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3D Printing in Personalized Medicine: A Pharmaceutics Perspective

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Abstract

The technology and ability of 3D printing have transformed the sphere of personalized medicine, allowing manufacturing of the customized drug delivery to address diverse needs of a specific patient with regard to physiologic, pharmacokinetically, and therapeutically oriented preferences. This review generates a pharmaceutics-oriented view of the use of novel 3D printing technologies such as the Fused Deposition Modeling (FDM), Stereolithography (SLA), and inkjet printing in the development of personalized dosage forms comprising of oral tablets, implants, microneedles, and transdermal patches. Animal model experimental preclinical research, such as that in rabbits, rats, and mice, has proven the capability of the technologies to perform zero order release and controlled release of drugs, the capability to release multiple drugs using staggered kinetics, and to provide site-specific or minimally invasive delivery. The results support the benefits of structural flexibility, programmable release profiles, and improved patient adherence, especially in the case of complex conditions and important vulnerable groups of patients (pediatric and geriatric). But there are still some impediments on the way to clinical application, such as thermal instability of labile drugs, biocompatibility issues, poor reproducibility in device operation, a lack of standard regulatory frameworks, and insufficient long-term safety documentation. The review ends with a purpose of identifying the future research and development directions that include the necessity of the use of superior biocompatible materials, inherent hybrid printing methods and scalability in production, as well as interdisciplinary cooperation to enable clinical translation and redefine the future of personalized drug treatment.

Key Words:

3D Printing, Personalised Medicine, Drug Delivery Systems, FDM, SLA, Inkjet Printing, Polypharmacy, Preclinical Studies

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1. INTRODUCTION

Personalized medicine has also seen the revolution in the shape of 3D printing also known as additive manufacturing that can be used to achieve optimal customization when using drug delivery systems which can then be used precisely to meet the needs of the individual patients. As opposed to the traditional manufacturing techniques that yield homogeneous forms of dosage, the

3D printing technique enables customization of drug shape and size, dose, and release patterns, all according to physiological and therapeutic needs of a patient. The potential of this creative solution in the cases of variable response to medication, patient adherence, and treatment of complicated conditions involving polypharmacy is enormous. Consequently, 3D printing is also fast being understood to be a revolutionizing instrument in the contemporary pharmaceutics[1].

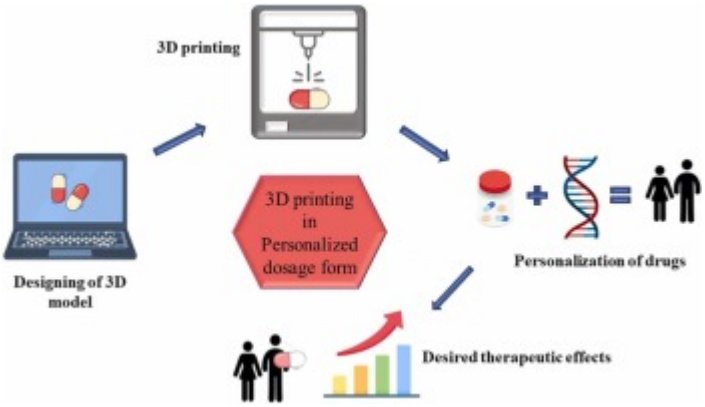

Figure 1: 3D Printing In Personalized Medicine[2]

In the pharmaceutical field, Fused Deposition Modeling (FDM), Stereolithography (SLA), and inkjet printing 3D printing methods have been experimented with toward producing oral tablets, transdermal patches, implants, and microneedle systems. Not only have these platforms provided a capability of generating complex geometries and multi-drug formulations, but they have also allowed the incorporation of responsive materials to facilitate a controlled and targeted drug release. A pioneer of pharmaceutical technology that allows to move to one-on-one therapy, 3D printing is in the process of discovering its further potentials, as preclinical and clinical studies have repeatedly confirmed its effectiveness.

1.1.Background Information and Context

Over the past several years, the pharmaceutical sciences and the technology of 3D printing have, in turn, opened the door to the new age of personalized medicine. The use of traditional drug manufacturing technologies is generally based on the one-size-fits-all approach that does not factor in the inter-individual variations of age, weight, metabolism, genetic composition, and disease progression. 3D printing covers this shortcoming by supplying ready-to-use, patient-specific drug products with tailoro-designed release kinetics and dosage. This technology is flexible enough to produce complex drug delivery systems that were otherwise impossible to produce using the conventional means, which makes it a revolutionary development in the sphere of pharmaceutics[3].

1.2.Objectives of the Review

The key objectives of this review are outlined as follows:

- To evaluate 3D printing technologies in personalized drug delivery.
- To analyze preclinical animal studies on safety and efficacy.
- To examine solutions for controlled release, polypharmacy, and targeted delivery.

- To identify strengths and limitations of 3D printing in pharmaceutics.
- To recommend future research and clinical translation strategies.

1.3.Importance of the Topic

The significance of this subject is that it could be the redefinition of drug development and delivery, making sure that a drug is directed to a specific patient profile, as opposed to a broad population. Individualized medication can greatly contribute to the successful course of treatment, reduce side effects, and increase patient compliance, particularly those with diverse needs, e.g. pediatrics, geriatrics, and chronically ill patients are the ones in need of such special medications. The trend of the healthcare profession is towards more personalized care models and that is why it is necessary to understand how 3D printing will impact pharmaceutics in terms of future research and clinical practice.

2. PRECLINICAL INSIGHTS INTO 3D PRINTED DRUG DELIVERY SYSTEMS

The preclinical stages have been key toward the provision of initial evidence towards the application of 3D printing technologies in drug delivery. The studies that have mostly been conducted on animal model organisms like rabbits, rats, and mice, have methodically examined the efficacy, pharmacokinetics, safety, and mechanical effects of the 3D- printed dosage forms and implants. They have also contributed into making it legit that printing of complex drug formulations that meet individual needs of patients is feasible. The step-wise methods such as fused deposition modeling (FDM), inkjet printing, and stereolithography (SLA) are the main examples of available printing methods as some of them have certain unique beneficial properties regarding the materials to be printed, the structure of the printing, as well as the modification of drug release (e.g. targeted).

Table 1: Summary of Key Studies on 3D Printing in Personalized Medicine

Author(s)	Study Title	Focus Area	Methodology	Key Findings
Araújo et al. (2019)[4]	The digital pharmacies era: How 3D printing technology using fused deposition modeling can become a reality	Fused Deposition Modeling (FDM) in pharmacy	Literature review and conceptual analysis	FDM is feasible for pharmaceutical applications with suitable polymers; integration with digital pharmacy platforms could revolutionize drug dispensing.
Azad et al. (2020)[5]	Polymers for extrusion-based 3D printing of pharmaceuticals: A holistic materials–process perspective	Materials science in pharmaceutical 3D printing	Review of polymer types and printing processes	Identifies and categorizes polymers suitable for extrusion-based 3D printing; emphasizes compatibility

				between materials and processes.
Beer et al. (2021)[6]	Scenarios for 3D printing of personalized medicines—A case study	Personalized medicine via 3D printing	Scenario analysis (case study)	Presents future scenarios showing the transformative potential of 3D printing in clinical pharmacy settings for tailored treatment.
Beer et al. (2023)[7]	Magistral compounding with 3D printing: a promising way to achieve personalized medicine	Compounding and regulatory perspectives	Exploratory research with stakeholder input	Highlights 3D printing as a scalable approach to magistral compounding; identifies regulatory and practical challenges in implementation.

2.1.Zero-Order and Controlled Drug Release Systems

One of the best milestones in this field was the work by Goyanes et al. (2015) who used FDM to print theophylline tablets and tested the same in a rabbit model. These tablets showed a sustained and constant drug release behaviour which was near zero-order kinetics within 24 hours. The findings showed significant decreases in the variability in plasma levels of the product to such an extent that the study results showed a remarkable decrease as compared to the traditional formulations which is of greater importance where a consistent treatment level is needed in chronic conditions such as asthma and COPD. The density, geometry and layer thickness of the printed tablets; the infill density, geometry, and layer thickness of the printed tablets were key factors in the determination of the release rate and are also crucial aspects that are harder to manipulate in conventional manufacturing processes[8].

Conjoint with this, there is another research which had used the same FDM technology to fabricate ibuprofen-loaded tablets in use of timed anti-inflammatory indoctrination in rabbits. The release pattern was matched to circadian rhythms of inflammation proving the capability of 3D printing in administering drugs in rhythm with the biological processes. Such meticulousness of release kinetics made possible merely by structural changes favors the paradigm of personalized medicine in which not only the content of a drug can be tailored to individual patient needs but also the way it is delivered over time.

2.2.Multi-Drug Delivery and Polypharmacy Solutions

The versatility of 3D printing also applies to the composition of a multi-drug system, which is especially important in the case of patients with comorbidities that are characterized by several

drugs in one regimen. SLA-based microneedle arrays with co-encapsulated multiple drugs were realized using Seoane-Via cano et al. (2021). Such microneedles were tested using animal models (rats) to allow the concurrent yet regulated delivery of two active pharmaceutical ingredients (APIs), with little to no cross-interference. Ability of independent control of the release profile of each API in the same dosage form overcomes critical polypharmacy related challenges including drug-drug interactions and adherence-related issues[9].

Also, in preclinical study based on an inkjet printing that aimed at treatment of epilepsy, the design of multilayer tablets consisting of carbamazepine and phenytoin was performed. Independent layers of drugs were incorporated so that drugs could be released in staggered phases. The work also included rat studies that validated the time-dependent delivery of the both agents and resembled the clinical concept, in which timed polytherapy is related to the treatment of seizures. Such researches show the potential of 3D printing to design smart drug delivery systems that can be programmed to implement intricate pharmacology plans.

2.3. Implantable and Transdermal Systems

In addition to use in oral formulations, 3D printing has enabled new concepts in implantable and transdermal delivery systems. An injection with biodegradable, polylactic acid (PLA) made through FDM made localized and sustained delivery of chemotherapeutic drugs into the tumor-bearing mouse models. The drug-releasing performance of the implants was good (working drug release over an extended duration coupled with high regional drug concentrations and low systemic response). There were very substantial therapeutic effects reported by histological analysis and tumor volume analysis that proved the basis of future applications of using targeted delivery in cancer treatment[10].

Microneedle patches that were printed via SLA and other high-resolution technologies were used to discuss transdermal applications. This was coated on the rat skins and their permeability, mechanical performance and histopathological changes were evaluated. The microneedles compared to common hypodermic needles attained effective introspection in transdermal penetration with minimal pain, tissue injury and constant absorption of the drug. These delivery systems are especially promising in the case of vaccines, hormones and peptide drugs which need administration which is effective but is non-invasive.

2.4. Methodological Considerations

Various analytical methods were combined in the preclinical studies to provide a thorough assessment of the work of 3D-printed formulations. PK variables like the maximum concentration (Cmax), time of reaching the peak (Tmax) and the area under the curve (AUC) were carefully determined to the knowledge of absorption characteristics. Imaging methods such as micro-computed tomography (micro-CT), scan electron microscopy (SEM) (micro-CT) and scan electron microscopy (SEM) were used to test structure integrity, distributions of drugs and morphological consistency of the printed constructs. Histopathological tests were done to

determine compatibility of tissue and response to inflammation especially transdermal and implant systems[11].

Also, the aspect of the mechanical properties like the tensile strength, flexibility, and the time of disintegration were examined to make sure that the products made online comply with the pharmaceutical standards of quality. The content uniformity of drugs was followed to tell their homogeneity which is essential in doses accuracy. Nevertheless, these studies turned out to be limited by the fact that the size of used samples was small, the observation periods were limited, and the biocompatibility after the acute stage was not thoroughly tested, limiting their direct transfer to clinical practice[12].

2.5. Strengths and Weaknesses

Strengths

In drug delivery research, 3D printing has been found to offer much usefulness in the preclinical studies, especially in terms of providing a huge degree of control over the rate of drug release, drug dosage, and drug structures. This enables creation of patient-centered treatment that could increase drug compliance levels, diminish prescription frequency, and even help decrease treatment expenses. Some major advantages include the inclusion of multiple active pharmaceutical ingredients (APIs) delivered as a single dosage form whose release profile can be programmed separately to meet the challenges of polypharmacy. Furthermore, the technology facilitates fast experimental design and optimization of formulation through iterations, which may simplify preclinical development. Fused deposition modeling (FDM), stereolithography (SLA), have been shown to be very reliable at providing reproducibility and efficacy toward generating favorable spatial drug distribution, and are thus quite appropriate towards pharmaceutical applications on small scales[13].

Weaknesses

In spite of the good benefits attached, multiple limitations obstruct the use of 3D printing in the delivery of drugs. Thermal and mechanical stresses involved in processes such as fused deposition modeling (FDM) are known to break down sensitive compounds such as peptides and proteins and therefore limits their application. Other challenges are inter-printer variability, lack of regular protocol and questions regarding biocompatibility and toxicity of printable materials, all of which make regulatory approval more difficult. The question of the ability of 3D-printed drug formulations to guarantee scale-up production has not been answered yet, the absence of animal testing results on long-term pharmacodynamics and biocompatibility raises safety issues with developing schemes of clinical translation. Moreover, the develops regulatory regime is not always clear in terms of 3D printed drugs, and plenty of preclinical research conflagration will not have adequate toxicological or metabolic data that it is to be accepted in the approval process. Accessibility is also restricted by their high prices of drug grade printers and resources used in resource tight environments[14].

3. 3D PRINTING APPLICATIONS IN PRECLINICAL DRUG DELIVERY: STRATEGIES AND TARGETS

The revolution made by the 3D printing technologies on pharmaceutical sciences, particularly in the preclinical research on drug delivery, is the ability to manipulate both the architecture of the drug formulation and release behavior. Such innovations allow the researcher to formulate a dose form by targeting pathological goals, anatomical site, pathological model and scientific needs in terms of pharmacokinetics. In rodents, rabbits, and bigger animal-model preclinical studies, 3D printing is providing additional possibilities in creating controlled, site-specific, and multi-drug release patterns approximating human responses, and contributing to translation research. In this section, these applications are grouped by the delivery strategies and the therapeutic targets and critically review methodology, results and issues.

Figure 2: 3D Bioprinting Applications in Drug Delivery and Testing Systems[15]

3.1. Controlled and Sustained Drug Release

- Strategy: The purpose of controlled drug release is that the drug in the plasma remains in a therapeutic range with no fluctuations so common in regular dosing. 3D printing can achieve this by space design dosage forms, changing aspects such as the inner design, surface to volume ratio, shellcore structure and polymer characteristics.
- Technologies and Preclinical Applications: Producing extended-release systems involves use of two technologies known as FDM (Fused Deposition Modeling) and SLA (Stereolithography) which are widely used in the making of extended-release systems. As an example, Goyanes et al. (2015) 3D-printed theophylline tablets utilizing FDM technology that was used to print theopilline tablets in rabbit models. These tablets have zero-order release profile 24 hours, which points to a stable and long-term therapeutic effect. On the same note, SLA based hydrogel matrices impregnated with diclofenac were administered in rats to manage inflammation where the analgesic activity was prolonged with later peak plasma peak[16].
- Critical Insights: The systems deal with dose dumping issue that is common in traditional oral medications. Diffusion and erosion rates were adjusted by introducing geometrical changes to the geometry such as honeycomb infill or multilayered barriers. There is

however a challenge of formulation stability. FDM cannot efficiently be used with thermolabile medications since the processing temperatures are too high, whereas the use of photoinitiators in SLA raises the issues of non-eliminated toxicity and chronic tissue incompatibility. In addition, standardized dissolution testing procedures are usually absent to test 3D-printed dosage forms in animal models.

3.2. Multi-Drug Delivery and Polypharmacy Optimization

- Strategy: 3D printing allows spatial separation or layering of loading of various active pharmaceutical ingredients (APIs), and this can be a strong approach to polypharmacy. This is important in the part of comorbid conditions because there need to be many drugs that have synergistic effects and yet different pharmacokinetic behavior.
- Technologies and Preclinical Uses: Inkjet printing has been successfully applied to produce the multilayer tablets in an antiepileptic treatment in animal-based models: rat (carbamazepine or phenytoin and carbamazepine). The sequential release profile granted initial release of one drug with sustained action of the other simulating conditions of a real-patient treatment timeline. The other innovation entailed the SLA-printed microneedle arrays with insulin and GLP-1 analogs, in the case of diabetic mice. The advantage of these systems has been in the achievement of improved glycemic control through the utilization of release times and depth of tissue penetration.
- Critical Insights: In this case, the examples show that human drug regimens can be replicated in these animal models by the use of 3D printing. Compartmentalization minimizes the potential of a drug-drug interaction in the gastrointestinal tract and time staggered release is possible due to differential breakdown rates of the polymers. Chemically stable and physically consistent structure development is however a difficult venture and this is particularly so with the hydrophilic-hydrophobic API combinations. Long term storage stability, possible layers migration of the API and device reproducibility constrains larger use in a small scale environment[17].

3.3. Site-Specific and Targeted Delivery Systems

- Strategy: Improved/Targeted Drug Delivery: Drug delivery is achieved with strict targeting of anatomical niches through 3D Printing of implants, scaffolds and intravaginal intratumoral devices.
- Technologies and Preclinical Applications: FDM was used to manufacture biodegradable implants of doxorubicin loaded and then introduced to the mice intratumorally. These implants demonstrated local cytotoxicity and little systemic toxicity as demonstrated by tumor shrinkage and decreased levels of serum toxicity markers. The tenofovir and dapivirine vaginal rings encapsulated in an inkjet print were tested on sheep models to replicate antiviral action against HIV, and the test resulted with maintaining the mucosal tenofovir and dapivirine drug concentration without uptake in the system.
- Critical Insights: Capability of customization of the device geometry guarantees optimum anatomical fit and retention. This applies particularly to tissues undergoing high turnover or highly dynamic environments (e.g. vaginal mucosa). Still, the reproducibility and

mechanical stability under stress conditions are hard to get. The fabrication sterility, as well as biocompatibility of materials used is also an important consideration especially to implantable systems. Moreover, upscale of small to large animal models include huge scaling of design parameters, as well as potential exposure of unexpected pharmacokinetics differences[18].

3.4. Transdermal and Minimally Invasive Systems

- Advantage: Microneedle arrays and transdermal patches provide a painless, self-dose-able delivery system of macromolecules and vaccines with avoidance of gastrointestinal destruction, or first-pass degradation and processing.
- Preclinical Applications and Technologies: Such technologies as SLA and inkjet printing have been used to produce microneedles carrying antigens of mice vaccines. They entered the stratum corneum but did not affect dermal nerves, so they helped to make an effective antigen presentation and gave potent immune stimulation. Transdermal patches of lidocaine made through extrusion printing demonstrated enhanced skin penetrating as well as analgesic duration in comparison with the commercial gels in rat models.
- Critical Insights: Microneedles signal the presence of an affordable scalable method of chronic and prophylaxis care. Insertion success rates and drug permeation are also critically influenced by geometry as well as length and sharpness of printed needles. But, the materials must have a tradeoff between strength and either dissolution or biodegradability (e.g., PLA, PEGDA). The consistency and printer resolution of printers used also play an important role in the performance and reliability of microneedles during preclinical testing[19].

3.5. Personalized Medicine and Pediatric Applications

- Strategy: Dosage forms that are customised according to patient age, weight or preference become essential in pediatrics and geriatrics. Patient specific dosing and taste masking can be done by 3d printing as well as engaging shapes to increase adherence.

- Technologies and Preclinical Applications: Extrusion and binder jetting methods allowed the designing of animal 3D-printed, chewable, animal-shaped pills with dose adjustments to juvenile piglet models, to represent childhood consumption. These forms enhanced better tolerability and repeated dosing testing of pharmacokinetic research. Different percentages of infills were also applied to adjust the disintegration time and releasing of taste.
- Critical Insights: These compounded-based drugs enhanced experimental simulating of childhood reactions as well as compliance. In addition, the mini-tablets and low dose printed films make a controlled exposure that is appropriate to toxicity studies in little animals. But in such microdoses it is technically challenging to ensure uniformity, and animal variability in behavior brings a degree of difficulty in interpretation of both acceptability and palatability results.

4. ADVANCING PERSONALIZED PHARMACEUTICS THROUGH 3D PRINTING: PRECLINICAL INSIGHTS FROM ANIMAL MODELS

One area that 3D printing has had a bigger impact is personalized pharmaceutics where precise drug formulations can be created to meet specific physiological and therapeutic needs of individuals. The preclinical animal model studies have been important in testing the effectiveness, safety, and feasibility of these tailor-made drug delivery systems. The models are important platforms through which assessments of pharmacokinetics, therapeutic response and biocompatibility can be made prior to proceeding to human clinical trials[20].

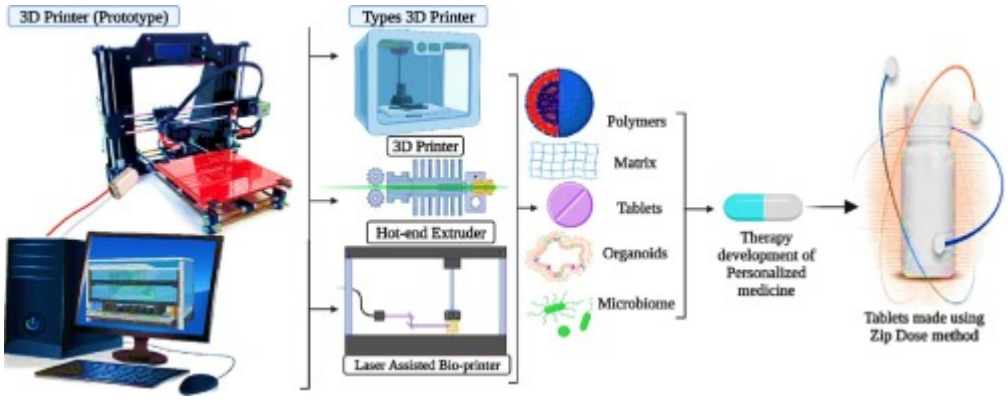

Figure 3: 3D Printing Techniques for Personalized Medicine and ZipDose Tablet Fabrication[21]

It has also found one of the most prominent uses in the sphere of manipulated and prolonged drug renovation. Taking advantage of Fused Deposition Modeling (FDM), researchers were able to manufacture tablets with user-designed release patterns by varying the geometry, infill percentage and type of polymer. As an example, pharynxophylline-loaded tablets in rabbits exhibited extended therapeutic activity lasting 24 hours and thus decreased the frequency of administering drugs and increased compliance, which is an obvious concern in the treatment of chronic diseases. These studies emphasize the potential of 3D printing as a method to develop dosage forms that attune to the circadian systems, as well as unique metabolism.

Animal models have proved to be important in proving the viability of 3D-printed multi-drug systems as well. Where drugs are taken in matched dosage patterns, such as epileptic therapy, rat-studies have demonstrated success in selective release in inkjet-printed multilayered tablets of carbamazepine and phenytoin. In a similar manner, microneedle patch based SLA has also performed with combinations of insulin and GLP-1 analogs in diabetic mice with synergistic effects on glycemic control. The above observations validate the potential of overcoming polypharmacy problems by way of spatio-temporal programmed drug delivery systems.

A great stride has been made in targeted and localized-based drug delivery using 3D printed implants and site specific delivery of drugs. Another example of it is FDM-printed biodegradable implants that release chemotherapeutic agents with noticeable effects on the reduction of the tumor in murine cancer models with little-to-no systemic side effects. Also transdermal microneedle

systems tried in rodent models have proven to deliver efficient and painless drug administration, which makes potential further use in vaccination and pain management.

In addition, the flexibility of 3D printing in terms of flexibility in drug dosage and formulations have proved particularly relevant in both pediatrics and geriatrics where the requirements of a patient have a central role. Mini-tablet, chewable and palatable dosage forms, using modified shape and flavor, have been tested using animal models that represent the juvenile or geriatric physiology. Such innovations do not only create an alternative approach to therapeutic adherence but also lead to age-appropriate drug development precedence.

5. DISCUSSION

The results of preclinical studies prove that 3D printing technology, such as FDM, SLA, and inkjet printing, has substantial benefits associated with the customization of drug delivery and possesses the capacity to provide individualized release profile, multi-drug combinations, and patient-specific formulations. Such systems also increase the precision and compliance under pediatric and geriatric requirements and hold a considerable promise as a part of revolutionizing the manufacturing process of pharmaceutical products towards becoming a more personalized and cost-effective type. Nevertheless, they do still have some problems, such as sensitive drug thermal degradation, photoinitiator toxicity, and that there are no long-term safety studies. The possibilities of future research must concentrate on more sophisticated animal models, biomaterial that is stable, reliable and biocompatible, hybrid printing technology and regulatory path to facilitate clinical translation[22].

5.1.Interpretation and Analysis of Findings

The available preclinical data illustrate that FDM, SLA, and inkjet printing are unique 3D printing techniques allowing a considerable benefit in personalized drug delivery, including the customization of their structural and release profiles as well as dosage forms. Experiments with animal models have proved the possibility of obtaining zero-order kinetics, multi-drug delivery and targeted therapy, with a change towards greater precision of therapy and patient adherence. Such systems serve to successfully mirror sophisticated human treatment routines, in addition to offering solutions to the particular populations that have distinct requirements, including pediatrics and geriatric courses of action[23].

5.2.Implications and Significance

The potential impact of these technologies is immense, and it may turn traditional pharmaceutical development more patient-oriented and personalized. 3D printing allows producing composites of many APIs, administration through non-invasive methods (e.g., microneedles), and making products available on-demand, which may have a dramatic effect in terms of cutting the fiscal aspects of healthcare delivery and increasing its availability. With successful preclinical demonstration, the likelihood of the translation of such systems into clinical practice especially as an approach to management of chronic diseases and personalized therapies is possible[2].

5.3.Gaps and Future Research Directions

However, despite such accomplishments, it still has major gaps to address. The current studies have the limitation of short term observation, small sample size, and lack of long-term safety data. Such challenges as thermal degradation of sensitive drugs in FDM, possible toxicity of photoinitiators in SLA, and the absence of commonplace quality protocols should be solved. The topics that should be addressed in the future research are large-scale, longitudinal animal research with more advanced model animals, creation of thermally and chemically stable biocompatible materials, and enhancement of multi-material and hybrid printing solutions. Also, it is essential to have agreements with regulating bodies to formulate effective guidelines and help otherwise 3D printed pharmaceuticals to translate to clinical usability[25].

6. CONCLUSION

3D printing is a revolutionary development of personalized medicine whereby the level of specificity in designing and production of patient-specific drug delivery systems is unrivaled. The application of technologies to non-clinical studies, e.g. Fused Deposition Modeling (FDM), Fused Deposition Modeling (FDM), Stereolithography (SLA) and ink jet-printing, has made significant advancements in drug delivery areas in controlled and sustained release of drugs, multi- drugs and site-specific release. Such advances have demonstrated better pharmacokinetics, greater efficacy with respect to their therapeutic effects, and higher compliance including the vulnerable populations like the pediatric, geriatric and chronically ill patients who may need special dosing and route of administrations. Also, the application of combining a number of active pharmaceutical ingredients (APIs) into the same dosage form will help to meet polypharmacy and chronic issues of disease management. Nonetheless, although these are encouraging moves, the clinical practice of the 3D-printed pharmaceuticals is hampered by a number of issues such as the biocompatibility and thermal stability of materials, variations in the print resolution, the absence of uniform manufacturing and validation methods, and the regulatory uncertainty. Future research should focus on the optimization of pharmaceutically acceptable forms, scale-up procedure and effective quality control to achieve full potential of this technology and to encourage the collaboration across disciplines of engineering, pharmacists and regulatory agencies. Through these, 3D printing may lead to the redefinition of personalized drug therapy and changing the face of contemporary pharmaceutics.

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