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Manufacturing AS STRATEGY

HOW AI, 3DP & AGILE MANUFACTURING ARE RESHAPING PHARMA & PATIENT CARE

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Pharma manufacturing is no longer just operational—it's strategic, political, and time-sensitive.

Pharmaceutical manufacturing is changing quickly as AI, additive manufacturing, and digital technologies create new ways to develop, produce, and deliver medicines. In this eBook, experts from Aprecia, academia, and industry explore how advanced manufacturing is helping pharma respond to regulatory pressures, support personalized therapies, and shape a more agile, patient-centric future for drug development.



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Aprecia's pharmaceutical 3DP platform integrates powder handling, printing, and in-blister production into a single manufacturing workflow.



KYLE SMITH
President & COO, Aprecia

Rethinking Oral Drug Manufacturing

Aprecia's Kyle Smith discusses how pharmaceutical 3D printing, AI-enabled development, and more flexible manufacturing models can improve speed, patient usability, and product differentiation.

BY TIM WRIGHT, EDITOR, CONTRACT PHARMA

Drug developers are being asked to do more on several fronts at once: shorten timelines, control costs, reduce supply chain risk, and create products that work better for patients in everyday use. New tools—including AI, digital manufacturing, and pharmaceutical 3D printing—are giving companies more options for meeting those demands and challenging some of the long-standing assumptions around how oral solid dose products are developed and produced.

In this Q&A, Kyle Smith, president and chief operating officer of Aprecia, discusses how advanced manufacturing can help sponsors address these changing expectations. He explains how pharmaceutical 3D printing can support more patient-friendly dosage forms, accelerate development, reduce scale-up and regulatory risk, and create opportunities for meaningful product differentiation throughout the commercial lifecycle.

Contract Pharma: *What forces are converging right now to fundamentally change how pharma should think about drug product design and manufacturing?*

Kyle Smith: Pharma is at a pivotal moment where multiple market forces are colliding with ready innovation—forcing the industry to rethink how drugs can be developed and manufactured. The industry is under sustained pressure to reduce cost of goods, accelerate time to market, and improve development efficiency all while delivering more patient-centric therapies. But now, digital manufacturing environments are a reality, and regulatory bodies are signaling the shift from "if," to "how" this will scale responsibly.

At the same time, we're seeing a rapid shift toward personalized medicine, fueled by advances in data, diagnostics, and

AI-driven insights. This shift is raising expectations for therapies that are not only effective, but tailored—whether that's through individualized dosing, optimized drug delivery forms, or formulations designed to meet the needs of specific patient populations.

On top of that, ongoing supply chain disruption and geopolitical pressure to onshore pharmaceutical manufacturing has made it clear that traditional, centralized, batch-based models are no longer sufficient. They were built for scale and uniformity, not flexibility, precision, and speed.

What's emerging instead is a new paradigm—one defined by agile manufacturing, AI, digital integration, and design-for-patient principles from the beginning. The companies that succeed will be those that can connect API and drug product formulation, clinical response, manufacturing, and all related data into a more adaptive, responsive system.

CP: *To what extent is FDA emphasis on real-world usability influencing drug product development decisions?*

Kyle: The new emphasis is having a meaningful and growing impact on drug product development. There's increasing recognition—both within the FDA and across the industry—that clinical efficacy under trial conditions alone isn't enough. Real-world usability plays a critical role in whether a therapy actually delivers its intended outcomes.

We see this reflected in a stronger emphasis on patient experience, adherence, and accessibility. If a patient can't easily take medication due to swallowing difficulty, complex dosing, or tolerability issues, then even the most effective therapy can fall short in practice.

As a result, usability is moving upstream in development. It's no longer something addressed post-approval or through lifecycle management—it's becoming a core design factor. That includes considerations for dosage form selection, patient experience, disintegration profile, dose flexibility, and ease of administration.

From our perspective, this aligns directly with where Aprecia can add value. Our end-to-end advanced manufacturing technology enables precisely engineered dosage forms, developed for real-world use from day one, rather than trying to adapt later.

CP: *Where do traditional oral solid dose approaches fall short in meeting today's expectations around flexibility and adherence?*

Kyle: Traditional oral solid dose development and manufacturing was built around consistency and scale, but not necessarily around flexibility or patient variability. Fixed-dose formats and rigid production processes limit the industry's ability to respond to increasingly complex therapeutic needs.

That rigidity shows up in several ways. Patients are often asked to adapt to the drug, rather than the drug being designed for the patient. Whether it's multiple pills, difficult-to-swallow tablets, or limited dosage forms, these constraints can create real barriers to adherence. This is especially evident in pediatric dosage forms. Using adapted World Health Organization age-appropriateness methodology, Butler University researchers identified persistent gaps in conventional pediatric formulations. Among the findings, researchers noted that tablets and capsules account for 58% of authorized pediatric oral formulations despite limitations for younger patients — particularly around swallowability and dosage form size. While liquid formulations can help address swallowing challenges, they present their own limitations as excipients may exceed recommended thresholds. For formulation teams, it also restricts innovation. Combining multiple functionalities—like modified release, taste masking, multiple APIs, and precise dosing—into a single dosage form is challenging with conventional approaches.

What we're seeing now is a shift toward dosage forms that are more adaptable, more intuitive to use, and better aligned with how patients live. That requires a different formulation and manufacturing foundation—one that enables flexibility by design, not as an afterthought.

CP: *How can manufacturing technology directly influence clinical utility in oral drug products?*

Kyle: Manufacturing technology has a much more direct impact on clinical utility than it's often given credit for. The way an API is manufactured determines its structure, and that structure ultimately influences how it behaves in the drug product manufacturing process, in the body and, ultimately, how patients experience it.

When you can precisely control attributes like porosity, density, and internal architecture, you can directly affect manufacturing processability, dissolution, absorption, and overall bioavailability. That opens the door to designing therapies that are not just pharmacologically effective but clinically optimized for real-world use.

We've seen this play out in areas like rapidly disintegrating high-dose tablets, where the manufacturing approach enables a form factor that significantly improves accessibility for patients who would otherwise struggle with traditional tablets.

More broadly, advanced manufacturing allows you to integrate multiple performance characteristics into a single dosage form. That can reduce pill burden, simplify regimens, and provide flexible methods of administration, all of which contribute to improved patient compliance and outcomes.

CP: *What capabilities does pharmaceutical 3D printing enable that are difficult to achieve with conventional manufacturing?*

Kyle: 3D printing changes the design space for oral solid dose medications. Instead of being constrained by the mechanics of compression or molding, you're working with a component of deposition approaches that enable a much higher degree of precision, control, and flexibility.

3DP manufacturing allows for complex internal structures, tailored release profiles, and highly specific dosing in ways that are difficult—if not impossible—with traditional methods. This is both meaningful to the patient and the sponsor in that these novel dose forms may improve patient acceptability and create meaningful differentiation and IP protection years beyond typical molecule level patent protection. It also enables rapid iteration and clinical supply, which is critical in early development when speed and formulation testing matter most.

From a strategic standpoint, this also creates meaningful differentiation. The ability to design unique dosage forms with embedded functionality introduces new opportunities for intellectual property and lifecycle management. These are not easily replicated products—they're engineered solutions.

Just as importantly, when you pair 3D printing with digital

"Patients are often asked to adapt to the drug, rather than the drug being designed for the patient."

KYLE SMITH, APRECIA

tools and AI-driven formulation insights, you begin to unlock a more integrated development model—one where design, testing, and manufacturing are tightly connected. For example, one key feature of 3DP is its ability to generate multiple dosage strengths from a single formulation by varying validated process parameters, enabling matrixing or bracketing approaches for process validation and finished product stability studies when multiple strengths are proposed.

CP: *How do features like flexible dosing, rapid disintegration, or alternative administration routes translate into clinical or commercial value?*

Kyle: These features sit at the intersection of clinical performance and market differentiation. On the clinical side, they directly address some of the most persistent challenges in healthcare—adherence, tolerability, and accessibility. A dosage form that disintegrates easily, or that can be precisely tailored to a patient's needs, removes friction from the treatment experience. With multiple administration options, the same dosage form applies across a broad range of patient profiles from pediatric to geriatric and special needs groups.

From a commercial perspective, that translates into stronger product differentiation in crowded markets. It creates a more compelling value proposition not just for patients, but for providers and payers as well. It also opens up opportunities across the lifecycle. Whether it's improving an existing product through reformulation or extending exclusivity with a differentiated dosage form, these capabilities provide tangible levers for long-term value creation.

From Product Development Teams to Commercial Life Cycle Management functions, our technology and IP provide value to not only new chemical entities but also future LCM line extensions.

CP: *In what ways can advanced manufacturing approaches serve as a competitive differentiator for sponsors?*

Kyle: Speed to market and flexibility in dosage form design are becoming defining competitive advantages in this industry, and Aprecia's advanced manufacturing technologies sit at the center of both.

When you move away from traditional scale-up models and into agile manufacturing, you eliminate many of the bottlenecks that slow development. With no traditional tech transfer or scale-up required, the path from formulation to finished product becomes far more streamlined, saving roughly 18-36 months. You can prototype rapidly, move from concept to clinical supply in significantly shorter timeframes, and make decisions earlier with better data. Just as importantly, maintaining a consistent dosage form from early development through commercialization can eliminate the need for bioavailability/bioequivalence studies between dosage forms, reducing both clinical development risk and timeline.

Aprecia's manufacturing technology addresses the need toward more integrated, end-to-end development and manufacturing approaches—what we describe as "powder-to-package." The ability to go from raw material to finished, primary packaged product in a matter of hours has changed how companies think about timelines and supply chains.

Onshoring is another critical dimension. Distributed, U.S.-based manufacturing not only reduces risk, but also improves responsiveness and control. In today's environment, that's not just an operational advantage—it's a strategic one. Together, these capabilities allow sponsors to move faster, adapt more easily, and bring more differentiated products to market.

CP: *How can advanced manufacturing approaches help sponsors reduce development and regulatory risk?*

Kyle: One of the biggest advantages of Aprecia's advanced manufacturing is the ability to reduce uncertainty earlier in the development process. The use of AI tools developed specifically for our platforms and known molecule characteristics enables project teams to rapidly explore multiple formulation pathways, generate validation data faster, and make more informed go/no-go decisions. That alone can significantly reduce both time and capital at risk.

From a regulatory standpoint, technologies that incorporate real-time monitoring, continuous processing, and quality-by-design principles are well aligned with where the FDA is heading. They enable a higher level of process understanding and control, which ultimately supports more robust submissions.

Risk reduction is further strengthened through the deployment of PAT technologies that enable continuous quality attribute monitoring and real time decision making at the individual dose level. Integrated with dose-level 2D barcoding, these capabilities create a framework with blockchain-like traceability, connecting process, analytical, and quality data for every tablet produced. The result is enhanced control, with 100% of tablets inspected and a data-rich manufacturing environment that supports both proactive risk mitigation and greater regulatory confidence.

There's also a practical benefit in eliminating traditional scale-up challenges. When the process you use in development is the same as the one you use in commercial production, you remove a major source of variability and risk.

Aprecia's approach combined with AI-enabled development and data analytics offer a path toward a more predictable, efficient, and resilient development model.







From Data to Decision in Real Time

Five ways 3DP binder jetting is redefining agile manufacturing in a Pharma 4.0 world.

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We live in a Pharma 4.0 world. Data is integrated. Quality systems are embedded. Realtime oversight and digital traceability are no longer aspirational goals, they are baseline expectations.

Yet many tablet manufacturing processes still rely on models built for a different operating reality. They depend on batch averages, downstream testing, and indirect signals of quality rather than direct evidence from production itself. As portfolios become more complex and timelines tighten, those gaps are becoming harder to ignore.

This tension, between modern operating expectations and legacy production models, is forcing manufacturers to reassess not just how efficiently tablets are developed and manufactured, but how quality control, and confidence are achieved. Binder jet 3D printing is emerging as a precise manufacturing approach designed for how the industry operates today.

"Pharma 4.0 is about giving teams the right data, at the right level of granularity, to make confident, compliant decisions in real time. 3DP binder jetting helps make that happen," said Steve Hammond, strategic material science and PAT advisor, who has spent more than 30 years leading PAT efforts at Pfizer.

The limitations of traditional manufacturing

Conventional tablet manufacturing has delivered scale and reliability for decades, but it relies heavily on indirect quality indicators. Batch averages, destructive sampling and end-of-line testing remain the primary tools for confirming performance.

While these methods meet regulatory requirements, they also introduce inefficiencies. Variability between tablets can be masked. Release decisions may occur late in the process. Ex-

cess material, overprocessing, and rework occur to compensate for this inherent uncertainty.

These challenges are not the result of poor execution. They are structural features of manufacturing models designed for a different era.

Why 3DP binder jetting is built for Pharma 4.0

Binder jet 3D printing changes the mechanics of how tablets are made, enabling speed, precision, and integrated quality.

The following five features show why this model is gaining attention as a scalable manufacturing option redefining agility in a Pharma 4.0 environment.

1. Tablets Are Manufactured Directly in the Primary Package

One of the most distinctive features of in-blister binder jet 3D printing is that the tablets are manufactured directly inside pre-formed blister cavities. Tablet handling and transfer steps are removed entirely.

This reduces risk by minimizing physical movement and limits potential damage. It also creates a clear line of traceability from powder input to packaged unit. Each tablet can be linked to its specific production parameters, supporting 100% tablet inspection, unit-level inspection, serialization and digital records without additional processing steps (*see Figure 1*).

2. Quality Monitoring is Transformed by AI-infused PAT Throughout the Layering Process

Unlike traditional compression, which forms a tablet in a single step, binder jet 3DP constructs tablets layer by layer. Each layer becomes an opportunity to verify quality as it happens.

Embedded Process Analytical Technology (PAT) monitors tablet mass, API content, structural integrity, and surface quality. This granular visibility directly supports quality-by-design principles and allows for multiple opportunities to observe, evaluate and adjust the process in real time.

Early operational modeling suggests this approach:

- Drives reduced cycle time through integrated unit operations
- Achieves ~99% material yield, minimizing waste
- Eliminates tech transfer, accelerating time to market by ~18+ months

3. Real-Time Decisions Keep People at the Center

Advanced manufacturing does not eliminate the role of people, it elevates it.

In the binder jet workflow, operators and quality assurance teams remain central to decision-making. By way of a central control architecture, they review real-time PAT feedback, assess trends and make contextual judgments that automation cannot do alone.

Teams can make adjustments in real time, working within approved control strategies while production moves forward. "Automation generates signals; people turn those signals into decisions. That's what makes real time release both scalable and compliant," said Kyle Smith, President and COO, Aprecia Pharmaceuticals.

4. Designed for Operational Efficiency, Not Just Compliance

Additive manufacturing, specifically binder jet 3DP, is built not only to meet regulatory expectations but to optimize operational performance.

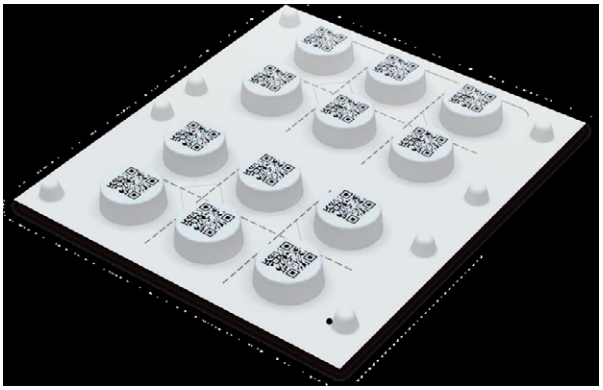


Figure 1. Tablets manufactured directly in blister cavities can be linked to unit-level information including material ID, lot number, tablet mass, API content, release status, and quality metadata, creating a digital record for every tablet.

Conventional manufacturing often compensates for uncertainty with buffers, more material, more testing, and more time. Binder jet 3D printing reduces the need for those buffers by making the process itself more predictable. Digital twin technology allows us to model, monitor, and optimize every step from development through primary packaging, so product is validated virtually before material is ever committed.

By reducing overprocessing and rejected materials, this approach is designed to lower cost of goods sold. With an unparalleled 99% batch yield, it also enables more efficient use of APIs due to precise, tablet-level control, supports rapid supply of additional strengths or batch sizes and simplifies scale-up since no transfer is required.

5. A Distributed, Pharma 4.0-Ready Future

Binder jet 3DP supports the future of end-to-end distributed manufacturing. Multiple sites can operate under a common control strategy, producing tablets to the same standards with consistent oversight. This supports geographic redundancy, reduces supply chain risk, and opens opportunities to manufacture closer to patients or points of care.

Looking ahead

Binder jet 3D printing is not simply an incremental improvement to existing tablet manufacturing. It represents a different way of embedding quality, visibility, and control into production from the start. By shifting insight upstream and making individual tablets observable, binder jet 3DP addresses many of the structural limits of traditional models.

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HALA M. FADDA, Ph.D.
Professor of Pharmaceutical Sciences,
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Pediatric Formulation Gaps and the Role of Novel Dosage Forms

Butler University's Hala Fadda discusses swallowability, dose flexibility, patient acceptance, and the need for more age-appropriate medicines.

BY TIM WRIGHT, EDITOR, CONTRACT PHARMA

Pediatric medicine has come a long way, but dosage form design is still a stubborn challenge. Many products available for children are not always built around how kids actually take medicine—whether they can swallow it, whether the dose can be adjusted safely, or whether the formulation is acceptable for both patients and caregivers. As a result, families and healthcare providers often still rely on splitting tablets, compounding, or other workarounds that can make dosing more complicated than it should be.

In this Q&A, Hala M. Fadda, Ph.D., Professor of Pharmaceutical Sciences at Butler University and Pediatric Formulations Chair for the International Pharmaceutical Federation, discusses the most significant formulation gaps facing pediatric populations today, the growing importance of patient-centric dosage form design, and why technologies such as orally disintegrating tablets and pharmaceutical 3D printing may help shape the future of pediatric drug delivery.

Contract Pharma: *Where do you still see the biggest gaps in pediatric dosage forms?*

Hala M. Fadda: Despite meaningful regulatory progress,

significant gaps persist in pediatric medicines development. A central issue is the continued reliance on off-label prescribing of medicines authorized for adults, often requiring formulation manipulation such as splitting or compounding, which can compromise dose accuracy, safety, and efficacy. These challenges are especially pronounced in neonates and infants, where limited clinical evidence and heightened sensitivity to excipients restrict formulation options.

Another significant gap is the limited availability of truly age-appropriate formulations. While some pediatric products exist, they are not always optimized for all age groups in terms of administration, acceptability, or dosing flexibility. This reflects a disconnect between regulatory approval and real-world usability.

Additionally, there are critical knowledge gaps in excipient safety. There is limited robust evidence available on acceptable excipient exposure levels and maximum daily intake thresholds for children.

Finally, there is a lack of formulations which provide dose flexibility, this is essential for the heterogenous pediatric population due to weight-based dosing requirements and rapid developmental changes. Overall, these gaps highlight the need for more targeted, evidence-based, and patient-centric formulation strategies.

CP: *Why are swallowability and dose flexibility still such major challenges?*

Prof. Fadda: Swallowability and dose flexibility remain major challenges because they are rooted in both physiological limitations and formulation constraints. Young children, particularly those under five years old, often cannot safely swallow large tablets or capsules, creating a need for alternative formulations. Furthermore, children exhibit heightened sensitivity to taste, and unpleasant flavors can lead to refusal, making oral administration difficult even when swallowing is physically possible.

Dose flexibility is equally problematic because pediatric dosing typically depends on body weight or developmental stage, requiring precise and accurate dosing to different pediatric age groups. However, many available formulations are fixed- dose systems that require splitting or compounding to achieve pediatric doses, which can introduce dosing variability. This challenge is intensified by variability in pediatric physiology and metabolism, and caregiver dependence, meaning that even small dosing errors can have significant clinical consequences.

A considerable proportion of liquid formulations contains excipients with safety concerns, including ethanol and propylene glycol, which present the risk of cumulative exposure in pediatric patients receiving multiple treatments. Thus, underscoring the need to develop products using excipients with positive risk assessment, or the development of solid dosage forms such as granules or orally disintegrating tablets.

CP: *What kinds of novel dosage forms or technologies show the most promise?*

Prof. Fadda: Several emerging dosage forms and technologies show strong potential to address current limitations in pediatric drug delivery. Buccal and transmucosal systems are particularly promising because they allow rapid drug absorption while bypassing first-pass metabolism, making them useful in acute conditions such as seizures or pain.

Orodispersible films, wafers, and strips are gaining attention as they dissolve quickly in the mouth without requiring water, improving ease of administration and patient compliance. However, their main limitation is restricted drug loading capacity.

Among the most promising technologies are non-conventional solid dosage forms such as orally disintegrating tablets (ODTs), chewables, pellets and granules that combine ease of administration, dose flexibility, acceptability and safe excipients, aligning with the growing emphasis on patient-centric drug development.

CP: *How important is patient acceptability to adherence in pediatric care?*

Prof. Fadda: Patient acceptability is a critical determinant of adherence in pediatric care and is key to ensuring accurate dose administration. Children are highly sensitive to sensory factors such as taste, texture, smell, and appearance, and negative experiences can lead to refusal of medication. Taste is one of the most important factors influencing adherence, as many active pharmaceutical ingredients are inherently bitter.

Acceptability also includes dosage form size, volume, and ease of administration, all of which vary in importance depending on the child's age and developmental stage. Caregiver involvement further complicates adherence, as administration often depends on the caregiver's ability to deliver the medication effectively and consistently. Poor acceptability can result in missed doses, incomplete therapy, and reduced therapeutic outcomes.

Improving acceptability is essential for ensuring successful treatment, particularly in chronic conditions where long-term adherence is required. Pediatric drug product design must prioritize palatability, ease of administration, and overall user experience alongside clinical effectiveness.

CP: Could technologies like pharmaceutical 3D printing play a bigger role in patient-centric drug development moving forward?

Prof. Fadda: Pharmaceutical 3D printing, as exemplified by SPRITAM, closely aligns with key pediatric quality target product profile attributes outlined by the World Health Organization (WHO) pediatric quality product profile assessment tool (PQP-PAT), including dose flexibility, patient acceptability, excipient safety, and ease of administration.

The technology has strong potential to transform pediatric medicine by enabling highly individualized, flexible, and user-friendly dosage forms, making it a key area for future research and implementation. As the industry continues moving towards patient-centric development, pharmaceutical 3DP could play an important role in improving both adherence and therapeutic outcomes in pediatric populations.

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Aprecia's 3DP manufacturing system produces tablets directly within blister cavities, supporting integrated quality control and traceability.

Advancing Personalized Medicine with 3DP

How additive manufacturing is enabling personalized oral therapies.

APRECIA PHARMACEUTICALS

Pharmaceutical manufacturing is entering a new era, one defined by personalization, precision, and patient-specific care models. Yet while therapeutic science continues to advance rapidly, oral dosage manufacturing has not kept pace. Traditional tablet production remains optimized for scale, not variability, creating a structural mismatch between what modern medicine can envision and what manufacturing has traditionally delivered.

Additive manufacturing, particularly 3DP binder jetting, removes these constraints by enabling flexible, precise and data-rich production. For drug product developers and innovators navigating increasingly individualized care models, 3DP creates a realistic and operationally credible path to personalized oral drug delivery.

Why personalization will outpace traditional oral dosage manufacturing

Personalization is no longer a niche concept and is now becoming a defining expectation across healthcare. Precision oncology, rare disease therapies and central nervous system (CNS) treatments increasingly rely on individualized dosing, adaptive regimens and patient-specific formulations. Yet, oral dosage forms remain constrained by manufacturing models built for uniformity, not personalization. Tablets are still produced in fixed strengths, built around single APIs and manufactured through batch-based processes that favor uniformity over variability.

Traditional tablet production excels at producing identical units efficiently, but it struggles to accommodate the flexibility required for patient-specific dosing, combination therapies, or formulations tailored to administration needs. Challenges such as swallowing difficulty, dosing requirements, and non-standard strengths are often addressed individually, but remain difficult to solve at scale through traditional manufacturing.

As a result, oral therapies often lag behind the personalization seen in other therapeutic areas. The limitations of

"Personalized medicine changes the manufacturing equation, introducing the need for speed, flexibility, and precision that can be validated at the unit level."

KYLE SMITH, APRECIA

fixed-strength tablets, rigid batch models and the difficulty of adjusting doses can make it challenging to deliver individualized regimens through traditional approaches.

From a manufacturing perspective, personalized medicine introduces a new set of requirements: speed without sacrificing quality, flexibility without regulatory risk, and precision that can be validated at the unit level. This is where additive manufacturing comes into play, introducing a production model capable of supporting these demands without adding significant conversion cost.

"Personalized medicine changes the manufacturing equation, introducing the need for speed, flexibility, and precision that can be validated at the unit level," said Kyle Smith, President and Chief Operating Officer, Aprecia.

Additive manufacturing: the structural enabler of personalization

Additive manufacturing, particularly 3DP binder jetting, represents a meaningful shift in how oral therapies can be designed and manufactured. By precisely controlling where and how print fluid is deposited onto a powder substrate, binder jetting enables fine control over tablet structure, dose accuracy, and release behavior. This makes it possible to adjust strengths, explore multidrug or multimatrix constructs, and introduce greater formulation complexitdy without the proportional increases in cost, risk or setup time.

"Additive manufacturing, combined with Aprecia technology, enables pharma and biotech to not only be patient focused but also to tackle some of its toughest manufacturing challenges," said Andrew Karazim, Chief Commercial Officer, Aprecia.

Market research across compounding and specialty pharmacy environments consistently highlights the current limitations in personalized care—limited flexibility, slow turnaround times, and difficulty producing easy to administer, pediatric appropriate doses.

Aprecia's 3DP binder jetting directly addresses these obstacles on an industrial scale. Flexible production and quick turnarounds allow manufacturers to respond to changing dose or formulation requirements instantaneously without lengthy changeovers. The technology can also support a range of performance profiles including traditional hardness to orodispersible tablets (ODT) with tailored porosity, offering easier to swallow options for patients who struggle with conventional tablets. These same capabilities are particularly valuable in pediatric and specialty populations, where nonstandard strengths, rapid development timelines and patient-centric formats can meaningfully support individualized care and offer innovator companies another means for competitive advantage in the marketplace.

From a practical manufacturing standpoint, these capabilities translate directly into use-case value:

- Individual blister coding enables patient or prescription specific traceability, creating a direct link between each tablet and its intended use.
- The incremental forming process ensures that 100% of tablets undergo inspection, providing visibility and confidence into units that fall outside standardized strength ranges.
- Real time data capture supports release decisions without waiting for end of line testing, which is important for personalized or on demand production models.
- The ability to run multiple matrices or dosators within the same system further enables structural and compositional variation without equipment changes.

Personalized medicine is advancing quickly, and oral dosage forms need a manufacturing approach that can adapt just as rapidly. For pharmaceutical leaders evaluating how to operationalize personalization responsibility, additive manufacturing offers a practical, scalable foundation that aligns flexibility, precision and regulatory confidence within a single production model.

CASE STUDY HIGHLIGHT:

Research presented at AAPS demonstrated that binder jetting 3DP can successfully produce modified release tablets, even when incorporating a highly water-soluble drug at high drug load. Click **HERE** for more information.

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More Than Manufacturing

Pharmaceutical 3D printing is changing how companies think about dosage forms, patient use, and product design.

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For years, pharmaceutical manufacturing was largely viewed as the back end of drug development—the part that scaled a formulation once the science was already established. But that line of thinking has started to shift. Increasingly, manufacturing technology itself is becoming part of the therapeutic conversation.

One place you can really see that shift happening is around pharmaceutical 3D printing, or additive manufacturing. Not that long ago, it still felt like something the industry talked about more in theory than in practice. Now it's showing up more often in regulatory conversations and real-world development strategies. Regulators are asking tougher questions about how patients actually take medicines—whether a dosage form is easy to use, flexible enough for different populations, or creates challenges around administration and adherence. At the same time, drug developers are looking for ways to stand out beyond the molecule itself, especially in crowded therapeutic areas where the patient experience can end up mattering just as much as the clinical data.

You can see the mindset changing a bit across the industry too. Manufacturing used to sit mostly in the background once the formulation work was done. Now it's becoming part of the bigger discussion around how a product performs outside the clinic—how easy it is for patients to take, how flexible the dosing can be, and even how regulators look at the overall value of the therapy.

Pharmaceutical 3DP sits at the center of that conversation.

The technology's ability to create highly porous dosage forms, flexible strengths, personalized regimens, and alternative administration approaches is giving drug developers new ways to think about oral dosage design—particularly for patient populations that have historically been difficult to serve with conventional tablets and capsules. Its versatility supports a broad spectrum of drug products, including high-dose and microdose therapies, ODT alternatives, pediatric formulations, high-potency drugs such as cancer treatments, and liquid alternatives, delivering key benefits such as improved swallowability and precise dosing.

And regulators are clearly paying attention.

Earlier this year, the European Medicines Agency (EMA) released new Questions & Answers guidance focused specifically on implementing 3DP technology for solid oral dosage forms.[1] The document describes 3DP as "an emerging technology with great potential in pharmaceutical applications," highlighting its ability to support patient-centric dosage forms, personalized medicines, flexible dosing, and adaptable drug combinations.

What stands out about the guidance is that it doesn't treat 3DP like some experimental side topic anymore. The conversation is much more grounded in practical things—patient usability, flexible dosing, personalized treatment approaches, and how medicines actually get used outside controlled clinical settings.

Those same themes are increasingly showing up across the pharmaceutical industry.

Similar signals are also emerging from the FDA, particularly around patient-focused drug development (PFDD), real-world treatment experience, and advanced manufacturing initiatives that tie product design more closely to clinical utility and patient outcomes.[2]

The move toward patient-centric drug design

Patient-centricity has become one of the most commonly used phrases in biopharma over the last several years. But in practice, much of the discussion has focused on clinical trial participation, decentralized studies, or digital engagement tools.

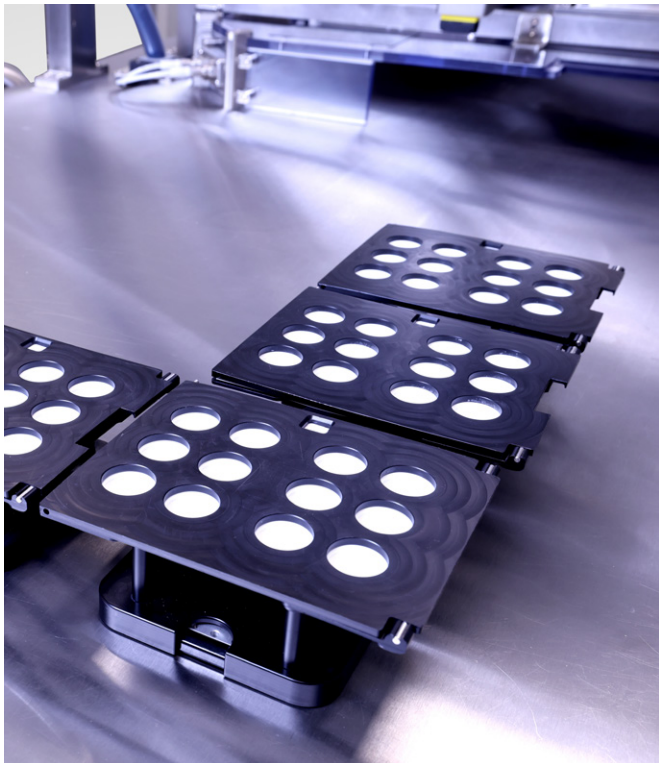
Dosage form design is now becoming part of that conversation as well.

For many patients, particularly pediatric, geriatric, neurologic, and polypharmacy populations, the challenge isn't simply accessing therapy. It's taking the medication consistently and correctly.

A lot of the everyday challenges around oral medications still haven't gone away—patients struggling to swallow tablets, caregivers crushing pills for feeding tubes, complicated dosing adjustments, or adherence problems tied to how difficult a therapy is to take consistently. And historically, solving those kinds of issues hasn't always been easy with conventional manufacturing approaches, especially without creating multiple versions of the same product or adding more complexity to development.

That is where pharmaceutical 3DP has begun attracting attention.

Because additive manufacturing builds dosage forms layer by layer from digital designs, it offers a level of structural and dosing flexibility that conventional compression methods can struggle to achieve. In practical terms, that can mean rapid-dispersing tablets, individualized dosing strengths, multi-drug combinations, or formulations designed specifically around administration needs.



Blister trays used within Aprecia's pharmaceutical 3D printing platform help support flexible, patient-centric oral dosage forms and unit-level traceability.

Importantly, these are not theoretical advantages anymore.

Aprecia's Spritam, the first FDA-approved 3D printed drug product, demonstrated how highly porous structures could enable rapid disintegration with a sip of liquid. While initially recognized as a manufacturing milestone, the broader significance may now be more apparent years later: the technology showed that dosage form engineering itself could improve administration and patient usability.

That idea is getting more attention as regulators spend more time looking at what happens after a drug leaves the clinical setting and enters the real world, where administration, adherence, and patient experience can all affect outcomes.

Manufacturing as a differentiator—not just a process

For a long time, manufacturing conversations mostly revolved around scale, efficiency, timelines, and supply reliability. Those things still matter, obviously, but the discussion has broadened. More companies are starting to ask a different set of questions around manufacturing—can it make a therapy easier for patients to use, help simplify dosing, improve adherence, or create a product experience that stands apart from more conventional formulations?

In that sense, advanced manufacturing platforms are becoming differentiators in their own right.

The recent EMA guidance reflects this shift directly. The agency specifically noted that 3DP can facilitate "a wide spectrum of dosage levels, shapes, flavors, colors, or drug combinations," tailored to specific patient groups and disease conditions.

What makes the guidance interesting is that it spends less time talking about the technology itself and more time talking

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PROFESSOR HALA FADDA, BUTLER UNIVERSITY

about patients. A lot of the examples center around flexibility, usability, and tailoring dosage forms to different populations—which is something pharma has struggled with for years, especially in pediatrics.

That came up in a recent Butler University paper looking at pediatric oral formulations.[3] The research, led by Hala Fadda, Ph.D., Butler University Professor of Pharmaceutics and Pediatric Formulations Chair, International Pharmaceutical Federation, found there are still plenty of gaps when it comes to making medicines easier for children to take. Swallowability was a major issue, along with dose flexibility and administration challenges tied to conventional tablets and capsules.

The paper looked at more than 200 pediatric oral products and found that standard tablets and capsules still dominate the market, even for younger age groups where they're often difficult to use. The authors also pointed to concerns around certain excipients used in liquid formulations and argued that more patient-friendly dosage approaches are still lacking.

"Both acceptability and precise dosing are critical when it comes to real world outcomes," said Fadda in an interview with *Contract Pharma* regarding the study. "The most effective medicines consider the patient experience, including tolerability, administration, and the practicalities of daily use."

That's part of the reason technologies like pharmaceutical 3DP are getting more attention. Not necessarily because the technology itself is flashy, but because it potentially gives developers more room to rethink how oral medicines are designed and administered for different patient populations.

Why flexibility matters

One of the more important aspects of pharmaceutical 3DP is not simply the ability to print tablets. It's the ability to adjust dosage strength and product characteristics through digital process parameters rather than entirely separate manufacturing setups.

That distinction could become increasingly important as the industry continues moving toward personalized medicine and smaller patient populations.

The EMA guidance specifically acknowledged this advantage, noting that 3DP can generate multiple dosage strengths from the same formulation through validated process parameters. The agency further stated that matrixing or bracketing approaches may be acceptable for process validation and stability studies when multiple strengths are proposed.

In practical terms, that means companies may be able to streamline development approaches while supporting a broader range of dosing options.

For therapies requiring titration, individualized dosing, or narrow therapeutic windows, that flexibility could become increasingly valuable.

There's also growing interest in what this could mean for orphan drugs and rare disease therapies, where patient populations are often too small to fit neatly into traditional large-scale manufacturing models. One advantage of additive manufacturing is the ability to work with smaller batches and make adjustments more quickly without overhauling an entire production setup, which could make a lot more sense for highly targeted therapies.

Even though most of the conversation today is still focused on oral solid dosage forms, it also feels like part of a broader change happening across the industry. Pharma has traditionally been built around large-scale, standardized manufacturing. But there's clearly more interest now in therapies and dosage forms that can be adapted more easily for different patients, different dosing needs, and different real-world use cases.

Real-world usability is becoming a regulatory discussion

One of the clearest signals emerging from both FDA and EMA thinking is that regulators are paying closer attention to how products are actually used by patients.

In the U.S., that shift has become increasingly visible through FDA patient-focused drug development guidance, which places greater emphasis on treatment burden, administration characteristics, and how therapies function in routine patient use—not just controlled clinical settings.

That includes questions around administration complexity, adherence barriers, swallowing challenges, and dose flexibility.

The Butler University study underscores why this matters. Researchers found that less than one-third of oral formulations

approved for neonates met criteria for age-appropriateness, while many products still required manipulation, complex measurement, or administration workarounds.

In other words, efficacy alone does not necessarily guarantee patient adherence.

That creates pressure on developers to think beyond the molecule itself and consider how dosage form design can influence treatment success in real-world settings.

That's part of why pharmaceutical 3DP keeps coming up in these discussions. The technology gives developers more flexibility to design dosage forms around how patients actually take medications instead of trying to make patients fit around the limitations of conventional manufacturing.

Rapid-dispersing tablets are the example most people recognize first, but the technology could potentially go much further than that. The real appeal is the possibility of building multiple patient-focused features into the same dosage form—things like adjustable dosing, easier administration, better swallowability, or even combining more than one therapy into a single product.

FDA has also publicly acknowledged additive manufacturing as an emerging pharmaceutical manufacturing paradigm capable of enabling dosage forms and performance characteristics difficult to achieve through conventional methods.

The concept of "clinical utility" is becoming broader than traditional efficacy and safety endpoints alone.

Polypills, personalization, and the future of oral dosage forms

Another area drawing interest is the potential for 3DP to support combination therapies and personalized regimens.

Managing multiple medications is already a challenge across healthcare, especially for older patients dealing with several chronic conditions at once. The more complicated the regimen becomes, the harder adherence can be—not just for patients, but for caregivers too.

That's another area where pharmaceutical 3DP is drawing interest. There's growing discussion around the idea of more individualized combination products, sometimes called polypills, where multiple active ingredients could potentially be built into a single dosage form with tailored dosing or release characteristics.

It's still an emerging area, and there's obviously a lot that still needs to evolve, but the direction makes sense. Healthcare is already moving toward more personalized treatment strategies and trying to reduce some of the complexity patients face managing therapies day to day.

For pediatric populations, the ability to tailor dosage strength and administration characteristics may be especially meaningful. The Butler University researchers specifically noted that flexible and acceptable pediatric formulations remain an ongoing industry gap.

At the same time, regulators appear increasingly open to engaging with the technology.

The EMA guidance repeatedly references Quality by Design (QbD), process control strategies, digital manufacturing oversight, and real-time monitoring approaches as appropriate frameworks for 3DP manufacturing.

Those ideas also align closely with FDA's broader Quality by Design and Advanced Manufacturing Technology initiatives, which encourage manufacturing approaches capable of improving product performance, flexibility, and quality consistency.[4]

That suggests the discussion has moved beyond whether additive manufacturing belongs in pharma. The conversation is increasingly becoming about how to implement it effectively and consistently.

The broader strategic picture

None of this means conventional manufacturing disappears. Traditional tablet production remains highly efficient and appropriate for many therapies.

But advanced manufacturing technologies are expanding the range of what oral dosage forms can do.

Part of the reason this matters is because the market itself is changing. Sponsors are facing more pressure to stand out, and that differentiation is no longer coming only from the molecule. More attention is being paid to the patient side of the equation too—how easy a therapy is to take, how well patients stay on it, and whether the overall treatment experience creates advantages beyond the core clinical data.

Manufacturing platforms that can support those goals may become increasingly valuable.

In many ways, pharmaceutical 3DP represents a convergence point between several larger industry trends happening simultaneously:

- Patient-centric drug development
- Personalized medicine
- Real-world evidence and usability
- Regulatory modernization
- Smaller and more targeted patient populations
- Flexible manufacturing models
- Digital process control and Quality by Design

What once seemed like a niche technology is gradually becoming part of a much larger strategic conversation.

And increasingly, that conversation is no longer just about how drugs are manufactured.

It's about how manufacturing itself can shape the therapy experience.

For companies exploring advanced oral dosage technologies, that may ultimately become the biggest opportunity of all.

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