




# Emerging workforce readiness in regenerative healthcare

Saranya P Wyles<sup>1,2,3</sup> , Dileep D Monie<sup>4</sup> , Christopher R Paradise<sup>1</sup>, Fredric B Meyer<sup>4,5</sup>,  
Richard E Hayden<sup>1,6</sup> & Andre Terzic<sup>\*,1,3,7,8</sup> 

<sup>1</sup>Center for Regenerative Medicine, Mayo Clinic, Rochester, MN 55905, USA

<sup>2</sup>Department of Dermatology, Mayo Clinic, Rochester, MN 55905, USA

<sup>3</sup>Department of Molecular Pharmacology & Experimental Therapeutics, Rochester, MN 55905, USA

<sup>4</sup>Mayo Clinic Alix School of Medicine, Rochester, MN 55905, USA

<sup>5</sup>Department of Neurologic Surgery, Mayo Clinic, Rochester, MN 55905, USA

<sup>6</sup>Department of Otolaryngology, Mayo Clinic, Phoenix, AZ 85054, USA

<sup>7</sup>Department of Cardiovascular Medicine, Rochester, MN 55905, USA

<sup>8</sup>Department of Clinical Genomics, Mayo Clinic, Rochester, MN 55905, USA

\*Author for correspondence: Tel.: +1 507 284 2747; [terzic.andre@mayo.edu](mailto:terzic.andre@mayo.edu)

The biology of regenerative medicine has steadily matured, providing the foundation for randomized clinical trials and translation into validated applications. Today, the growing regenerative armamentarium is poised to impact disease management, yet a gap in training next-generation healthcare providers, equipped to adopt and deliver regenerative options, has been exposed. This special report highlights a multiyear experience in developing and deploying a comprehensive regenerative curriculum for medical trainees. For academicians and institutions invested in establishing a formalized regenerative medicine syllabus, the Regenerative Medicine and Surgery course provides a patient-focused prototype for next-generation learners, offering a dedicated educational experience that encompasses discovery, development and delivery of regenerative solutions. Built with the vision of an evolving regenerative care model, this transdisciplinary endeavor could serve as an adoptable education portal to advance the readiness of the emergent regenerative healthcare workforce globally.

First draft submitted: 16 September 2020; Accepted for publication: 5 February 2021; Published online: 24 February 2021

**Keywords:** clinical course development • education • medical curriculum • next generation • proficiency • readiness • regenerative medicine

## Regenerative education readiness

For the things we have to learn before we can do them, we learn by doing them.

— Aristotle, 384–322 BC

Essential to regenerative medicine adoption is the build-out of a specialized multidisciplinary workforce armed with the skillset needed to carry out regenerative care [1]. The evolution of clinical practice from a traditional ‘fighting disease’ to an aspirational ‘restoring health’ paradigm [2] has exposed a readiness gap in the education of next-generation providers [3]. Indeed, regenerative approaches remain underemphasized in medical school and residency education, limiting proficiency in applying innovative solutions [4,5]. Technology advances (developmental and cell biology, material sciences, tissue engineering, nanomedicine, etc.) have created a ‘biopotented’ healthcare ecosystem, enabling targeted disease repair and organ restoration strategies [6]. Accordingly, the preparedness of healthcare professionals must evolve to match growing opportunities.

The regenerative blueprint remains nascent as it undergoes validation with the perspective of ensuring standardized and scalable dissemination, and demonstrable utility [7]. Notwithstanding, providing accessibility and affordability while addressing social and health inequities is paramount in offering equitable regenerative care [8]. Ultimately, bringing forth the ‘regeneration for all’ horizon requires robust standard operation procedures for cost-effective biomanufacturing [9], rigorous US FDA regulatory pathways, optimized clinical trial design and

execution [10,11], and expert guidelines for patient selection. Accordingly, emphasis is placed on development of new medical education curricula aimed to introduce transdisciplinary regenerative technologies across specialties to adequately prepare the frontline workforce for regenerative care delivery [12]. This prioritization is timely as practitioners increasingly face a rapidly aging global population [13]. The unproportioned burden of lifelong, chronic degenerative conditions, including cardiovascular disease, cancer and diabetes [14], imposes the need for regenerative solutions poised to contribute in addressing the noncommunicable diseases pandemic.

Analysis of clinical trials across worldwide registries indicates that studies utilizing hematopoietic stem cells derived from bone marrow, adipose tissue, umbilical cord blood or peripheral blood are the mainstay regenerative biotherapeutics [15]. The regenerative armamentarium is however increasingly diverse, spanning a toolkit that encompasses not only cell-based but also tissue-engineering, acellular and ever-evolving molecular reparative approaches [16]. As regenerative technologies continue to refine [17], new and complementary skillsets will be needed to prepare the upcoming generation of physicians for regenerative practice. Fostering and developing a scholarly interest, genuine proficiency and ultimately real mastery in regenerative medicine are essential steps in the evolution of healthcare as it adapts and adjusts to future delivery requirements [18]. Rapidly growing interest in this field is countered by limited tools to educate the next-generation workforce. Assessment of medical student awareness has indeed identified deficiencies of core regenerative medicine competencies. It is therefore incumbent upon educators and education systems to develop and implement the means to efficiently and timely disseminate new knowledge to medical trainees that matches the evolution of the field.

### Mayo Clinic prototype

To address the recognized curricular deficit and to educate next-generation healthcare providers, Mayo Clinic has launched, under the auspice of the Mayo Clinic Center for Regenerative Medicine and in conjunction with the Mayo Clinic Alix School of Medicine, prototypical regenerative medicine education programs for medical students and residents, complementing graduate-level regenerative science education. These education initiatives recognize that Mayo Clinic has over the past decade highlighted regenerative medicine as a strategic investment in the future of healthcare. Institutional strategy, envisioned as a science-driven practice advancement priority, is executed through a discovery-translation-application mandate [19], deployed across medical, surgical, radiology and laboratory medicine specialties [20], framing the education imperatives in building the future workforce.

Here, a multiyear experience (2014–2019) in developing and deploying a comprehensive regenerative medicine and surgery course for medical trainees is shared. Guiding principles for the dedicated course included) early introduction of regenerative medicine concepts in medical education training; dynamic teaching methods such as interactive, simulation and laboratory experiences to maximize student engagement; multidisciplinary, patient-centric approach to comprehend bench-to-bedside translation and iterative optimization; all-inclusive group discussion involving patients and faculty along with students; and online education modules and medical student presentations to ensure learning proficiency [21].

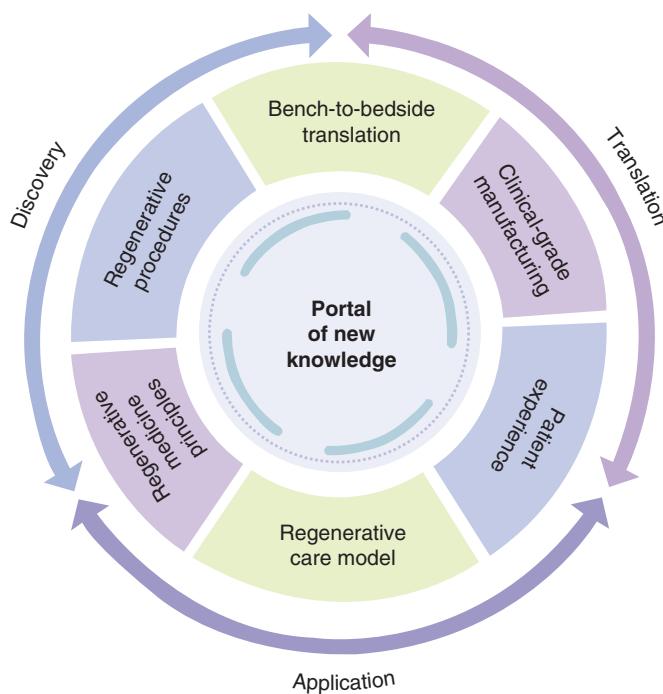
### Plan: Equipping the next generation with regenerative medicine skillsets

#### Curriculum design

The Regenerative Medicine and Surgery course is built with the vision of an evolving regenerative care model. The course is designed for next-generation learners, offering an educational experience that encompasses discovery, development and delivery of regenerative solutions thereby ensuring regenerative healthcare workforce readiness (Figure 1). The peer-designed learning model is cross-disciplinary, organized by medical/graduate students, faculty specialty leaders and support academic staff. Launched in 2014, and iterative in nature with yearly updates, the course is hosted and supported by the Mayo Clinic Center for Regenerative Medicine and the Mayo Clinic Alix School of Medicine. Collaboration with Regenerative Medicine Minnesota, the University of Minnesota, the NIH Alliance for Regenerative Rehabilitation Research & Training, Hospital General Universitario Gregorio Marañon, the University of Zurich Institute for Regenerative Medicine, the University of Belgrade and University College London has offered access to a national and international pool of learners.

#### Curriculum content

Course content includes topics that cover more than 15 medical and surgical specialties. Sessions reflect the maturity of the regenerative field, with didactics covering areas such as regenerative immunotherapy for hematologic malignancies; nerve reconstruction in neurosurgery; facial reanimation and composite allotransplant in



**Figure 1. Regenerative healthcare workforce readiness.** Built with the vision of an evolving regenerative care model, the patient-centric Regenerative Medicine and Surgery course provides a prototype curriculum, a portal of new knowledge for next-generation learners. This course offers a dedicated educational experience that encompasses discovery, development and delivery of regenerative.

plastic and microsurgery; hybrid core decompression and osteochondral grafts in orthopedics; platelet-rich plasma interventions in physical and sports medicine; cellular and acellular therapies for neurodegenerative, cardiac and kidney disease; and tissue engineering and neo-organogenic regeneration for aerodigestive pathologies. Evolution of annual course content reflects latest scientific discoveries and ongoing clinical trials targeting validated regenerative solutions. Herein, ‘validated’ is defined as process of establishing consistent, high-quality evidence, developed in compliance with the FDA and their clinical-grade GMP guidelines. Accordingly, an average of 10 regenerative clinical trials are presented at each course iteration, such as mesenchymal stem cells in amyotrophic lateral sclerosis and multiple systems atrophy; mononuclear cell therapy for hypoplastic left heart syndrome; lineage-specified cardiopoietic stem cells for chronic heart failure; stem cells for bronchiolitis obliterans, renal artery stenosis, avascular necrosis of the hip and osteoarthritis of the knee; stem cell-coated fistula plugs for Crohn’s disease; stromal cells for host versus graft disease; and stem cells for relapsed ovarian cancer, underscoring inter- and trans-specialty clinical testing.

### Learning objectives

Learning objectives encompass a patient-centric content, ensuring that major regenerative medicine concepts and practices relevant for the learners are presented. Areas of emphasis with stated learning objectives include:

- (1) Regenerative medicine: principles to practice: grasp the fundamental principles, tools and platforms driving regenerative science to applied care; describe the diagnostic and therapeutic applications of regenerative medicine and surgery.
- (2) Regenerative procedures: comprehend delivery of regenerative therapeutics and how current techniques are used to provide validated regenerative solutions.
- (3) Bench-to-bedside translation: understand the translational process, including pre-clinical study and clinical trial execution, regulatory steps and bioethics.
- (4) Clinical-grade manufacturing: demonstrate proficiency in the current practice of process/product development, advanced manufacturing, quality control and quality assurance.
- (5) Patient experience and regenerative care model: become familiar with how innovation reaches patients through commercialization and educated outreach; demonstrate an understanding for regenerative medicine contributions to meet patient and societal needs.

## Action: implementation of the regenerative medicine curriculum

### Content delivery

Beyond didactic lectures, students engage in various workshops: patient simulated consults, laboratory experiences, bench-to-bedside translation models, anatomical surgical procedures and community engagement.

Designed as a patient-centric curriculum, participants begin the course with patient interviews to learn about patient perspective on complex, chronic (degenerative) disease and regenerative options typically considered as adjunct to current standard of care. Targeted questions cover real patient experiences with cell-based/tissue-based regeneration, presented as actual or simulated provider–patient experiences. Designated faculty members observe group student interviews at a specialized simulation center; students and faculty members debrief on the acumen pertinent to the effective provider–patient examination ensuring initial familiarity with approaches in regenerative care.

Complementing clinical know-how, laboratory experiences such as stem cell culture, *ex vivo* disease models and 3D bioprinting showcase an overview of regenerative sciences platforms. Participants also learn about bench-to-bedside translation by observing small animal- and large animal-studies pertaining to guided stem cell delivery and tissue engineering. Hands-on surgical procedures demonstrated in the anatomy cadaver laboratory include ultrasound-guided joint injection and surgical procedures for degenerative conditions. These sessions are led by physician subject matter experts from various medical/surgical specialties and doctorate-level scientists.

Furthermore, participants engage public communities by providing a group presentation on a regenerative medicine topic of their choice to invited local audiences. Resources such as the ‘Start as a Stem Cell’ game, developed by the University of Edinburgh, are utilized to teach local high school students about the basic properties of stem cells including self-renewal and differentiation. These experiences collectively facilitate establishment of a concomitant ‘Regenerative Medicine and Surgery’ Interest Group at the medical school, which promotes career exploration and community engagement during the academic year.

### Course learners

For medical students, this course is embedded in the first-year medical school curriculum, which consists of block courses such as pre-clinical integrations (basic doctoring, senior sages program), anatomy, histology, pathology, immunology, microbiology, pharmacology, biochemistry, genetics and science of healthcare delivery. It is offered as a pre-clinical elective known as ‘selective’, which are extracurricular blocks throughout pre-clinical/clinical training at the Mayo Clinic Alix School of Medicine in Rochester, Minnesota, and Scottsdale/Phoenix, Arizona. The selective framework allows students to engage in career exploration or skill development [22,23]. By virtue of a condensed 1 week integrative format, the ‘Regenerative Medicine and Surgery’ course utilizes the discover-translate-apply platform to deliver key components of the regenerative care lexicon for the next-generation healthcare practitioner during the 30–35 hour week.

For graduate students, this course is offered for two credits through the Mayo Clinic Graduate School of Biomedical Sciences and the Mayo Clinic Regenerative Sciences Training Program. Coursework is graded dichotomously as either satisfactory (S) or non-satisfactory (N). Attendance and completion of final examination are required to achieve a passing S grade.

### Faculty & staff

To expose participants to a broad expertise, within a framework of multidisciplinary team-based learning, the course comprises 18–24 faculty including healthcare providers/educators from medical/surgical/radiology/laboratory medicine specialties, doctoral-level basic scientists, biomedical engineer scientists, translational/regulatory scientists and clinician-scientists. Visiting faculty lecturers from leading international institutions are also invited to provide a global perspective on advancing regenerative sciences and translational applications. To foster student–faculty mentorship, a regenerative medicine career panel is offered at course conclusion including panelists who actively engage in innovative translational research and transformative clinical practice.

Supporting staff consists of teaching assistants (course alumnae from prior years). Student leaders ensure the logistics (securing dates and times for the curriculum), promote course awareness (by email, face-to-face communication in classroom and advertising at the student interest group) and facilitate participant engagement (through teaching assistant small group discussions). Faculty and specialty leaders are selected based on expertise in regenerative sciences and regenerative care in addition to advances in the field.

**Table 1. Regenerative Medicine and Surgery course student demographics (n = 131).**

Sex	Female	64	49%
	Male	67	51%
Age	18–24	71	54%
	25–34	56	43%
	35–40	3	2%
	>40	1	1%
Undergraduate major	Science	115	88%
	Non-science	16	12%
Current program	Medical school (MD)	95	73%
	Medical scientist training program (MSTP: MD/PhD)	13	10%
	Graduate school (PhD)	10	8%
	Post-baccalaureate/pre-medical	6	5%
	Residency/clinical fellowship	7	5%
Career plans	General internal medicine, family medicine, general pediatrics or internal medicine-pediatrics	8	6%
	Subspecialty internal medicine or pediatrics (cardiology, pulmonary, etc.)	19	15%
	Surgical field (general surgery, ophthalmology, otolaryngology, urology, orthopedic surgery, etc.)	43	33%
	Other direct patient care (anesthesia, dermatology, emergency medicine, obstetrics and gynecology, psychiatry, neurology)	21	16%
	Other non-direct patient care (radiology, pathology)	14	11%
	Undecided	26	20%

### Outcome measures

Outcome measures are quantified using survey methodology comprised of questions regarding participants' backgrounds, self-perceived knowledge/confidence in skills and interests/career plans. Answer choices include a Likert familiarity scale with choices of not familiar at all (scored as 1), slightly familiar (scored as 2), moderately familiar (scored as 3), very familiar (scored as 4) and extremely familiar (scored as 5). Participants are provided open-text field responses to elaborate on certain questions, and respond via an emailed survey prior to the course start date and upon course completion. The survey, to date, has been distributed to 215 total participants enrolled in course offerings from 2016 to 2019; it was completed by 131 participants.

### Statistical analyses

Study data is assembled and analyzed in Microsoft Excel and JMP 9.0 (SAS Institute, Cary, NC, USA). Two-tailed, matched-pairs t-test is performed to analyze differences between post-course and pre-course survey responses. Values of mean  $\pm$  standard deviation (SD), 95% CI and p-values are presented. p-values reflect two-sided tests of significance.  $p < 0.05$  is considered statistically significant. Parametric testing is selected for Likert scale analysis with  $n = 131$  students.

## Evolution: evaluation of the new path for a specialized workforce

### Participant characteristics

Of the 215 total students enrolled in the course from 2016 to 2019 and to whom the survey was distributed, 61% ( $n = 131$  students) completed the survey (Table 1). Participants ranged from medical students (MD program;  $n = 95$ ; 73%), medical scientist trainees (MD, PhD;  $n = 13$ ; 10%), graduate students (PhD program;  $n = 10$ ; 8%), residency/registrar medical trainees or clinical research fellows ( $n = 7$ ; 6%), and pre-medical/post-baccalaureate students ( $n = 6$ ; 5%). Of the respondents, 64 (49%) were female and 67 (51%) were male. The majority of participants reported undergraduate training in science major ( $n = 115$ ; 88%). Students self-reported the following career plans: general internal medicine, family medicine, general pediatrics or internal medicine-pediatrics ( $n = 8$ ; 6%); subspecialty internal medicine or pediatrics ( $n = 19$ ; 15%); surgical specialty ( $n = 43$ ; 33%); other direct patient care such as emergency medicine ( $n = 21$ ; 16%); other indirect patient care such as radiology, pathology or patient research ( $n = 14$ ; 11%); or undecided ( $n = 26$ ; 20%).

**Table 2. Pre-assessment and post-assessment survey responses and analysis for the Regenerative Medicine and Surgery course (n = 131).**

Course objectives	Mean score (standard deviation) <sup>†</sup>			95% CI <sup>‡</sup>	p-value <sup>§</sup>
	Pre-course	Post-course	Difference		
<b>1. Regenerative medicine: principles to practice</b>					
Understand the fundamental principles, tools and platforms of regenerative medicine; describe the diagnostic and therapeutic applications of regenerative medicine and surgery	2.4 (1.0)	4.3 (0.7)	1.8 (1.1)	1.6–2.0	<0.01
<b>2. Regenerative procedures</b>					
Understand the challenges to effective delivery of regenerative therapeutics; understand how current techniques are being used to provide regenerative solutions	2.2 (0.9)	4.2 (0.7)	2.0 (1.1)	1.8–2.2	<0.01
<b>3. Bench-to-bedside translation</b>					
Understand how current ethical issues have influenced the progress of stem cell research; understand the techniques used to deliver cell-based biologics in models of disease	2.4 (1.0)	4.2 (0.8)	1.8 (1.2)	1.6–2.0	<0.01
<b>4. Clinical-grade manufacturing</b>					
Understand and demonstrate proficiency in the current practice in Mayo's Regenerative Medicine Clinic; understand how cells are generated for clinical utilization (clinical-grade GMP)	1.8 (0.8)	4.2 (0.7)	2.4 (1.0)	2.2–2.6	<0.01
<b>5. Patient experience and regenerative care model</b>					
Understand the steps to bring discovery into the clinic through commercialization and community outreach; demonstrate an understanding for regenerative medicine and its contribution to meet patient and societal needs	1.9 (1.0)	4.1 (0.8)	2.2 (1.2)	2.0–2.4	<0.01

<sup>†</sup>Scores and differences were reported on a 5-point Likert scale (1, not at all familiar; 5, extremely familiar).  
<sup>‡</sup>CI = Confidence interval for mean score difference, using a normal distribution.  
<sup>§</sup>p < 0.05 was used as the significance criterion.

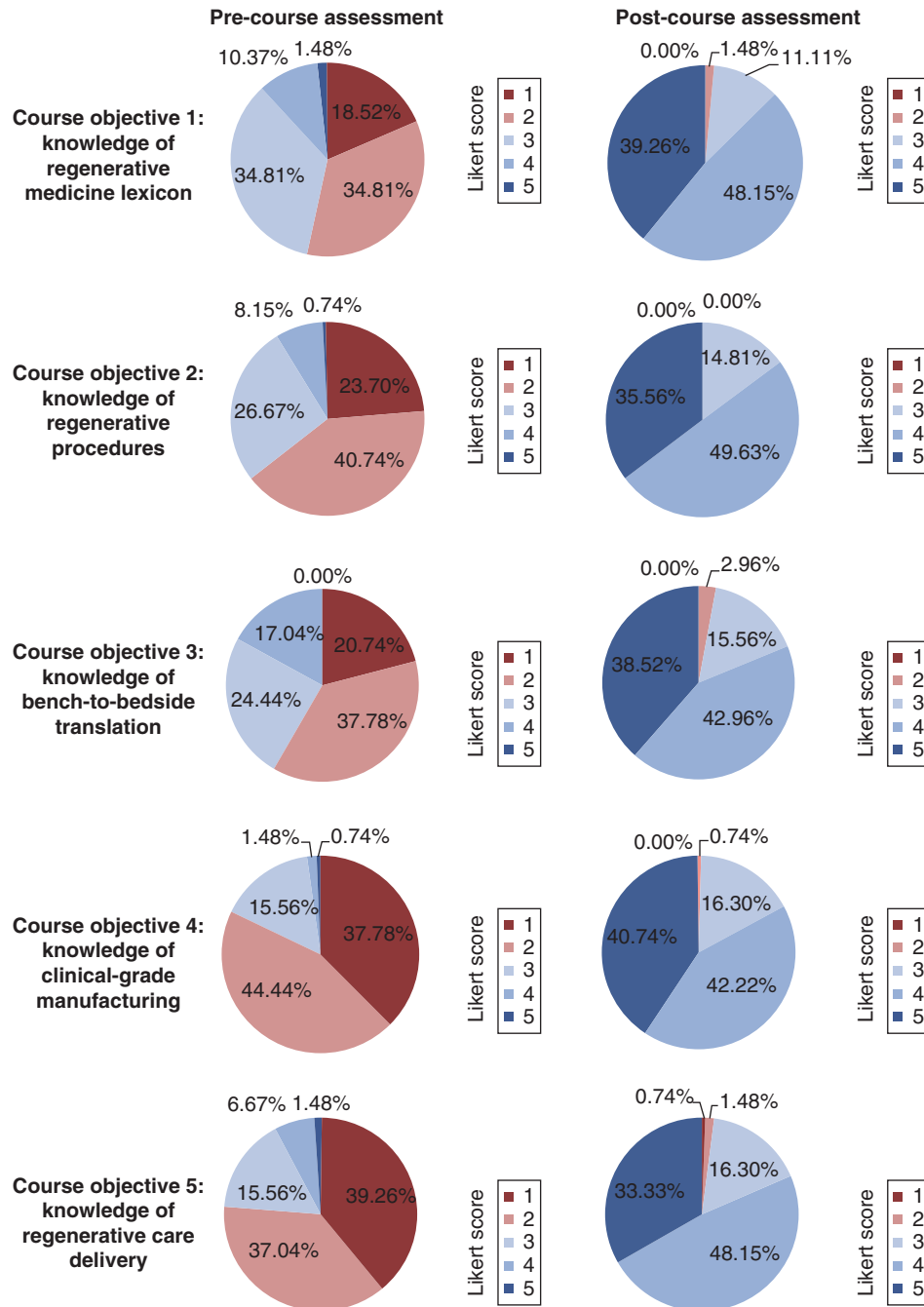
### Course impact on self-perceived student knowledge

Assessment of student familiarity with course objectives was analyzed in students who responded to the pre- and post-course surveys (n = 131 students; 61%) from 2016 to 2019. Course objectives with the largest increases in understanding were as follows: clinical-grade manufacturing (mean difference ± SD, 2.4 ± 1.0; 95% CI 2.2–2.6; p < .01), patient experience and regenerative care model (mean difference ± SD, 2.2 ± 1.2; 95% CI 2.0–2.4; p < .01), and regenerative procedures (mean difference ± SD, 2.0 ± 1.1; 95% CI 1.8–2.2; p < .01) (Table 2). In these categories, participant familiarity significantly increased in the percentage rating high Likert score (value of 4 corresponding to 'very familiar' and value of 5 corresponding to 'extremely familiar'): clinical-grade manufacturing pre-course high Likert rating 2.2% to post-course high Likert rating 82.9% (p < .01); patient experience and regenerative care model pre-course high Likert rating 8.2% to post-course high Likert rating 81.5% (p < .01); and regenerative procedures pre-course high Likert rating 8.9% to post-course high Likert rating 85.2% (p < .01) (Figure 2).

### Longitudinal exposure

Continual integration across medical training is essential to progressively reinforce regenerative medicine and surgery principles as well as introduce latest developments. Data collected on the course impact on student interest suggest that 98% students recommend the course to their peers and 97% students report that the course positively impacted the way they practice medicine.

Early exposure to the regenerative lexicon is fostered with longitudinal incorporation including specialty-specific grand rounds, domain-relevant lectures and practice exposure to reinforce regenerative medicine enterprise. Medical students and residents engaged in current topics such as CRISPR/Cas9 gene editing, proton beam therapy and CAR-T cell therapy during their clinical clerkships [24]. In subsequent years, the next-generation cohort (n = 28 students) participated as course teaching assistants. Based on medical student interest, the 'Regenerative Medicine and Surgery' clinical elective was established to allow advanced medical trainees to participate in clinical trial development and investigational new drug application for regenerative therapies. Fourth-year medical students (n = 10) and internal medicine/preliminary internal medicine residents (n = 12; post-graduate years 1–3) have participated in this specialty-tailored clinical elective. Success was documented by increased medical trainee awareness and proficiency,



**Figure 2. Self-perceived student knowledge and skills confidence (n = 131). Course impact.** Pre- and post-course surveys were distributed to students taking the course between 2016 and 2019 (survey was distributed to n = 215 and completed by n = 131). Students selected whether they were extremely familiar (score of 5), very familiar (4), moderately familiar (3), slightly familiar (2) or not familiar at all (1) with a given statement. Pre- and post-course surveys were statistically analyzed using two-tailed, matched-paired t-test and depicted in graphical form as a percentage. Results reflect impact on self-perceived student knowledge and skills confidence.

and contributed to specialty identification, research engagement, clinical acumen and education-driven practice advancement [1].

### Digital curriculum

Recent COVID-19 restrictions to traditional learning models led to a rapidly re-envisioned deployment of a virtual 'Regenerative Medicine and Surgery' course among several pandemic-provoked innovations at Mayo Clinic [25]. Implemented in the 2020 digital format, course content across medical and surgical specialties included online clinical trial highlights, patient stories, digital didactic lectures, virtual human anatomy laboratory sessions, video tours of clinical-grade manufacturing facilities, trainee career panels and networking sessions [21]. Engaging more than 50 transatlantic learners including medical students, graduate students, post-baccalaureate students, residents and clinical fellows, the digital format catalyzed a global community of learners and provided expanded connectivity. Indeed, this course will continue to mature into the global forefront. Future courses will target a broader learner base, enabling a more objective evaluation of social impact. It will be important to understand the social impact across diverse communication and among various digital learners.

### Conclusion

Regenerative medicine approaches remain underemphasized in medical school and residency education, limiting proficiency in applying innovative solutions. To address the recognized curricular deficit and to educate next-generation healthcare providers, we present a multiyear experience in developing and deploying a comprehensive regenerative medicine and surgery course for medical trainees. Designed as a patient-centric curriculum, the syllabus extends beyond didactic lectures with patient-simulated consults, laboratory experience, bench-to-bedside translation models, anatomical surgical procedures and community engagement. Assessment of student familiarity increased significantly in course objectives focused on clinical-grade manufacturing, the patient-centered regenerative care model and regenerative procedures. This education framework, along with associated metrics, also translated into the virtual platform. Moving forward, the acquired experience from the virtual classroom offers a digital foundation applicable to a spectrum of educational pathways needed in the build-out of workforce readiness.

### Future perspective

Regenerative medicine is exposed to major challenges and opportunities [26]. A decade from now, if you were to ask a physician what it would mean to provide regenerative care for their patient, perhaps the answer would include an armamentarium of curative interventions, which alter the economics of chronic disease management in a diverse aging population. Indeed, acceleration in this field is anticipated with ongoing innovation, including for example the introduction of additive manufacturing technology, digital design and use of artificial intelligence for biofabrication of functional organ structure [27]. As regenerative therapies continue to permeate the future clinical landscape with validated solutions and confirmed utility, global readiness for clinical adoption must be prioritized [28,29]. Yet the portal for next-generation healthcare providers to access adequate training in regenerative care counseling remains narrow. To prepare for the projection that regenerative medicine will be on the vanguard of healthcare in the upcoming decade [30], medical schools and residencies should offer comprehensive, patient-centered regenerative medicine and surgery courses, either in-person or virtual. The collective experience of an innovative, transdisciplinary curriculum presented in this work could serve as a playbook to be implemented globally given its digital format.

### Financial & competing interests disclosure

Supported by the Mayo Clinic Center for Regenerative Medicine, the Mayo Clinic Alix School of Medicine, and Regenerative Medicine Minnesota. Funds supported curriculum development and student scholarship. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

No writing assistance was utilized in the production of this manuscript.

### Open access

This work is licensed under the Attribution-NonCommercial-NoDerivatives 4.0 Unported License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>



### Executive summary

#### Plan: preparation of a next-generation regenerative skillset

- Offer a comprehensive educational experience that encompasses discovery, development and delivery of patient management modalities.
- Modules should allow learners to describe the diagnostic and therapeutic applications of regenerative medicine and surgery; understand the translational process, including pre-clinical study and clinical trial execution, regulatory steps and bioethics; and demonstrate proficiency in the current practice of process/product development, advanced manufacturing, quality control and quality assurance.

#### Action: implementation of the regenerative medicine curriculum

- Deploy various workshops for the next-generation learner: patient simulated consults, laboratory experiences, bench-to-bedside translation models, anatomical surgical procedures and community engagement.
- Recruit a broad spectrum of instructors including healthcare providers/educators from medical/surgical specialties, doctoral-level basic scientists, biomedical engineer scientists, translational/regulatory scientists and clinician-scientists.

#### Evolution: evaluation of the new path for a specialized workforce

- Early exposure to the regenerative lexicon is fostered with longitudinal incorporation including specialty-specific grand rounds, domain-relevant lectures and practice exposure to reinforce regenerative medicine enterprise.
- Assess outcomes related to increased medical student awareness and proficiency, and contributed to specialty identification, research engagement, clinical acumen and education-driven practice advancement.
- Adopt new competencies annually to introduce latest translational developments across diverse and digital platforms including options for the new virtual learner. The digital aspect of the course allows for translatability to other countries.

## References

Papers of special note have been highlighted as: ● of interest; ●● of considerable interest

1. Wyles SP, Hayden RE, Meyer FB, Terzic A. Regenerative medicine curriculum for next-generation physicians. *NPJ Regen. Med.* 4, 3 (2019).
- **Inaugural regenerative medicine curriculum.**
2. Hargraves IG, Behfar A, Foxen JL, Montori VM, Terzic A. Towards regeneration: the evolution of medicine from fighting to building. *Br. Med. J.* 361(k1586), 1–3 (2018).
3. Wyles SP, Terzic A. Building the regenerative medicine workforce of the future: an educational imperative. *Regen. Med.* 14(7), 613–615 (2019).
4. Knoepfler PS. Call for fellowship programs in stem cell-based regenerative and cellular medicine: new stem cell training is essential for physicians. *Regen. Med.* 8(2), 223–225 (2013).
5. Bussell II, Stuppel A, Moody KJ, Lefkowitz DM. Call to action: medical students for regenerative medicine. *Rejuvenation Res.* 13(1), 1–2 (2010).
6. Hunsberger J, Simon C, Zylberberg C *et al.* Improving patient outcomes with regenerative medicine: how the Regenerative Medicine Manufacturing Society plans to move the needle forward in cell manufacturing, standards, 3D bioprinting, artificial intelligence-enabled automation, education, and training. *Stem Cells Transl. Med.* 9(7), 728–733 (2020).
7. Terzic A, Pfenning MA, Gores GJ, Harper CM Jr. Regenerative medicine build-out. *Stem Cells Transl. Med.* 4(12), 1373–1379 (2015).
- **Prototype for institutional regenerative medicine readiness.**
8. McMahon DS, Thorsteinsdottir H. Making stem cells count for global health. *Regen. Med.* 6(Suppl. 6), 163–166 (2011).
9. Lomax GP, Torres A, Millan MT. Regulated, reliable, and reputable: protect patients with uniform standards for stem cell treatments. *Stem Cells Transl. Med.* 9(5), 547–553 (2020).
10. Behfar A, Terzic A. Regeneration for all: an odyssey in biotherapy. *Eur. Heart J.* 40(13), 1033–1035 (2019).
11. Li MD, Atkins H, Bubela T. The global landscape of stem cell clinical trials. *Regen. Med.* 9(1), 27–39 (2014).
12. Chlan LL, Tofthagen C, Terzic A. The regenerative horizon: opportunities for nursing research and practice. *J. Nurs. Scholarsh.* 51(6), 651–660 (2019).
13. Waldman SA, Terzic A. Health care evolves from reactive to proactive. *Clin. Pharmacol. Ther.* 105(1), 10–13 (2019).
14. Terzic A, Waldman S. Chronic diseases: the emerging pandemic. *Clin. Transl. Sci.* 4(3), 225–226 (2011).
15. Nelson TJ, Behfar A, Terzic A. Strategies for therapeutic repair: the “R(3)” regenerative medicine paradigm. *Clin. Transl. Sci.* 1(2), 168–171 (2008).

16. Webster A. Regenerative medicine and responsible research and innovation: proposals for a responsible acceleration to the clinic. *Regen. Med.* 12(7), 853–864 (2017).
- **Perspective on responsible acceleration of regenerative medicine.**
17. Marks P, Gottlieb S. Balancing safety and innovation for cell-based regenerative medicine. *N. Engl. J. Med.* 378(10), 954–959 (2018).
- **US FDA perspective on regenerative medicine.**
18. Shapiro SA, Smith CG, Arthurs JR, Master Z. Preparing regenerative therapies for clinical application: proposals for responsible translation. *Regen. Med.* 14(2), 77–84 (2019).
19. Waldman SA, Terzic A. Managing innovation to maximize value along the discovery–translation–application continuum. *Clin. Pharmacol. Ther.* 101(1), 8–12 (2017).
20. Terzic A, Harper CM Jr, Gores GJ, Pfenning MA. Regenerative medicine blueprint. *Stem Cells Dev.* 22(Suppl. 1), 20–24 (2013).
21. Wyles SP, Meyer FB, Hayden R, Scarisbrick I, Terzic A. Digital regenerative medicine and surgery pedagogy for virtual learning in the time of COVID-19. *Regen. Med.* 15(8), 1937–1941 (2020).
- **Virtual learning platform for regenerative medicine curriculum.**
22. Tien M, Aiudi CM, Sviggum HP, Long TR. A peer-designed selective in anesthesiology, critical care, and perioperative medicine for first- and second-year medical students. *J. Clin. Anesth.* 31, 175–181 (2016).
23. Antiel RM, Thompson SM, Camp CL, Thompson GB, Farley DR. Attracting students to surgical careers: preclinical surgical experience. *J. Surg. Educ.* 69(3), 301–305 (2012).
24. Sterner RM, Hedin KE, Hayden RE *et al.* A graduate-level interdisciplinary curriculum in CAR-T cell therapy. *Mayo Clin. Proc. Innov. Qual. Outcomes* 4(2), 203–210 (2020).
25. Farrugia G, Plutowski RW. Innovation lessons from the COVID-19 pandemic. *Mayo Clin. Proc.* 95(8), 1574–1577 (2020).
26. Cossu G, Fears R, Griffin G, Ter Meulen V. Regenerative medicine: challenges and opportunities. *Lancet* 395(10239), 1746–1747 (2020).
27. Castilho M, de Ruijter M, Beirne S *et al.* Multitechnology biofabrication: a new approach for the manufacturing of functional tissue structures? *Trends Biotechnol.* 38(12), 1316–1328 (2020).
28. Faulkner E, Spinner DS, Ringo M, Carroll M. Are global health systems ready for transformative therapies? *Value Health* 22(6), 627–641 (2019).
29. Gardner J, Webster A, Barry J. Anticipating the clinical adoption of regenerative medicine: building institutional readiness in the UK. *Regen. Med.* 13(1), 29–39 (2018).
- **Roadmap for the build-out of regenerative medicine institutional readiness.**
30. Terzic A, Folmes CD, Martinez-Fernandez A, Behfar A. Regenerative medicine: on the vanguard of health care. *Mayo Clin. Proc.* 86(7), 600–602 (2011).