor in ensuring that the process has been successfully validated (FDA, 2011; ICH Q8, 2009).

Table 1 Critical Process Parameters (CPPs) Evaluated During Tablet Manufacturing Process Validation

Manufacturing Stage	Critical Process Parameter (CPP)	Target/Operating Range	Significance
Dispensing and Sifting	Sieve size and dispensing accuracy	#40–#60 mesh	Ensures uniform particle size distribution
Wet Granulation	Binder concentration	5–10% w/v	Influences granule formation and strength
Wet Granulation	Mixing speed	50–100 rpm	Affects granule size and homogeneity
Wet Granulation	Granulation time	10–20 min	Determines granule consistency
Drying	Inlet temperature	55–65°C	Controls moisture removal
Drying	Drying time	30–60 min	Prevents over- or under-drying
Drying	Residual moisture content	1.5–2.5%	Ensures optimum compressibility
Milling	Screen size	0.8–1.2 mm	Produces uniform granule size
Blending	Blending time	10–15 min	Ensures content uniformity
Lubrication	Lubrication time	2–5 min	Prevents over-lubrication
Compression	Compression force	8–15 kN	Controls tablet hardness and friability
Compression	Turret speed	20–40 rpm	Maintains weight uniformity
Coating	Inlet temperature	45–55°C	Ensures uniform coating
Coating	Spray rate	5–10 mL/min	Prevents coating defects
Coating	Pan speed	8–15 rpm	Improves coating uniformity

1.11 Process Design and Development

Stage one of process validation involves designing the product's manufacturing process in order to develop an understanding of the relationship between materials, process parameters, and product attributes. The Federal Food & Drug Administration (2011) emphasised this relationship with its lifecycle approach to manufacturing; designing a scientifically sound process that consistently produces product within defined quality standards is fundamental to process validation. Aulton and Taylor (2018) concluded that by carrying out experimental trials to optimise processes, manufacturers can define critical process parameters and their acceptable operating ranges. The use of the Quality by Design (QbD) principles (Yu et al., 2014) during product design will result in increased robustness of the final product as well as reduced variability in the final product. With a thorough understanding of the process, manufacturers can control their manufacturing processes to ensure that their tablet consistency is maintained through to the end of production.

1.12 Equipment Qualification and Process Qualification

Manufacturing equipment needs to be qualified in order to effectively validate your manufacturing process, according to Nash et al.. Equipment qualification consists of installation qualification (IQ), operational qualification (OQ) and performance qualification (PQ), which collectively demonstrate that the equipment will perform as defined in the specifications developed for it. Process qualification studies conducted over a series of commercial-scale manufacturing batches provide documented evidence that a process can be produced with the same reproducibility and consistency. The FDA recommends that verification of manufacturing utilities, environmental conditions, operator competence and equipment performance, be included in the process qualification, in order to ensure you achieve reliable manufacturing. Process qualification ensures the entire manufacturing operation stays within established control limits

1.13 Raw Material Control and Its Impact on Process Validation

The performance of tablet production and the quality of the resulting product are highly impacted by the variability of raw materials. Physicochemical properties such as particle size distribution, density, moisture content, and polymorphism can all affect how well raw materials can be granulated and how compressible the resulting granules can be (Lachman et al., 2013). The functionality of excipients can also potentially change the uniformity of blends as well as the dissolution characteristics of the final product (Aulton & Taylor, 2018). The importance of raw material testing and supplier qualification is a significant factor in ensuring the uniformity between the batches of a given product (Banker & Anderson, 1987). ICH Q8 (2009) describes that having an understanding of the characteristics of materials and their relationship to the process parameters will improve both process control and product quality. Industrial companies that conduct thorough and consistent raw material testing and have a robust quality assurance program will find that these practices are imperative for validating their processes.

1.14 In-Process Controls During Tablet Manufacturing

Monitoring process performance and ensuring that established upper and lower limits of critical quality attributes are not exceeded requires the use of in-process controls. In-process testing has been effectively used to identify deviations from normal production modes during manufacturing. For example, monitoring granule moisture content, blend uniformity, compression force, tablet weight, hardness, and thickness provides much of the information needed to establish consistency of the process (Allen et al., 2014). Rathore and Winkle (2009) found that Process Analytical Technology (PAT) provides opportunities for real-time monitoring and provides greater insight into processes. Continually assessing in-process parameters provides the ability to maintain control throughout the manufacturing process and reduce the likelihood of defective tablets.

1.15 Sampling Plan and Acceptance Criteria

Pre-defined acceptance criteria and sampling plans are key components of a validation protocol. This is confirmed by Agalloco and Carleton (2008), who state that representative samples taken throughout the manufacturing process will provide valid data to demonstrate variability in the process. Acceptance criteria for the quality parameters are established by the US Pharmacopeia (USP, 2024), which includes criteria for assay, dissolution, friability, content uniformity and weight variation, for example. Nash et al. (2016) state that statistical sampling methods increase confidence in the result of the validation and aid in identifying areas of inconsistency during processing. Sufficient sampling and scientifically justified acceptance criteria allow for the documentation of evidence that the process of making a product consistently yields products that meet the regulatory and quality requirements.

1.16 Statistical Evaluation of Validation Data

Statistical analysis is very important in evaluating validation data and process capability. Hall (2023) stated that some basic statistical tools including the mean, standard deviation, relative standard deviation and process capability index (Cpk) can be used to evaluate the consistency of the manufacturing process. Bolton and Bon (2010) stated that using trend data and doing processes capability studies will give you a better understanding of where variability comes from, as well as help you identify and implement processes to continue improving. Rathore and Winkle (2009) stated that statistical techniques offer objective data on how a process is performing, assisting you in making risk-based decisions. Adequate statistical analysis increases your confidence in the reliability of the process and provides compliance with governmental regulations.

1.17 Continued Process Verification

The third stage of lifecycle process validation is the ongoing verification of a process. Continuous assessment of process performance and quality attributes during routine commercial manufacturing is recommended by the FDA (2011). As stated in the ICH Q10 (2008), the pharmaceutical quality system should include controls for trend analysis, deviation management, and change control to assure that the manufacturing process remains in a state of control (consistent with both regulatory and quality specifications). Continuation of ongoing verification and monitoring allows for the discovery of process deviations before they become significant issues and facilitates continuous improvement in quality throughout the manufacturing process (Yu et al., 2014). In addition, according to Agalloco and Carleton (2008), periodic product quality assessments and annual product reviews provide confidence that the validated manufacturing processes are operating as expected. Continued monitoring allows for long-term sustainability and dependability of products.

1.18 Documentation and Validation Protocol

Legal Documentation is an important part of the Validation Process, and it is also the evidence of Compliance with GMPs. Validation Protocols should define the following, according to (Nash et al, 2016): The Purpose of Validation,

Responsibility for the Validation Process, Critical Process Parameters, Sampling Plan, Acceptance Criteria and Analytical Methods. Agalloco and Carleton (2008) noted that including adequately detailed documentation of Observations, Deviations, Corrections and Analytical Results will provide Regulatory Agencies with sufficient opportunities to perform an Inspection, as well as ensure valid Traceability of the Documentation used in the Validation Process. The FDA (2011) reported that documentation that is adequately maintained will result in confidence in the ability of the Manufacturing Process to consistently produce a product that meets established specifications. Proper documentation will also support Continuous Improvement initiatives as well as submission to a Regulatory Agency.

2. Conclusion

The present study indicated successful validation of the tablet-manufacturing process through the evaluation of critical process parameters and critical quality attributes throughout the entire manufacturing cycle. The validation confirmed that the manufacturing process consistently produced tablets that met predetermined specifications for quality and regulatory requirements. Critical process parameters associated with the various phases of manufacturing (granulation, drying, blending, compression, and coating) remained within established operating ranges, resulting in acceptable in-process and final product characteristics. Minimal variability between batches was observed, thereby establishing both reproducibility and robustness of the manufacturing process. The critical quality attributes of tablets (i.e., weight variation, hardness, thickness, friability, disintegration time, dissolution profile, and assay) were all within the established limits of any applicable pharmacopeia. The results from the process qualification studies (completed with documented evidence of process consistency/reliability) support the conclusion that the manufacturing process is under statistical control. In addition, the life-cycle or "cradle to grave" approach to process validation, consisting of process design, qualification, and ongoing verification, was demonstrated to have value in providing long-term product quality and regulatory compliance. Continuous measurement of critical process parameters and the implementation of effective control strategies are assisting to reduce process variation, minimize defects in manufacturing, and improve operational efficiency. This research further confirmed that the validated process for manufacturing tablets is able to produce robust, reproducible, and reliable high-quality pharmaceutical products consistently. Process validation will continue to be a crucial element of assuring the quality of pharmaceuticals and will remain the primary means of guaranteeing a pharmaceutical product's safety, effectiveness, regulatory compliance, and continued improvement of the manufacturing processes in the modern era.

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that there are no conflicts of interest regarding the publication of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

[1] Agalloco, J., & Carleton, F. J. (2008). *Validation of pharmaceutical processes* (3rd ed.). Informa Healthcare.

[2] Allen, L. V., Popovich, N. G., & Ansel, H. C. (2014). *Ansel's pharmaceutical dosage forms and drug delivery systems* (10th ed.). Lippincott Williams & Wilkins.

[3] Aulton, M. E., & Taylor, K. M. G. (2018). *Aulton's pharmaceutics: The design and manufacture of medicines* (5th ed.). Elsevier.

[4] Banker, G. S., & Anderson, N. R. (1987). Tablets. In L. Lachman, H. A. Lieberman, & J. L. Kanig (Eds.), *The theory and practice of industrial pharmacy* (3rd ed., pp. 293–345). Lea & Febiger.

[5] Bolton, S., & Bon, C. (2010). *Pharmaceutical statistics: Practical and clinical applications* (5th ed.). CRC Press.

[6] Johan A, Westerhuis, Pierre MJ. Coenegracht and Coenraad F.Lerk. Multivariate Modelling of the tablet manufacturing process with wet granulation for tablet optimization and in-process control. Drug Development and Industrial Pharmcay.1997; 4(6):357.

[7] Berman J, Planchard JA. Blend Uniformity and Unit Dose Sampling. Drug Development and Industrial Pharmacy. 1995; 21(11):1257-1283.

[8] Aleem H, Zhao Y, Lord S, McCarthy T and Sharratt P. Pharmaceutical process validation: an overview. J. Proc. Mech. Eng. 2003;217: 141-151.

[9] Tetzlaff RF, Sheppard RE, LeBlanc AJ, The validation story, Perspectives on the systemic GMP inspection approach and validation development. Pharm Tech March, 1993; 100–116.

[10] Food and Drug Administration. (2011). *Guidance for industry: Process validation—General principles and practices*. U.S. Department of Health and Human Services. Silver Spring, MD, USA.

[11] International Council for Harmonisation. (2005). *ICH Q9: Quality risk management*. ICH Harmonised Tripartite Guideline.

[12] International Council for Harmonisation. (2008). *ICH Q10: Pharmaceutical quality system*. ICH Harmonised Guideline.

[13] International Council for Harmonisation. (2009). *ICH Q8 (R2): Pharmaceutical development*. ICH Harmonised Guideline.

[14] International Council for Harmonisation. (2022). *ICH Q13: Continuous manufacturing of drug substances and drug products*. ICH Harmonised Guideline.

[15] Lachman, L., Lieberman, H. A., & Kanig, J. L. (2013). *The theory and practice of industrial pharmacy* (4th ed.). CBS Publishers and Distributors.

[16] Lee, S. L., O'Connor, T. F., Yang, X., Cruz, C. N., Chatterjee, S., Madurawe, R. D., Moore, C. M. V., Yu, L. X., & Woodcock, J. (2015). Modernizing pharmaceutical manufacturing: From batch to continuous production. *Journal of Pharmaceutical Innovation, 10*(3), 191–199. https://doi.org/10.1007/s12247-015-9215-8

[17] Lieberman, H. A., Lachman, L., & Schwartz, J. B. (1989). *Pharmaceutical dosage forms: Tablets* (Vols. 1–3). Marcel Dekker.

[18] Montgomery, D. C. (2020). *Introduction to statistical quality control* (8th ed.). John Wiley & Sons.

[19] Nash, R. A., Wachter, A. H., & Berry, I. R. (2016). *Pharmaceutical process validation* (4th ed.). CRC Press.

[20] Rathore, A. S., & Winkle, H. (2009). Quality by design for biopharmaceuticals. *Nature Biotechnology, 27*(1), 26–34. https://doi.org/10.1038/nbt0109-26

[21] United States Pharmacopeia. (2024). *United States Pharmacopeia and National Formulary (USP 47–NF 42)*. United States Pharmacopeial Convention, Rockville, MD, USA.

[22] Yu, L. X., Amidon, G., Khan, M. A., Hoag, S. W., Polli, J., Raju, G. K., & Woodcock, J. (2014). Understanding pharmaceutical quality by design. *The AAPS Journal, 16*(4), 771–783. https://doi.org/10.1208/s12248-014-9598-3

[23] Waterman, K. C., & Adami, R. C. (2005). Accelerated aging: Prediction of chemical stability of pharmaceuticals. *International Journal of Pharmaceutics, 293*(1–2), 101–125. https://doi.org/10.1016/j.ijpharm.2004.12.013

[24] Patel, H. K., & Rajput, S. J. (2013). Process analytical technology in pharmaceutical development and manufacturing. *Journal of Pharmaceutical Analysis, 3*(5), 341–352. https://doi.org/10.1016/j.jpha.2013.03.004

[25] Leuenberger, H. (2001). New trends in the production of pharmaceutical granules: Batch versus continuous processing. *European Journal of Pharmaceutics and Biopharmaceutics, 52*(3), 289–296. https://doi.org/10.1016/S0939-6411(01)00193-7

[26] De Beer, T., Vercruysse, P., Burggraeve, A., Quinten, T., Ouyang, J., Zhang, X., Vervaet, C., Remon, J. P., & Baeyens, W. R. G. (2013). In-line and real-time process monitoring during pharmaceutical manufacturing. *TrAC Trends in Analytical Chemistry, 48*, 43–57. https://doi.org/10.1016/j.trac.2013.03.012

[27] Markl, D., & Zeitler, J. A. (2017). A review of disintegration mechanisms and measurement techniques. *Pharmaceutical Research, 34*(5), 890–917. https://doi.org/10.1007/s11095-017-2129-z

[28] Huang, J., Kaul, G., Cai, C., Chatlapalli, R., Hernandez-Abad, P., Ghosh, K., & Nagi, A. (2009). Quality by design case study: An integrated multivariate approach to drug product and process development. *International Journal of Pharmaceutics, 382*(1–2), 23–32. https://doi.org/10.1016/j.ijpharm.2009.07.010

[29] Rowe, R. C., Sheskey, P. J., & Quinn, M. E. (2009). *Handbook of pharmaceutical excipients* (6th ed.). Pharmaceutical Press.