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RECENT ADVANCES IN MICROFLUIDICS FOR THE PREPARATION OF DRUG AND GENE DELIVERY SYSTEMS

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Abstract: Microfluidic technology has emerged as a transformative platform in pharmaceutical sciences for the preparation of advanced drug and gene delivery systems. Conventional nanoparticle fabrication methods frequently encounter limitations such as poor reproducibility, broad particle-size distribution, low encapsulation efficiency, batch-to-batch variation, and inadequate control over physicochemical properties. Microfluidic systems overcome many of these challenges by enabling precise manipulation of microscale fluid dynamics, rapid mixing, controlled nanoprecipitation, and highly reproducible formulation conditions. Recent advances in microfluidic technologies have significantly accelerated the development of lipid nanoparticles, polymeric nanoparticles, liposomes, nanoemulsions, micelles, and nucleic acid delivery systems intended for targeted and personalized therapeutics. Microfluidics-based fabrication techniques provide enhanced control over particle morphology, size distribution, surface characteristics, drug loading, and release kinetics. These systems are particularly valuable in the preparation of gene delivery vehicles including messenger RNA, plasmid DNA, siRNA, and CRISPR-associated delivery platforms. The growing success of mRNA vaccines and nanomedicine has further intensified scientific interest in scalable microfluidic manufacturing systems for pharmaceutical applications. Advances in lab-on-a-chip technologies, artificial intelligence-assisted process optimization, continuous-flow synthesis, and automated pharmaceutical engineering have expanded the clinical and industrial relevance of microfluidic systems. Pharmacists contribute significantly through formulation optimization, medication safety monitoring, therapeutic evaluation, patient counseling, quality assurance, and translational pharmaceutical research. Despite promising progress, important challenges remain regarding industrial scalability, device standardization, manufacturing costs, regulatory approval pathways, and large-scale commercialization. This manuscript discusses recent developments in microfluidic technologies for drug and gene delivery systems, including fabrication techniques, pharmaceutical applications, physicochemical advantages, clinical relevance, pharmacist interventions, regulatory considerations, emerging opportunities, and future perspectives within precision medicine and nanotherapeutic development.

Keywords: *Microfluidics; Drug delivery systems; Gene delivery; Nanomedicine; Lipid nanoparticles; Controlled drug delivery; Lab-on-a-chip; Precision medicine; Pharmaceutical nanotechnology; Microfluidic synthesis.*

1. INTRODUCTION

Drug and gene delivery systems have become increasingly important within modern pharmaceutical sciences due to their ability to improve therapeutic efficacy, reduce systemic toxicity, enhance bioavailability, and provide targeted treatment approaches for complex diseases [1]. Conventional pharmaceutical delivery systems often face limitations related to poor drug solubility, instability, rapid degradation, nonspecific biodistribution, and inadequate therapeutic concentration at disease sites [2]. Nanotechnology-based drug delivery systems have therefore emerged as promising alternatives for overcoming these limitations and improving clinical outcomes. Nanocarriers including liposomes, polymeric nanoparticles, nanoemulsions, micelles, dendrimers, and lipid nanoparticles have demonstrated substantial potential in targeted drug and gene delivery applications [3]. These systems provide controlled drug release, prolonged circulation time, enhanced cellular uptake, and improved protection of sensitive therapeutic agents such as nucleic acids and proteins. However, traditional fabrication techniques including bulk mixing, solvent evaporation, emulsification, and sonication often produce inconsistent formulations with poor reproducibility and large particle-size variability [4]. Microfluidic technology has emerged as an innovative solution for addressing these manufacturing challenges. Microfluidics involves the precise manipulation of fluids within microscale channels that allow highly controlled mixing conditions, rapid nanoprecipitation, and continuous-flow synthesis [5]. The technology enables accurate control over fluid dynamics, diffusion processes, and reaction kinetics, resulting in highly reproducible nanoparticle formulations with narrow size distributions and optimized physicochemical properties. Recent advances in microfluidic engineering have significantly expanded applications within pharmaceutical nanotechnology and precision medicine. Microfluidic systems are increasingly utilized for the fabrication of lipid nanoparticles, polymeric nanocarriers, liposomes, hydrogels, and gene delivery systems containing siRNA, plasmid DNA, mRNA, and CRISPR-associated therapeutic agents [6]. The rapid development of mRNA vaccines during the COVID-19 pandemic further highlighted the importance of scalable microfluidic platforms for nanoparticle production and pharmaceutical innovation [7]. Pharmacists play important roles within microfluidic-based pharmaceutical systems through formulation development, quality assurance, therapeutic monitoring, medication counseling, and translational nanomedicine research [8]. Despite remarkable progress, important limitations remain regarding industrial scalability, device standardization, manufacturing complexity, regulatory frameworks, and cost-effectiveness. This manuscript reviews recent advances in microfluidics for the preparation of drug and gene delivery systems, emphasizing fabrication strategies, pharmaceutical applications, physicochemical advantages, pharmacist interventions, regulatory considerations, challenges, and future opportunities in nanomedicine and precision therapeutics.

2. PRINCIPLES OF MICROFLUIDIC TECHNOLOGY IN PHARMACEUTICAL SCIENCES

Microfluidics refers to the science and engineering of manipulating small fluid volumes within microscale channels typically ranging from micrometers to millimeters in dimension [9]. At microscale levels, fluid behavior differs significantly from conventional macroscopic systems because laminar flow predominates and turbulence is minimal. This controlled environment enables precise manipulation of fluid interactions, solvent exchange, diffusion kinetics, and nanoparticle self-assembly. The Reynolds number within microfluidic systems is generally low, promoting stable and predictable fluid flow patterns [10]. Controlled mixing processes enable homogeneous nanoparticle formation and improved encapsulation efficiency. Rapid solvent diffusion and antisolvent precipitation facilitate generation of nanoparticles with highly controlled size distributions and surface properties. Microfluidic platforms commonly employ continuous-flow systems in which pharmaceutical components are introduced through interconnected microchannels. Controlled mixing occurs at junctions such as T-junctions, Y-junctions, staggered herringbone mixers, and flow-focusing geometries [11]. These systems allow precise adjustment of flow rate ratios, solvent composition, temperature, and channel geometry to optimize nanoparticle synthesis. Microfluidics provides several advantages compared to conventional fabrication methods. These include reduced reagent consumption, high reproducibility, continuous production capability, enhanced scalability potential, precise process control, and improved formulation consistency [12]. These characteristics have significantly expanded pharmaceutical applications involving nanomedicine and gene delivery systems.Recent innovations integrate artificial intelligence, computational fluid dynamics, automation systems, and machine learning algorithms into microfluidic platforms. These technologies improve process optimization, predictive modeling, formulation reproducibility, and industrial scalability.

3. TYPES OF MICROFLUIDIC SYSTEMS USED IN DRUG DELIVERY

Several microfluidic device designs are currently utilized for pharmaceutical nanoparticle synthesis and drug delivery applications. Each system possesses unique advantages depending on formulation requirements and therapeutic objectives. T-junction microfluidic systems represent among the simplest and most widely utilized platforms for nanoparticle fabrication [13]. In these systems, two fluid streams intersect at perpendicular channels, enabling controlled solvent exchange and nanoparticle self-assembly. T-junction systems are frequently used for liposome preparation and polymeric nanoparticle synthesis.Y-junction devices facilitate smoother fluid convergence and improved mixing efficiency compared to perpendicular systems. These devices are commonly employed in nanoemulsion fabrication and controlled nanoprecipitation processes [14].

Flow-focusing microfluidic systems utilize converging fluid streams to generate highly monodisperse droplets and nanoparticles. The technology supports production of liposomes, microgels, polymeric nanoparticles, and nucleic acid delivery vehicles with highly uniform physicochemical properties [15]. Staggered herringbone mixers enhance chaotic advection within laminar flow systems, improving rapid mixing and nanoparticle homogeneity [16]. These systems are particularly valuable for scalable production of lipid nanoparticles used in mRNA delivery. Droplet-based microfluidics generates discrete microdroplets serving as isolated reaction chambers for pharmaceutical synthesis. These platforms enable precise encapsulation of drugs, proteins, nucleic acids, and biological materials [17].Recent developments also include centrifugal microfluidics, organ-on-chip systems, digital microfluidics, and 3D-printed microfluidic devices that further enhance pharmaceutical manufacturing flexibility and personalized medicine applications.

4. MICROFLUIDIC PREPARATION OF LIPID NANOPARTICLES

Lipid nanoparticles have become among the most important nanocarriers in modern pharmaceutical sciences, particularly following their successful utilization in mRNA vaccine delivery systems [18]. Microfluidic technologies have significantly improved lipid nanoparticle fabrication through precise control of self-assembly kinetics and nanoparticle size distribution. In microfluidic lipid nanoparticle synthesis, lipid components dissolved in organic solvents are rapidly mixed with aqueous buffers containing nucleic acids or therapeutic agents [19]. Controlled solvent diffusion promotes spontaneous nanoparticle formation with high encapsulation efficiency and reproducible particle size.

Microfluidic preparation offers several advantages compared to conventional bulk mixing methods. Nanoparticles produced through microfluidic systems exhibit narrower size distributions, improved stability, enhanced reproducibility, and reduced batch-to-batch variability [20]. These characteristics are critical for clinical translation and regulatory approval. Messenger RNA delivery systems represent a major application of microfluidic lipid nanoparticle synthesis. COVID-19 mRNA vaccines demonstrated the clinical potential of lipid nanoparticle-mediated nucleic acid delivery [21]. Microfluidic technologies enabled rapid and scalable manufacturing of lipid nanoparticles encapsulating mRNA therapeutic payloads. Microfluidic lipid nanoparticle systems are also increasingly investigated for cancer therapeutics, gene editing applications, vaccine development, and personalized medicine approaches.

5. POLYMERIC NANOPARTICLES AND NANOFORMULATION

Polymeric nanoparticles fabricated using microfluidic systems have demonstrated substantial potential for controlled drug delivery and targeted therapeutics [22]. Biodegradable polymers such as poly (lactic-co-glycolic acid), polyethylene glycol, chitosan, alginate, and polylactic acid are frequently utilized in nanoparticle fabrication. Microfluidic nanoprecipitation allows controlled polymer self-assembly and highly reproducible particle formation. Precise manipulation of solvent composition, flow rates, and mixing kinetics enables optimization of nanoparticle size, morphology, and drug encapsulation efficiency [23].Polymeric nanoparticles improve therapeutic performance by enhancing drug solubility, prolonging circulation time, reducing systemic toxicity, and facilitating targeted drug delivery. Controlled release characteristics further improve therapeutic efficacy and patient compliance. Microfluidic systems have also enabled fabrication of multifunctional nanoparticles capable of responding to pH changes, temperature variations, magnetic fields, and enzymatic activity [24]. Stimuli-responsive nanoparticles provide opportunities for site-specific and personalized therapeutic delivery. Applications include anticancer drug delivery, antimicrobial therapy, gene delivery, neurological therapeutics, and regenerative medicine.

6. MICROFLUIDICS IN GENE DELIVERY SYSTEMS

Gene therapy has emerged as a promising strategy for treating genetic disorders, cancers, infectious diseases, and rare inherited conditions [25]. Efficient gene delivery systems remain essential for protecting nucleic acids from degradation and facilitating intracellular transport. Microfluidic technologies significantly improve preparation of gene delivery vehicles including lipoplexes, polyplexes, lipid nanoparticles, and hybrid nanocarriers [26]. Controlled mixing conditions enable stable complex formation between nucleic acids and carrier materials. Messenger RNA delivery systems currently represent one of the fastest-growing applications of microfluidic nanotechnology. Lipid nanoparticles prepared through microfluidics provide efficient encapsulation and delivery of mRNA therapeutics while minimizing immunogenicity and degradation [27]. Microfluidics also supports development of CRISPR-Cas9 delivery systems for gene editing applications. Controlled nanoparticle synthesis improves delivery efficiency, targeting accuracy, and therapeutic safety. Plasmid DNA delivery, siRNA therapeutics, antisense oligonucleotide systems, and viral vector alternatives are increasingly fabricated using microfluidic techniques due to improved reproducibility and formulation precision.

7. APPLICATIONS IN CANCER THERAPY

Cancer treatment remains among the most important applications of microfluidic-based drug delivery systems. Conventional chemotherapy frequently causes severe systemic toxicity due to nonspecific drug distribution [28]. Nanoparticle-based delivery systems improve therapeutic targeting while reducing adverse effects.Microfluidic-prepared liposomes and polymeric nanoparticles facilitate controlled delivery of anticancer drugs including doxorubicin, paclitaxel, docetaxel, cisplatin, and methotrexate [29]. Surface modifications enable active targeting toward tumor tissues through receptor-mediated interactions. Microfluidic systems also support co-delivery of multiple therapeutic agents including chemotherapeutic drugs, nucleic acids, immunotherapeutics, and imaging agents. Combination therapy approaches improve therapeutic efficacy while minimizing drug resistance. Tumor microenvironment-responsive nanoparticles fabricated through microfluidics enable pH-sensitive and enzyme-triggered drug release mechanisms. Personalized nanomedicine approaches increasingly utilize patient-specific tumor biomarkers to optimize targeted therapy.

9. APPLICATIONS IN VACCINE DEVELOPMENT

Microfluidic technology has become critically important in vaccine formulation and delivery systems. Lipid nanoparticle-based vaccines demonstrated remarkable clinical success during the COVID-19 pandemic [30]. Microfluidic platforms enabled scalable and reproducible manufacturing of mRNA-containing lipid nanoparticles. Compared with traditional vaccine production methods, microfluidic fabrication improves particle uniformity, antigen encapsulation efficiency, and stability. These properties enhance immunogenicity and vaccine efficacy. Microfluidic vaccine platforms are currently being explored for influenza vaccines, cancer vaccines, HIV therapeutics, and personalized immunotherapy applications [31]. Rapid manufacturing capability further supports pandemic preparedness and emergency vaccine development.

10. PHARMACIST INTERVENTIONS AND CLINICAL CONTRIBUTIONS

Pharmacists play increasingly important roles within microfluidic-based pharmaceutical systems and translational nanomedicine research. Clinical pharmacists contribute to formulation optimization, therapeutic evaluation, medication safety assessment, and patient counseling [32].Hospital pharmacists participate in preparation and quality assurance of advanced drug delivery systems used in oncology, gene therapy, and personalized medicine. Pharmacists also monitor therapeutic outcomes, adverse drug reactions, and medication adherence among patients receiving nanoparticle-based therapies.

Research pharmacists collaborate with biomedical engineers, clinicians, and pharmaceutical scientists in developing optimized microfluidic formulations. Their expertise in pharmacokinetics, drug interactions, dosage optimization, and patient-centered care significantly improves clinical translation. Pharmacists additionally contribute to pharmacovigilance activities involving nanomedicines and gene delivery therapeutics. Patient counseling regarding administration techniques, storage conditions, therapeutic expectations, and adverse effect monitoring remains essential for optimizing treatment outcomes.Educational initiatives led by pharmacists further support healthcare professional training regarding nanomedicine and advanced pharmaceutical technologies.

11. ARTIFICIAL INTELLIGENCE AND AUTOMATION IN MICROFLUIDICS

Artificial intelligence has significantly enhanced microfluidic pharmaceutical engineering by improving process optimization, predictive modeling, and manufacturing efficiency [33]. Machine learning algorithms analyze complex formulation parameters to optimize nanoparticle characteristics and drug encapsulation efficiency. Automated microfluidic systems integrate robotics, sensors, computational fluid dynamics, and real-time monitoring technologies to improve reproducibility and scalability. AI-assisted systems can rapidly identify optimal flow conditions, solvent compositions, and formulation parameters. Digital twin technologies and computational simulations further enhance understanding of fluid dynamics within microfluidic devices. These technologies reduce experimental variability and accelerate pharmaceutical development timelines.AI-integrated microfluidics may substantially improve precision medicine by enabling individualized nanoparticle formulations tailored to patient-specific therapeutic needs.

12. CHALLENGES AND LIMITATIONS

Despite remarkable advancements, several limitations hinder widespread industrial implementation of microfluidic pharmaceutical technologies. Large-scale manufacturing remains among the most significant challenges [34]. Although microfluidic systems provide excellent reproducibility at laboratory scales, translating these processes into industrial production remains complex. Device fabrication costs and manufacturing infrastructure requirements may limit accessibility within resource-constrained settings. Standardization of microfluidic device design and operating protocols also remains insufficient across pharmaceutical industries. Regulatory frameworks for microfluidic-manufactured therapeutics remain under development. Pharmaceutical regulatory agencies require comprehensive validation regarding reproducibility, safety, scalability, and quality assurance [35].

Clogging of microchannels, material compatibility issues, solvent limitations, and sterilization challenges may further complicate large-scale pharmaceutical applications. Long-term stability studies and clinical evaluations are additionally required for many emerging microfluidic-based therapeutics before widespread commercialization can occur.

13. FUTURE PERSPECTIVES

Future developments in microfluidics are expected to further revolutionize precision medicine, nanomedicine, and personalized therapeutics. Integration of 3D printing technologies, organ-on-chip systems, and AI-assisted pharmaceutical engineering may significantly expand clinical applications [36].

Personalized microfluidic platforms capable of producing patient-specific nanomedicines and gene delivery systems may transform individualized healthcare delivery. Organ-on-chip technologies integrated with microfluidic systems may improve preclinical drug screening and reduce dependence on animal models. Continuous-flow manufacturing systems and automated pharmaceutical production platforms are likely to enhance industrial scalability and regulatory acceptance. Integration of wearable biosensors and real-time therapeutic monitoring may further support precision drug delivery. Microfluidic systems may also facilitate development of advanced regenerative medicine therapies, stem cell delivery systems, and personalized immunotherapies.

14. CONCLUSION

Microfluidic technology has emerged as a transformative platform for the preparation of advanced drug and gene delivery systems within modern pharmaceutical sciences. Precise fluid manipulation, controlled mixing, and continuous-flow synthesis provide substantial advantages over conventional fabrication methods, including improved reproducibility, narrow particle-size distribution, enhanced encapsulation efficiency, and scalable nanoparticle production. Recent advances in microfluidics have significantly improved fabrication of lipid nanoparticles, polymeric nanocarriers, liposomes, nanoemulsions, and nucleic acid delivery systems utilized in cancer therapy, vaccine development, gene therapy, and precision medicine. The rapid expansion of mRNA therapeutics further highlights the growing clinical relevance of microfluidic pharmaceutical engineering.Pharmacists continue to play critical roles in formulation development, therapeutic optimization, quality assurance, patient counseling, and translational nanomedicine research. Integration of artificial intelligence, automation systems, and computational modeling is expected to further enhance pharmaceutical manufacturing efficiency and personalized therapeutic design. Despite important challenges involving industrial scalability, regulatory approval, device standardization, and manufacturing costs, microfluidics remains one of the most promising technologies in advanced drug delivery and pharmaceutical innovation. Continued interdisciplinary collaboration, technological advancement, and regulatory development will be essential for successful clinical translation and commercialization of microfluidic-based therapeutics.

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18. REFERENCES

1. Torchilin VP. Multifunctional, stimuli-sensitive nanoparticulate systems for drug delivery. *Nat Rev Drug Discov*. 2014;13(11):813-827.
2. Allen TM, Cullis PR. Liposomal drug delivery systems: from concept to clinical applications. *Adv Drug Deliv Rev*. 2013;65(1):36-48.
3. Peer D, Karp JM, Hong S, FaroKhzad OC, Margalit R, Langer R. Nanocarriers as an emerging platform for cancer therapy. *Nat Nanotechnol*. 2007;2(12):751-760.
4. Danaei M, Dehghankhold M, Ataei S, et al. Impact of particle size and polydispersity index on the clinical applications of lipidic nanocarrier systems. *Pharmaceutics*. 2018;10(2):57.
5. Whitesides GM. The origins and the future of microfluidics. *Nature*. 2006;442(7101):368-373.
6. Tomeh MA, Zhao X. Recent advances in microfluidics for the preparation of drug and gene delivery systems. *Mol Pharm*. 2020;17(12):4421-4434.
7. Hou X, Zaks T, Langer R, Dong Y. Lipid nanoparticles for mRNA delivery. *Nat Rev Mater*. 2021;6(12):1078-1094.
8. Ventola CL. The nanomedicine revolution: part 2: current and future clinical applications. *PT*. 2017;42(12):742-755.
9. Sackmann EK, Fulton AL, Beebe DJ. The present and future role of microfluidics in biomedical research. *Nature*. 2014;507(7491):181-189.
10. Stone HA, Stroock AD, Ajdari A. Engineering flows in small devices: microfluidics toward a lab-on-a-chip. *Annu Rev Fluid Mech*. 2004;36:381-411.
11. Karnik R, Gu F, Basto P, et al. Microfluidic platform for controlled synthesis of polymeric nanoparticles. *Nano Lett*. 2008;8(9):2906-2912.
12. Valencia PM, Farokhzad OC, Karnik R, Langer R. Microfluidic technologies for accelerating the clinical translation of nanoparticles. *Nat Nanotechnol*. 2012;7(10):623-629.
13. Jahn A, Vreeland WN, Gaitan M, Locascio LE. Controlled vesicle self-assembly in microfluidic channels with hydrodynamic focusing. *J Am Chem Soc*. 2004;126(9):2674-2675.
14. Jahn A, Lucas F, Wepf R, Dittrich PS. Microfluidic mixing and the formation of nanoscale lipid vesicles. *Langmuir*. 2007;23(11):6289-6293.
15. Hood RR, DeVoe DL. High-throughput continuous flow production of nanoscale liposomes by microfluidic vertical flow focusing. *Small*. 2015;11(43):5790-5799.
16. Stroock AD, Dertinger SKW, Ajdari A, et al. Chaotic mixer for microchannels. *Science*. 2002;295(5555):647-651.
17. Teh SY, Lin R, Hung LH, Lee AP. Droplet microfluidics. *Lab Chip*. 2008;8(2):198-220.
18. Cullis PR, Hope MJ. Lipid nanoparticle systems for enabling gene therapies. *Mol Ther*. 2017;25(7):1467-1475.
19. Belliveau NM, Huft J, Lin PJ, et al. Microfluidic synthesis of highly potent limit-size lipid nanoparticles for in vivo delivery of siRNA. *Mol Ther Nucleic Acids*. 2012;1:e37.
20. Maeki M, Kimura N, Sato Y, et al. Advances in microfluidics for lipid nanoparticles and extracellular vesicles and applications in drug delivery systems. *Adv Drug Deliv Rev*. 2018;128:84-100.
21. Schoenmaker L, Witzigmann D, Kulkarni JA, et al. mRNA-lipid nanoparticle COVID-19 vaccines: structure and stability. *Int J Pharm*. 2021;601:120586.
22. Kumari A, Yadav SK, Yadav SC. Biodegradable polymeric nanoparticles based drug delivery

systems. *Colloids Surf B Biointerfaces*. 2010;75(1):1-18.

23. Capretto L, Cheng W, Hill M, Zhang X. Micromixing within microfluidic devices. *Top Curr Chem*. 2011;304:27-68.
24. Raza F, Zafar H, Zhang S, et al. Recent advances in cell membrane-derived biomimetic nanotechnology for cancer immunotherapy. *Drug Discov Today*. 2019;24(7):1444-1458.
25. Ginn SL, Amaya AK, Alexander IE, Edelstein M, Abedi MR. Gene therapy clinical trials worldwide to 2017: an update. *J Gene Med*. 2018;20(5):e3015.
26. Chen D, Love KT, Chen Y, et al. Rapid discovery of potent siRNA-containing lipid nanoparticles enabled by controlled microfluidic formulation. *Proc Natl Acad Sci U S A*. 2012;109(29):11758-11763.
27. Kulkarni JA, Witzigmann D, Chen S, Cullis PR, van der Meel R. Lipid nanoparticle technology for clinical translation of siRNA therapeutics. *Nat Nanotechnol*. 2021;16(6):630-643.
28. Shi J, Kantoff PW, Wooster R, Farokhzad OC. Cancer nanomedicine: progress, challenges and opportunities. *Nat Rev Cancer*. 2017;17(1):20-37.
29. Barenholz Y. Doxil® — the first FDA-approved nano-drug: lessons learned. *J Control Release*. 2012;160(2):117-134.
30. Pardi N, Hogan MJ, Porter FW, Weissman D. mRNA vaccines — a new era in vaccinology. *Nat Rev Drug Discov*. 2018;17(4):261-279.
31. Irvine DJ, Swartz MA, Szeto GL. Engineering synthetic vaccines using cues from natural immunity. *Nat Mater*. 2013;12(11):978-990.
32. Bawa R. Nanopharmaceuticals: nanopharmaceuticals and nanomedicine. *J Pharm Pract*. 2016;29(4):298-309.
33. Jiang F, Jiang Y, Zhi H, et al. Artificial intelligence in healthcare: past, present and future. *Stroke Vasc Neurol*. 2017;2(4):230-243.
34. Hood RR. Scale-up of microfluidic nanoparticle synthesis. *Curr Opin Colloid Interface Sci*. 2021;52:101418.
35. Ventola CL. The nanomedicine revolution: part 1: emerging concepts. *PT*. 2012;37(9):512-525.
36. Whitesides GM. The origins and future of microfluidics. *Angew Chem Int Ed Engl*. 2018;57(16):4258-4273.