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REVIEW

Advancing translational science education

Jessica M. Faupel-Badger[1] | **Amanda L. Vogel**[1] | **Christopher P. Austin**[2] | **Joni L. Rutter**[1]

[1]National Institutes of Health, National Center for Advancing Translational Sciences, Bethesda, Maryland, USA
[2]Flagship Pioneering, Cambridge, Massachusetts, USA

Correspondence
Jessica M. Faupel-Badger, National Center for Advancing Translational Sciences, 6701 Democracy Boulevard, Bethesda, MD 20892-4874, USA.
Email: badgerje@mail.nih.gov

Abstract
In this communication, the authors offer considerations for how the scientific community can capitalize on decades of translational science advances and experiential knowledge to develop new education opportunities for a diverse and highly skilled translational science workforce. Continued advancement of the field of translational science will require new education approaches that distill key concepts in translational science from past and ongoing research initiatives and teach this foundational knowledge to current and future translational scientists. These key concepts include generalizable scientific and operational principles to guide translational science, as well as evidence-informed practices. Inspired by this approach, the National Center for Advancing Translational Sciences (NCATS) has developed an initial set of guiding principles for translational science generated via case studies of multiple highly successful translational science initiatives, and is now teaching them via new education activities that aim to reach a broad scientific audience interested in translational science. Our goal with this review is to prompt continued conversation with the translational science community regarding capitalizing on our collective translational science knowledge to advance core content for translational science education and disseminating this content to a broad range of scientific audiences.

STIMULATING TRANSLATIONAL INNOVATION

The National Institutes of Health (NIH) established the National Center for Advancing Translational Sciences (NCATS) in 2011 to "...pursue opportunities for disruptive translational innovation."[1] Through its extramural awards and internal research programs, NCATS is serving as this productive disruptor of research processes by catalyzing the development of innovative methods, approaches, and technologies to advance translational science.[2] Translational science aims to develop solutions to the longstanding challenges or bottlenecks that stymie progress of all research along the translational spectrum.[2] Examples of these solutions include approaches to de-risking undruggable targets or untreatable diseases, developing more predictive in vitro and in vivo models of efficacy and toxicity, improving methods for clinical trial recruitment and diversification of trial participants, and enhancing recognition for scientists who participate in large cross-disciplinary research teams.[3–6] Through developing and disseminating evidence-informed practices that overcome these challenges, translational science approaches are benefiting all research that aims to improve human health, by accelerating the transformation of discoveries into interventions and treatments.

NCATS' transformative research programs offer striking examples of the potential of translational science to produce solutions to longstanding systemic bottlenecks that slow the translational process and rapidly generate innovations that address urgent public health needs.[7–10] Specific examples of translational science advances led or supported by NCATS help to elucidate the focus of translational science, and its potential wide-ranging impact. These include the Tissue Chip Program which, with a broad network of collaborators and awardees, has enabled a wide range of research using bioengineered devices to improve the accuracy and efficiency of drug screening and development as well as understanding of human organ function; the Rare Diseases Clinical Research Network (RDCRN), Platform Vector Gene Therapy (PaVe-GT) project and Bespoke Gene Therapy Consortium, which aim to accelerate development of new treatments and cures for rare diseases via the "many diseases, one approach" model through collaborative academic and public–private partnership models; and the SMART IRB platform, a product of the Clinical and Translational Science Award (CTSA) Program, which accelerates clinical research through the use of a single streamlined institutional review board platform for multisite clinical studies.[3,5,11–13] In addition, NCATS has contributed to advancing research on addiction and pain management by accelerating drug discovery and development efforts through identifying new targets via high-throughput screening, de-risking potential therapies, and exploring new methods for clinical trial design, recruitment, and outcomes analysis.[9,14–17]

More broadly, the international scientific community's responses to the COVID-19 pandemic have reflected our accumulated knowledge of wide-ranging strategies to accelerate translation – as evidenced in the development and deployment of diagnostics, vaccines, and treatments at an astounding pace. NCATS contributions to these efforts, including the COVID-19 OpenData Portal, National COVID Cohort Collaborative (N3C), and the Accelerating COVID-19 Therapeutic Interventions and Vaccines (ACTIV) initiative, exemplify how translational science and data innovations have accelerated preclinical and clinical COVID-19 research.[8,10] The NCATS COVID-19 OpenData Portal shares screening data from preclinical assays and animal studies immediately and without restrictions to enable a variety of drug repurposing activities to accelerate the search for effective therapies against the virus.[8] N3C provides a public data resource and dashboard for investigation of clinical symptomatology, demographics, and therapeutic responses in millions of patients with acute COVID-19 and post-acute sequelae of SARS-CoV-2 infection (PASC, also known as long COVID). N3C enables the unprecedented collection and harmonization of clinical electronic health record (EHR) data across over 80 hospitals, health care networks, CTSA hubs, and other institutions.[10] As a partner in the ACTIV initiative, NCATS has contributed via coordination and leadership of a multinational clinical trial within ACTIV-1 that recently demonstrated immune modulating drugs, when added to the standard of care, improved survival of individuals hospitalized with COVID-19.[18] The remarkable innovation and acceleration seen across a variety of research processes in response to the COVID-19 pandemic has advanced translational science and created a springboard for further growth of translational science knowledge.[7]

The field of translational science is now poised for rapid growth through application of recent translational innovations to new research challenges.[2] To enable this growth, we will need new approaches to convey our experiential knowledge to current and future translational scientists. We will also need a larger, more diverse translational science workforce. Here, we share an approach to advancing the content and reach of translational science education activities, toward achieving this vision.

FORMALIZING EXPERIENTIAL TRANSLATIONAL SCIENCE KNOWLEDGE TO ENABLE FUTURE RESEARCH SUCCESS

One highly promising approach for developing new education activities that enhance understanding of translational science strategies and solutions is to leverage the experiential translational science knowledge generated by research initiatives to date through case studies, short reports, or other means of documenting the processes, methods, and decisions that enabled the research. Aggregating and studying these products would contribute to producing a body of foundational knowledge in translational science from which to distill key scientific and operational principles and evidence-based practices. These approaches maximally leverage the collective experience of the translational science community by continuously identifying new content to add to this core body of knowledge to be taught to current and future translational scientists. This knowledge must then be transmitted to the broadest possible range of individuals interested in contributing to the work of translational science, which will require pedagogical methods that effectively convey translational science core content to a wide range of audiences (e.g., scientists working across the translational spectrum, administrators, collaborators), and education opportunities that span all education (undergraduate, graduate, postdoctoral, etc.) and career stages. Developing this knowledge base and innovative education approaches to convey it will be essential to produce and sustain a flourishing translational science workforce with the know-how to reengineer the translational ecosystem, develop translational science innovations, and apply these innovations to surmount challenges across the biomedical research landscape.

Toward these ends, NCATS has embarked on formalizing translational science knowledge and experience gained from NCATS-led or -supported translational science advances and conveying this knowledge via highly accessible educational opportunities for a broad scientific audience. NCATS staff have developed an initial set of generalizable scientific and operational principles that characterize effective translational science initiatives (Table 1; Figure 1).[4,5,10] These were developed based on NCATS' decade of investments in translational science, as well as in-depth case studies of four recent and disparate translational science initiatives that span the translational spectrum: (1) the discovery and development of a novel first-in-class drug candidate to treat metastatic cancer; (2) the development and use of human tissue chips to evaluate efficacy and toxicity of compounds; (3) the creation of an online resource to facilitate patient engagement in rare disease research, at scale; and (4) the establishment of N3C to accelerate research on COVID-19 and PASC.

These principles can be applied to any research project to guide effective, efficient, and impactful translation. Developing these principles required examining each of these four research initiatives to determine what it could teach us about the translational process at a systems-level and approaches to address challenges to translational efficiency. Lessons derived from these projects were examined for relevance not only within a particular initiative but across multiple initiatives, regardless of the disease or condition they address, and across the translational spectrum. Here, we share this set of scientific and operational principles as a work in progress and an example of an approach to distilling key experiential translational science knowledge into a format that can be broadly disseminated and taught to current and future translational scientists.

TEACHING TRANSLATIONAL SCIENCE PRINCIPLES

Identifying key principles for translational science, with relevance across the translational spectrum, provides the opportunity to teach these cross-cutting concepts across a wide range of education and training opportunities. In Spring 2020, NCATS staff had the opportunity to teach these principles of translational science to a broad scientific audience. NCATS launched a 7-week online translational science course, focused on applying translational science principles to advance preclinical to clinical translational research. The course has been offered twice per year since, to students from across diverse educational and career stages, and disciplinary and professional backgrounds.[19]

The course taught the translational science principles via a case study of a highly successful preclinical research initiative led by the NCATS intramural research program in collaboration with scientists at the National Cancer Institute, University of Kansas, and Northwestern University, which resulted in a compound currently in phase I clinical trials for the treatment of metastatic cancer. The case study demonstrated how these scientific and operational principles were implemented in practice in this case and described how they contributed to advancing the science.

Scientists who were engaged in the research initiative – including biologists, chemists, toxicologists, and clinical trialists, and others – served as faculty in the course. They discussed how approaches used within the initiative illustrated larger issues in translational science – including challenges and strategies for success – and how the translational science principles were reflected in the case, advanced the work, and could be applied broadly to advance preclinical and clinical research. For example, this case focused on addressing an unmet need (i.e., therapeutics focused specifically on cancer metastasis) where solutions have the potential to impact many diseases.

Based on the experience at NCATS, we believe that developing these education activities requires access to scientists who can provide invaluable first-hand accounts about the decision-making processes and the factors beyond the science itself that facilitated a successful outcome for the project. The scientists provided examples of where they had to take informed risks with the research direction and the payoffs these decisions produced with regard to advancing the research, how the collaborating partners were necessary to advance the research from preclinical research to a phase I clinical trial (the current state of the project), how the collaborations were formed and managed, and how these and other scientific and operational strategies that helped to advance this project could be used in other settings.[4,20] Throughout the course, students were asked to reflect on how the translational science principles presented during the course could be applied to their own current and future work activities.

More information about the course design, implementation, and evaluation, as well as additional details about the students who took this course, are included in recent publications.[19,21] As part of these publications, we have

TABLE 1 Initial compilation of scientific and operational translational science principles

Scientific Principles – These principles focus on factors directly related to the selection of the research question, research approaches, and research methods.

- Prioritize initiatives that address unmet needs: These initiatives focus on pursuing scientific goals that address unmet scientific, patient, or population health needs.
  - *Scientific Needs*: Contribute to research advances in under investigated areas of science or on scientific questions that present unique research challenges or disincentives (e.g., currently untreatable diseases; de-risking targets).
  - *Patient and Population Health Needs*: Advance research to develop solutions for unmet patient and population health needs.
- Produce cross-cutting solutions for common and persistent challenges: Develop innovations that address challenges across multiple research initiatives, projects, or diseases and conditions.
  - *Across Multiple Projects*: Advance research by identifying, developing, and testing solutions to common research roadblocks that have stymied multiple projects.
  - *Across Diseases*: Approach research challenges and development of solutions by seeking commonalities across research on a range of diseases and conditions.
- Emphasize creativity and innovation: Focus on increasing the impact of research through innovations in research methods, processes, and structures.
  - *Research Methods*: Pose innovative research questions and develop and implement innovations in research methods, technologies, and approaches that increase the impact of the research.
  - *Research Processes and Structures*: Develop and implement innovations in teamwork, partnerships, and operations that enhance the quality and impact of the research.
- Leverage cross-disciplinary team science: Engage all relevant expertise across disciplines, fields, and professions to produce research that advances translation.
  - *Advance Innovation*: Integrate concepts, theories, methods, technologies, and approaches from the range of disciplines, fields, and professions that can contribute to advancing the research goals.
  - *Increase Translational Potential*: Leverage knowledge integration to develop more holistic findings that are therefore more relevant to real-world applications.

Operational Principles – These principles focus on how team functioning, organizational environment, and the culture of science influence the research. Operational principles facilitate the science.

- Enhance the efficiency and speed of translational research: Implement evidence-informed practices and scientific and operational innovations to accelerate the pace of translational research.
  - *Science*: Develop and implement innovations in scientific approaches, methods, and technologies that accelerate the pace of translational research.
  - *Team Functioning*: Implement evidence-based practices to enhance the speed at which teams develop shared goals and improve team communication and coordination of work tasks.
  - *Decision making*: Implement milestone-based decision making to enable rapid agreement on go/no-go decisions, to enable resources to be used most efficiently.
  - *Organizational Environment*: Reward efficiency, enable rapid failures, and encourage redirection of resources to subsequent attempts.
- Utilize boundary-crossing partnerships to advance translation: Leverage cross-disciplinary research teams, patient engagement, community engagement, and cross-agency partnerships .
  - *Team Functioning*: Implement evidence-informed practices for collaborations, engagement, and partnership.
  - *Organizational Environment*: Provide leadership, policies, and physical spaces that facilitate boundary-crossing collaborations within and outside of one's organization.
  - *Recognition and Reward Systems*: Incentivize collaboration through recognition and reward systems that value team science, cross-disciplinary collaboration, patient and community engagement, and cross-agency partnerships.
  - *Science Policy*: Design funding opportunities that support and facilitate collaboration, engagement, and partnerships to achieve scientific goals.
- Use bold and rigorous research approaches: Develop ambitious research questions and implement transformative approaches that match the complexity of the translational problem being addressed.
  - *Science*: Explore historically intractable research questions with the goal of fundamentally changing the translational research ecosystem, focus on areas of research where other partners may lack incentives, and employ rigorous approaches that will enable the research to advance translational science regardless of whether the initial research objective is met (e.g., learning from failures).
  - *Team and Organizational Environments*: Encourage transformative ideas and risk-taking toward achieving the overall goal of improving the translational process.
  - *Recognition and Reward Systems*: Recognize the value of rigorously testing bold, paradigm-challenging ideas and do not penalize individuals and/or teams for informed risk taking or productive failures.
  - *Science Policy*: Develop funding opportunities that invite transformative research to address high need areas of science and unmet patient needs.

FIGURE 1 Summary graphic of translational science principles with brief titles and descriptions.

made the course syllabus, required readings, glossary, and evaluation instruments available, with the goal to disseminate these broadly so others will be able to adapt them for their own education activities.

BUILDING UPON AND AUGMENTING CURRENT TRANSLATIONAL SCIENCE EDUCATION OPPORTUNITIES

A robust nationwide network of academic medical centers is providing rigorous training and education opportunities in many domains essential to developing translational scientists and reaching hundreds of early career scientists each year.[22–24] These training and education opportunities center around core competencies and skills such as those developed by the Education Core Competency Work Group under the CTSA Education and Career Development Key Function Committee and the Characteristics of a Translational Scientist developed by Translation Together, an international collaboration of translational research organizations.[25–27]

In 2011, the Education Core Competency Work Group of the CTSA program hubs recommended 14 core competencies for clinical and translational research "...to be used to shape training experiences for junior investigators, by defining skills, attributes, and knowledge" to be conveyed.[27,28] Eight of these competencies comprised core research skills (e.g., establishing research questions and designing and implementing research studies; skills for literature critique, statistical analyses, and use of informatics; clinical research interactions), while six extended into cross-cutting skills with relevance to research collaboration (e.g., knowledge and skills for participating in or leading a cross-disciplinary team; community engagement); increasing diversity and equity in research; leadership/mentoring; and scientific communication. In addition to the competencies listed above, other areas of emphasis in translational science education and training programs have included developing knowledge in translation-related fields such as team science, regulatory science, and implementation science.[25,29,30]

More recently, in 2019, the Translation Together consortium, comprised of seven international organizations leading translational research efforts, put forward seven characteristics to be strived for among translational scientists. These characteristics assert that translational scientists must work in cross-disciplinary teams, understand the translational process at a systems-level, and develop

TABLE 2 Relationship between clinical and translational research competencies, characteristics of a translational scientist, and principles of translational science

Focus	Fourteen clinical and translational research core competencies areas[a,26,28,31]	Seven characteristics of a translational scientist[b,26]	Principles of translational science[32]
	Individual scientist	**Individual scientist**	**Research focused – approaches to addressing translational challenges**
	1. Clinical and translational research questions	1. Domain expert – Possesses deep disciplinary knowledge and expertise within one or more of the domains of the translational science spectrum ranging from basic to clinical to public health research and domains in between	1. Prioritize initiatives that address unmet needs – Pursue scientific goals that address unmet scientific, patient or population health needs
	2. Study design	2. Rigorous researcher – Conducts research at the highest level of rigor and transparency, possesses strong statistical analysis skills, and designs research projects to maximize reproducibility	2. Produce cross-cutting solutions for common and persistent challenges – Develop innovations that address challenges across multiple research initiatives, projects, or diseases and conditions
	3. Scientific communication	3. Skilled Communicator – Communicates with understanding with all stakeholders in the translational process across diverse social, cultural, economic, and scientific backgrounds, including patients and community members	3. Emphasize creativity and innovation – Focus on increasing the impact of research through innovations in research processes, structures, and methods
	4. Translational teamwork	4. Team player – Practices a team science approach by leveraging the strengths and expertise and valuating the contributions of all players on the translational science team	4. Leverage cross-disciplinary team science – Engage all relevant expertise across disciplines, fields, and professions to produce research that advances translation
	5. Literature critique	5. Systems thinker – Evaluates the complex external forces, interactions and relationship impacting the development of medical interventions, including patient needs and preferences, regulatory requirements current standards of care, and market and business demands	5. Enhance the efficiency and speed of translational research – Implement evidence-informed practices and scientific and operational innovations to accelerate the pace of translational research
	6. Research implementation	6. Boundary crosser – Breaks down disciplinary skills and collaborates with others across research areas and professions to collectively advance the development of a medical intervention	6. Utilize boundary-crossing partnerships – Leverage cross-disciplinary research teams and patient and/or community engagement to advance translation
	7. Sources of error	7. Process innovator – Seeks to better understand the scientific and operational principles underlying the translational process and innovates to overcome bottlenecks and accelerate that process	7. Use bold and rigorous approaches – Develop research questions and implement transformative approaches that match the complexity of the translational problem being addressed
	8. Statistical approaches		
	9. Biomedical informatics		
	10. Clinical research interactions		

TABLE 2 (Continued)

Focus	Fourteen clinical and translational research core competencies areas[a,26,28,31] — Individual scientist	Seven characteristics of a translational scientist[b,26] — Individual scientist	Principles of translational science[32] — Research focused – approaches to addressing translational challenges
	11. Cultural diversity		
	12. Leadership		
	13. Cross-disciplinary training		
	14. Community engagement		

[a]The 14 Domain Areas encompass approximately 100 competencies, with each area having 4–10 competencies or knowledge, skills, and abilities (KSAs).[27,28]

[b]Tsevat and Smyth proposed a model where the first four characteristics of a translational scientist and the first four key areas within the clinical and translational research competencies overlap, demonstrating the intersection between translational research and studying larger issues in the translational process (i.e., translational science).[31] In this model, the last three characteristics of a translational scientist were seen as being distinct to translational science.

new processes, in addition to being rigorous researchers, having deep knowledge within one or more domains of the translational spectrum, and being skilled communicators.[26] The authors note that any one of these characteristics could apply to investigators in any number of disciplines but "the full complement as described here is arguably unique to translational science."[26]

These frameworks reflect considerable effort from the community to provide a structure for evaluation outcomes of education and training programs with regard to the skills of the individual translational scientist. We propose complementing these frameworks with a focus on how to conduct research using approaches to address larger, systemic translational challenges, and enhance the effectiveness, efficiency, and impact of translational research, across the translational spectrum, as reflected in the translational science principles included here. A comparison of the CTSA-generated clinical and translational research competencies, the characteristics of a translational scientist, and the translational science principles is shown in Table 2. Adding instruction in the translational science principles would further unify translational science training and education activities and contribute to formalizing translational science as a distinct area of study.

These principles can be used to enhance existing and develop new translational science education and training content that is accessible to individuals across a range of education and career stages. The principles can also be used to assess the scope and breadth of translational science education and training opportunities as the field continues to grow and evolve, in order to identify strengths and areas for growth. In addition, we hope they will stimulate additional scholarship on core scientific and operational approaches that span the translational spectrum. Ultimately, incorporating these principles and related core concepts into education activities will enable translational researchers across all stages of the translational spectrum and disease areas to apply these to their own work, resulting in more robust, efficient, and predictive research for the development of new diagnostics, treatments, and interventions across all diseases and conditions.

EXPANDING TRANSLATIONAL SCIENCE EDUCATION TO ALL EDUCATION AND CAREER STAGES

In addition to distilling translational science experiential knowledge into a format that can be conveyed to a broad scientific audience, it will be critical to expand the scope of participants in translational science education activities in order to expand and diversify the expertise of the translational science workforce.[33] Most current translational science education and training opportunities are structured as multi-year pre- and postdoctoral fellowships.[31,34,35] This model of teaching the science of translation through pre- and postdoctoral fellowship opportunities provides the most comprehensive and intensive translational science training experience. However, this approach does not scale for education and training of the full range of scientists and collaborators needed to build the translational science enterprise, including early-career scientists just beginning to explore this field, as well as more established scientists, physicians, patient advocates, community partners, and others working across the translational spectrum.

To further establish the field of translational science and career paths within this field, we must provide a range of education activities that leverage translational science principles and are at the appropriate levels for participants at different education (e.g., undergraduate, graduate, and postdoctoral) and career phases, in order to reach both new and established scientists interested in this exciting field. For example, reaching individuals earlier in their education (e.g., undergraduate students) before they have embarked on a career path or decided on continuing their education in graduate or professional school would enable future scientists to begin to identify with translational science at a critical time in the development of their professional identities and may lead them to seek out additional options for developing these skills.[36,37] By developing additional entry points for exposure to the field of translational science, across training and career stages, and for individuals with varied disciplinary and professional backgrounds, we can expand the workforce to include a broader array of individuals with expertise to contribute to advancing the translational enterprise.

It will also be critical to enable translational science concepts to be more broadly disseminated through innovative technological and didactic approaches that can reach a large number and diverse range of individuals interested in translational science education and training. Courses in translational science are a key approach to accomplish this goal. As an example, the NCATS case study-based online course demonstrated high demand for this type of opportunity across educational and career stages, scientific backgrounds, career paths, and geographic areas. Course participants from the two sessions of the NCATS online course offered in 2020 ($n = 95$) included students from postbaccalaureate level to approximately half of whom had achieved a doctoral level degree.[19] Among those with a doctoral degree, over 30 different degree disciplines and a variety of career sectors (i.e., government, academia, non-profit) were represented.[19] At the end of the course, 99% of this diverse range of participants indicated the course goal of providing a unique window into translational science had been achieved.[19] This course ultimately provided a proof-of-concept for teaching translational science principles to a broad scientific audience.

EVALUATING FUTURE TRANSLATIONAL SCIENCE EDUCATION OPPORTUNITIES UTILIZING TRANSLATIONAL SCIENCE PRINCIPLES

Another imperative for the advancement of the translational science field is to rigorously evaluate new education offerings that utilize the translational science principles. This includes evaluating students' learning outcomes, such as changes in knowledge, skills, and attitudes relevant to translational science, and the impact of participation on students' scientific behaviors, research goals, and career plans. Evaluation efforts should also collect information about who is participating in translational science education activities and their educational goals, toward tailoring content to the breadth of interests and needs of the translational science workforce. Collectively, these evaluation data will establish the evidence for effective educational approaches to teaching translational science concepts and will build a foundation from which to continue to innovate on both content and modality.

The NCATS online translational science course was accompanied by a rigorous pre- and post-course evaluation. This evaluation sought to determine how effective the online course content and structure were to teach translational science concepts. The Kirkpatrick Evaluation Model was the basis for the course evaluation design. It identifies four levels of outcomes and impacts for educational offerings: (1) satisfaction with the course; (2) knowledge acquisition; (3) behavioral and attitudinal change; and (4) impact on performance.[38] Baseline and endpoint student surveys included scales assessing translational science knowledge and attitudes. These found statistically significant positive increases in both domains.[21]

With a 7-week, 1-credit hour online course, it was beyond the scope of the evaluation to follow students to assess the long-term impact of the course on their performance. Instead, the endpoint survey included questions about the impact of the course on goals and intentions for future professional activities, longstanding proxy measures for behavior change.[39] Students reported that the course impacted their skills and knowledge for cross-disciplinary team-based research and translational science, and influenced their planned scientific activities and career goals. The full evaluation methods, instruments, and findings are available in a recent publication.[21]

The evaluation also solicited student feedback related to enhancing and expanding the course. Based on this feedback, we developed new course components further emphasizing the translational science principles. These new components were part of the 2021 and 2022 offerings of the course. The course evaluation instrument was also enhanced, including a new scale on knowledge of the translational science principles. More information on the enhanced course and its evaluation will be shared in a future publication.

In addition to evaluating training and education activities utilizing the translational science principles, translational science practitioners and evaluators could test and validate these principles in practice and propose new principles to build the evidence at the foundation of the field. Dissemination of knowledge among translational researchers on how they have applied scientific and operational principles of translational science across a variety of research initiatives (spanning diseases, conditions, and phases of the translational spectrum) as well as organizational contexts, will help to establish effective strategies in translational science, and lead to further development of the translational science knowledge base. This includes knowledge of adaptations, utility, impact, and challenges related to implementing these principles in a variety of settings. With this "learning system" in place, ideally the efficiency and effectiveness of translational research to create and deliver diagnostics, treatments, and interventions more predictably will progressively improve; the time, difficulty, and cost of these efforts will progressively decrease; and both the biomedical research and healthcare systems will benefit.

ENGAGING THE BROADER COMMUNITY IN ADVANCING TRANSLATIONAL SCIENCE EDUCATION

The translational science principles proposed here highlight potential new core content to be conveyed in translational science education activities and contribute to efforts toward distinguishing the field of translational science. Our goal in sharing these translational science principles is to stimulate interest among the broader scientific community in developing new education opportunities where the subject is the translational process itself, including the common challenges or roadblocks that occur, generalizable principles that can be applied to overcome these challenges to advance translational research across the translational spectrum, and strategies that have been used effectively to do so. The ultimate goal is to increase the "flow rate" at which activities that enter the translational process ultimately lead to interventions, diagnostics, treatments, and cures. These approaches, and their impact on advancing translation, are depicted in Figure 2. Figure 2 also provides examples of how principles and related linked strategies can be implemented to advance translation, and includes a number of exemplar programs at NCATS that have implemented these principles in practice. The translational science principles shared here are a work in progress that we anticipate will continue to evolve based on additional case studies and the growing expertise of the translational science community. We also hope members of the broader scientific community will make additional contributions that expand and enhance our

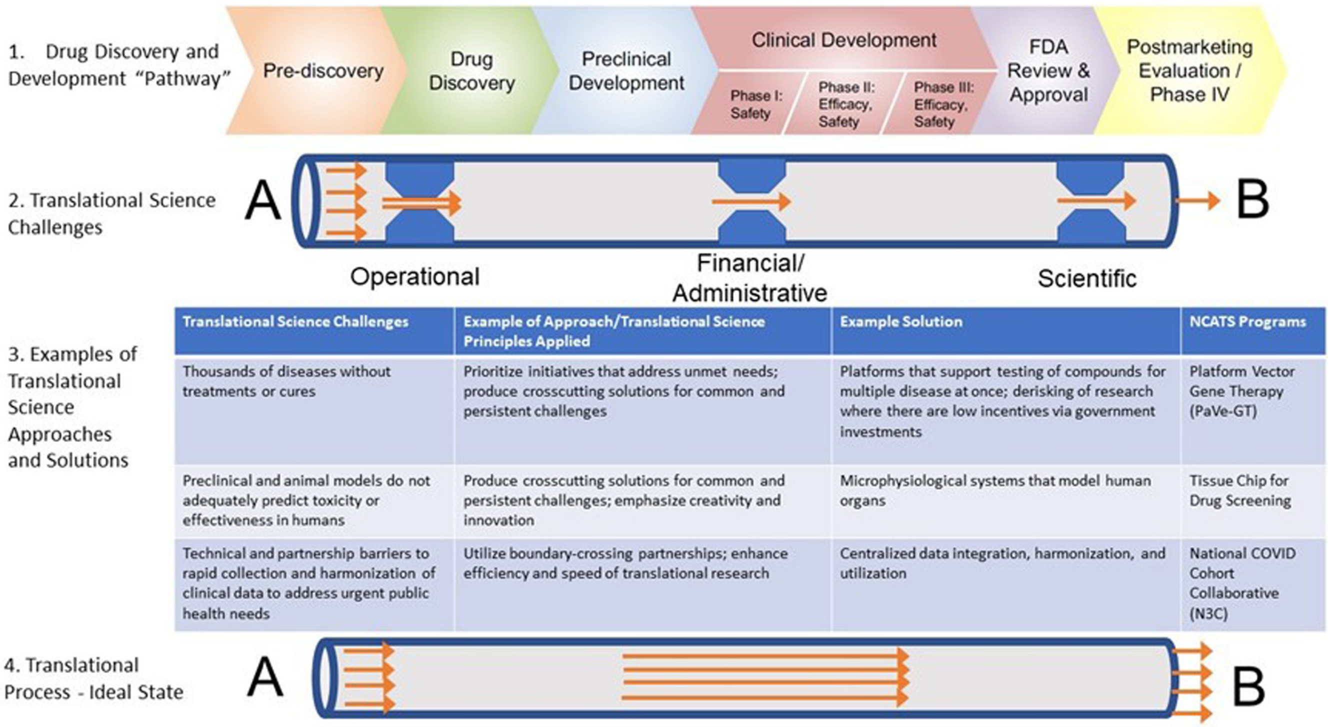

FIGURE 2 This figure uses the drug discovery and development pathway (part 1) to illustrate that while there may be numerous candidates identified at the early stages of research, very few of these will successfully traverse the translational process. In part 2 of the figure there are scientific and operational bottlenecks that slow the process and may eliminate some viable candidates. The bottlenecks shown here are meant only to be illustrative of the variety of challenges encountered and are not shown in any particular order. Further, this linear pathway simplifies a very complex process that is more accurately represented in the NCATS Drug Discovery, Development, and Deployment Maps (4DM). Part 3 of this figure provides specific examples of translational science challenges across a variety of research areas, how translational science principles have been applied to address these challenges, and the solutions that overcame these challenges. The goal is that by utilizing translational science principles and approaches, all research can be made more effective and efficient as depicted in part 4 of the figure.

understanding of generalizable scientific and operational principles guiding translational science approaches.

National Center for Advancing Translational Sciences has and will continue to engage the translational science education community in discussions about how best to advance the field of translational science and develop new approaches for translational science education. Goals include developing a shared understanding of the scope of the field, core knowledge in the field, key questions to be answered, modalities for education and training, and rigorous approaches for education evaluation and quality improvement. A shared understanding of the current scope and core knowledge in translational science will enable the community to refine and expand beyond the initial set of translational science principles offered here, as well as approaches to teach these concepts and related strategies for their implementation. It will also point to new directions for enhancing current and future education and training opportunities in translational science.

CONCLUSIONS

Future translational science education and training should include instruction in the field's strategic mission, core scientific and operational principles, and key strategies and approaches guided by these principles, which have been used effectively to advance translation. These additional skills and knowledge are needed to address an ambitious list of scientific and organizational challenges that hinder translational progress and develop solutions that will dramatically advance the translational enterprise (e.g., Figure 2). This solution-focus of translational science shared above highlights the centrality of identifying scientific and operational principles underpinning successful translation efforts.

Delineating the scope, foundational knowledge, and key applications of this knowledge in the field of translational science will enable the further advancement of the field, growth of translational science education opportunities, and development of the translational science workforce. Establishing translational science core concepts, including defining the scientific and operational principles underpinning translational science, identifying the variety of ways these can be implemented in practice, and with what degrees of adaptation and success across scientific and organizational contexts, will all be key to advancing this field. By conveying this knowledge through novel education opportunities accessible to varied and diverse audiences, we will be developing translational science practitioners who understand scientific and operational principles and can implement them in their own varied scientific and administrative activities, leading to more successful and impactful translation.

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CONFLICT OF INTEREST

The authors declare there are no conflicts of interest.

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ORCID

Jessica M. Faupel-Badger https://orcid.org/0000-0001-9729-3660
Christopher P. Austin https://orcid.org/0000-0001-7770-0708
Joni L. Rutter https://orcid.org/0000-0002-6502-2361

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