The Biophysicist

Summer School in Computational Physiology: A Collaborative Course in Modeling Excitable Tissues

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ABSTRACT Computational modeling of physiology is a multiscale, multidisciplinary field requiring a diverse set of skills and backgrounds. The Simula Summer School in Computational Physiology aims to teach graduate students from around the world practical methods for multiscale modeling of excitable tissues (specifically, the heart and brain). This joint summer school is collaboratively based on the complementary expertise and shared educational goals of three institutions: Simula Research Laboratory, the University of Oslo, and the University of California San Diego. The summer school's core goal is to promote successful research collaboration among the host institutions and to train excellent computational researchers. Keys to the success of this type of school include sustainable funding, close mentorship, and innovative, adaptive teaching tools. Using a combination of lectures, hands-on programming modules, and real-world projects in small groups with experienced scientific mentors, this unique program is an immersive way for young scientists to develop skills and network with future peers from around the world.

KEY WORDS computational physiology; multiscale modeling; mentorship

I. INTRODUCTION

A. Motivation and background

The Summer School in Computational Physiology (SSCP) is an initiative of the Simula-University of Oslo-University of California San Diego (Simula-UiO-UCSD) Research PhD Training Programme (SUURPh) (1, 2). SUURPh is funded by Kunnskapsdepartementet (KD), also known as the Norwegian Ministry of Education and Research. The total yearly funding of 10.5 million Norwegian kroner (NOK) supports eight PhD students who are jointly advised by scientists in Oslo and San Diego, as well as a scientific coordinator. The ongoing funding scheme began in 2014 and has successfully graduated 11 PhD students thus far. The PhD students are funded for 3–4 years with SUURPh funding, and the third round of hires is in process in 2024 as the current students finish their contracts.

SUURPh students are enrolled at the UiO in the faculty of mathematics and natural sciences and complete their degrees at UiO, but they are expected to complete a long-term research stay during their contract (generally between 3 months and 1 year) at UCSD to work with the UCSD supervisor more closely. PhD student fellowships and travel are

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funded by 8 million NOK yearly, 1 million NOK funds the coordinator position, 400,000 NOK is for consultants at UCSD, and 300,000 NOK is used for for additional discretionary travel funds associated with supervisor mobility.

The final portion of the SUURPh funding, 800,000 NOK per year, is allocated to SSCP to serve as a strengthening initiative for collaboration between Simula/UiO and UCSD. All SUURPh PhD students are required to take the course as part of their study plan, but the SSCP serves additional functions as an education and collaboration tool. SUURPh and the SSCP represent unique and successful initiatives by KD to promote collaboration in higher education and research between Norway and major institutions worldwide, particularly the United States and Europe.

The SSCP is a unique learning opportunity for young scientists because of the ability for them to benefit from close mentorship with leaders in the field. The initial coursework prepares attendees for an intensive research project in which a small group is paired with one or two lead scientists from Simula, UiO, and UCSD and approaches open research questions in computational physiology. The approach of the SSCP can be considered as a forum for intellectual apprenticeship, which helps reduce academic silos common in graduate education through multidisciplinary education and mentorship (3–5). Through the course, students with different scientific backgrounds attain skills in asking novel research questions, collaborating effectively with diverse thinkers, and networking with future mentors and colleagues.

B. Course development and overview

As part of the overall SUURPh initiative, SSCP has developed into a strong example of an international summer training program in its targeted discipline of computational physiology. Since its inaugural year in 2014, the school has grown in reach and focus, with steady growth and ongoing innovative approaches (Fig 1). To date, 217 students have been trained.

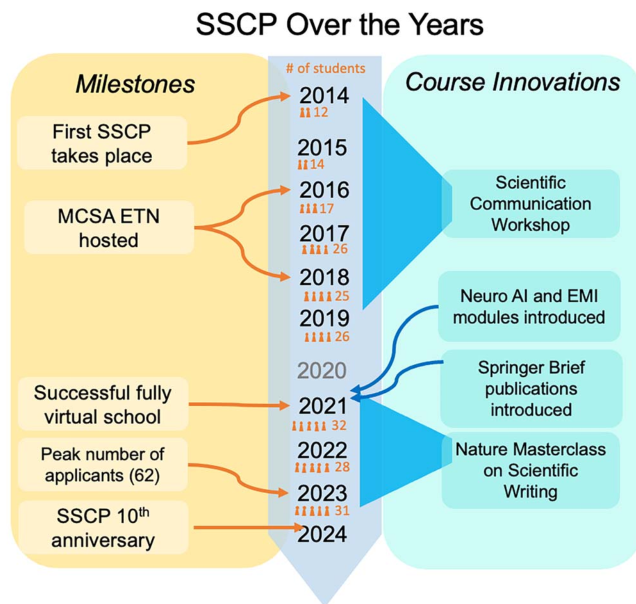

Fig 1. An overview of the SSCP over the years. Key milestones are indicated by year (left). The SSCP has undergone many innovations during its 10-year cycle, including those highlighted (right). EMI, Extracellular-Membrane-Intracellular Computational Model; MCSA ETN, Marie Skłodowska-Curie European Training Network.

The summer school is primarily tailored to interested first- or second-year PhD students and MSc students and is taught entirely in English. In 2023, 25 of the 31 students in the course were PhD students, and five were MSc students, with an additional postdoctoral scholar auditing the course. To increase accessibility and diversity among the students, the course has no fee, Simula reimburses travel costs for all attendees, and accommodation is also free for all attendees. These measures allow the school to promote equality and inclusion for top scholars, regardless of their personal or institutional funding opportunities.

The application process for the SSCP is rigorous, requiring a recommendation letter from an advisor, cover letter, curriculum vitae, and transcripts. Highest priority for acceptance is given to academic performance, followed by demonstrated need and interest for the training from the student and advisor, as well as relevance of the applicant's research to the course curriculum. The acceptance rate varies from year to year. In 2024, the acceptance rate was 38%, and in 2023, 48%.

The course curriculum, which has been updated steadily over a decade of conducting SSCP, has been developed on the basis of the broad expertise of scientists at Simula, UiO, and UCSD. The course opens in late June at Simula's premises in Oslo and focuses on two weeks of intensive lectures (~56 h of lecture), capped by targeted initial group project work. Then, in-person training sees a hiatus for the remote portion of the course, during which project teams and advisors typically meet virtually and make progress within the context of the particular project while at their home institutions. During this interim period, students dedicate ~80 h to project work. Students and project advisors reconvene for the second portion of the course in early August at UCSD. The latter portion focuses on project work and successful conclusion, including specific training modules variously focused on scientific presentation and writing, as well as lectures from invited speakers performing cutting-edge international research in computational physiology.

Table 1. A sample syllabus for part one of the SSCP at Simula in Oslo.

Course day	Example lecture
Sunday	Python tutorial (optional)
Monday	Physical chemistry and electrochemistry Mass transport and membrane biophysics
Tuesday	Ion channel gating Simulating the action potential
Wednesday	Electrical conduction in biology Quantitative aspects of calcium handling
Thursday	Fundamental cardiac mechanics Modeling myofilament dynamics
Friday	The Finite Element Method/FEniCS Electrophysiology modeling in FEniCS
Monday	The EMI Model Introduction to neuro-inspired artificial intelligence
Tuesday and Wednesday	Modeling tissue mechanics or NeuroAI (students choose a focus)
Thursday and Friday	Project work begins

EMI, Extracellular-Membrane-Intracellular Computational Model.

C. Course goals

The broad remit of SSCP is the practice of the following tenets.

(1) Ongoing development of inter-institutional collaboration among the founding institutions.
(2) Training of thoughtful, informed, and internationally minded computational scientists working in physiological research.
(3) Introduction of methods that permit these future scientists to move beyond their core discipline(s) in the conception and execution of projects to understand their work in a more holistic, multiscale, and multidisciplinary way.

II. METHODS

A. Syllabus and learning objectives

1. SSCP part one

Generally, the material covered by the SSCP focuses on fundamental principles of mathematical modeling in electrophysiology and biomechanics. Specifically, the lectures address cellular and subcellular biophysical processes responsible for electrical activation in cardiac muscle cells and neurons, frameworks for tissue-scale electrical signal propagation, and cellular- and tissue-level contractile mechanics in the heart. The general outline of the course curriculum and computational tools used in the course are outlined in Table 1, which offers a sample syllabus for the first part of the SSCP at Simula in Oslo.

SSCP lectures begin with basic biophysical concepts and coding exercises in physical chemistry and mass transport to develop a foundation of knowledge. The lectures then move to instruction on subcellular modeling (i.e., ion channel function, calcium handling, and sarcomere mechanics). The course then moves upward through space and time, teaching students how to model electrophysiology and mechanics in cardiac tissue by using finite element methods. Several lectures on the fundamentals of machine learning in physiological systems have been added, such as principal component analysis and bio-inspired artificial intelligence. To help students have a more personalized experience based on their interests, later lectures during part one are divided into several tracks for deeper modeling tutorials (e.g., cardiac mechanics, cardiac electrophysiology, neurophysiology, and machine learning).

In the final 3 d of part one, students are assigned to groups of two to four and then begin working together with a supervisor on a group research project in the group's area of interest. Projects are designed before the course by scientists at the three partner institutions on the basis of their own research and the course topics, and students are assigned to groups on the basis of their general areas of research interest. The projects allow groups to gain greater understanding of a particular model or set of models from the course material based on students' interests and background before entering the course. The groups work together on this project remotely throughout the month of July and during the second part of school, which is held in La Jolla at UCSD.

2. SSCP part two

During the second half of the course, which occurs in August, the students reconvene at UCSD to complete their project work and present their findings. During this period, cutting-edge research occurring at UCSD is highlighted through a series of guest lectures and laboratory tours in several departments (e.g., bioengineering, nanoengineering, mechanical and aerospace engineering, and neurosciences). Table 2 depicts a sample syllabus for SSCP part 2. Project groups are often led by teams of researchers from both Simula and UCSD, and the students' time at UCSD allows interaction with new research environments and enhancement of inter-institutional collaboration.

Because the work performed in SSCP projects is of consistently high quality, in 2020, a final goal for the SSCP became the creation of an anthology of short scientific papers based on student projects. To prepare students from various backgrounds for this task, the San Diego portion of SSCP begins with a 2-d course in scientific communication. From 2015 through 2019, Christine Haas conducted a workshop on scientific presentations in which students learned to create effective slides and to craft their scientific storytelling (6). From 2021 through 2023, a *Nature* masterclass in scientific writing and publishing was held in which two *Nature* editors in fields related to computational physiology conducted a series of hands-on activities aimed at helping students write compelling abstracts and structure their scientific papers (7).

Table 2. A sample syllabus for part two of the SSCP at UCSD.

Course day	Example lecture
Monday	Introduction to UCSD Project work with mentors
Tuesday and Wednesday	Scientific communication short course
Thursday–Monday	Assorted guest lectures; project work with mentors
Tuesday	Final presentations

After report submission in SSCP years 2021 to 2023, an abridged peer-review process was conducted by permanent scientists at Simula. Suitable reports were then published as a part of the ongoing Springer book series *Simula SpringerBriefs on Computing*, which includes a total of 29 short books. Three anthologies have been published thus far, and the work therein provides a more complete picture of the type of projects students complete in the course (8). The reports do not necessarily have to contain new results, but they often incrementally improve existing models or investigate new scientific problems by using existing model frameworks, thus providing fundamental new research experience to students. Students decide on authorship order as individual groups.

SSCP is an accredited 10-credit course within the European Credit Transfer and Accumulation System at UiO at both the Master's and PhD level in the biosciences department. The evaluation is conducted as a final presentation at the end of the school term, where groups present their methods and findings. For the PhD level course, a written report is also required.

B. Teaching tools

As detailed in the previous section, the SSCP lectures held in the June portion of the course cover various topics integral to a multidisciplinary perspective of computational physiology research. In addition to the use of traditional lecture methodologies, the integration of computational environments and relevant tools occurs early and often during the lecture portion of the course. These tools include working in Python; course organization via GitHub, Jupyter Hub, and Jupyter notebooks; and the FEniCS framework.

Day zero of the annual SSCP, typically a Sunday evening, includes a Python primer to orient students from various backgrounds. Those coming from a computer science or bioengineering program typically require less training in basic programming, but it is usual to see most students attend this optional session to assist one another and sharpen their skills for the start of the course the following morning.

This foundational lecture on Python and each year's collection of lectures and code-based exercises are organized in a separate repository inside of a public GitHub organization that can be accessed at the Simula-SSCP GitHub organization page. This centralized organization creates a single, shareable webpage where learners can view and download course content and reproducible code (9). All course materials are freely available to the public through the repository.

During the summer school period, Simula hosts a Jupyter Hub server with pre-allocated resources where students can view and run all code-based exercises without installing and deploying on a local machine (10). The Jupyter notebook exercises typically have code solutions organized in a separate collapsed cell, encouraging students to attempt exercises on their own or in groups before revealing the solution (11).

Finally, FEniCS is a mature, open-source software package for solving partial differential equations in a finite element framework that was initiated more than 20 years ago by several founding institutions, including Simula Research Laboratory (12). Given its broad, open-source reach and applicability across the computational physical sciences, it is often a core component of cardiac mechanics and electrophysiology lecture modules and group projects.

Table 3. Project list from the SSCP 2023.

Project title
Studying the Role of Astrocytic Membrane Properties on Microscopic Fluid Flow in Brain Tissue
Computational Modeling of Ephaptic Coupling in Myelinated and Unmyelinated Axon Bundles Using the EMI Framework
Augmentation of Cardiac Ischemic Geometry for Improving Machine Learning Performance in Arrhythmic Risk Stratification
Non-invasive Detection of Fetal Ischemia through Electrocardiography
Reconstruction of a Pancreatic Beta Cell Network from Heterogeneous Functional Measurements
The Impact of Mechano-Electric Feedback on Drug- and Stretch-Induced Arrhythmia Using a Computational Model of Cardiac Electromechanics
Impact of Modeling Assumptions on Hemodynamic Stresses in Predicting Cerebral Aneurysm Rupture Status

C. Group projects

Table 3 provides a list of the specific projects offered for SSCP 2023. As noted, students are matched to projects on the basis of applicants' fields of study and interests, with an eye toward composing teams diverse in expertise and experience. These projects are led by senior researchers from Simula, UiO, and UCSD who focus not only on project progress and results, but also on interpersonal dynamics and team-based science. Project leaders may encourage the teams to, for instance, establish ground rules for project collaboration and to initiate their own working schedules while retaining the role of supportive instructors and advisors. Although each project group and project is different, project advisors typically meet with student groups frequently during the last 3-d portion of part one of SSCP and then settle into an established weekly schedule for the remote portion of the course. Part two of SSCP is characterized again by intensive meetings and group work, with one or more advisors on site with the student groups. Shared meetings and check-ins may vary in frequency and duration, but all emphasize principles of supportive supervision, including active listening and the Questioning Wheel (13).

As an example, the Augmentation of Cardiac Ischemic Geometry for Improving Machine Learning Performance in Arrhythmic Risk Stratification project from SSCP 2023 extends on the previous work from the advisors, which involved both electrophysiological (EP) simulations and machine-learning tasks (14). The EP simulations involved risk stratification performed on cardiac models of ischemic cardiomyopathy. Machine-learning algorithms were then applied to cardiac features to predict arrhythmia. It was subsequently explored whether extending the cardiac model population through augmenting ischemic geometry improved the performance of the machine-learning algorithms.

During the SSCP, the project aim was to extend the augmented population, preferably by using a new augmentation method. Optionally, the number of cardiac features used to train the machine-learning algorithms could be increased to explore the ability of the algorithms to predict arrhythmia. The learning-outcome main objectives of the work were multifold: students learn to use openCARP for running EP simulations and gain insights into links between properties of ischemia and arrhythmia in cardiomyopathy through using different cardiac features to train machine-learning algorithms (15). The students would additionally incorporate techniques within machine learning, such as cross-validation and evaluating classification performance.

Students were offered this summary, together with specific tasks and recommended pre-reading, at the start of the SSCP project period. In this particular example, specific tasks were as follows:

(1) Run simulations in openCARP for risk stratification by using biventricular cardiac models.
(2) Augment ischemic geometries to extend the model population. Students preferably use an augmentation method that is different from the one described in Maleckar *et al.* (14). One possible new approach is to retag elements that separate tissue regions in existing cardiac meshes, which could be done manually or, for example, by using graph networks.
(3) Calculate cardiac features to train machine-learning algorithms. Depending on which augmentation methodology and cardiac features are used, students may have to write their own scripts for this task.
(4) Investigate how the choice of cardiac features affects prediction of machine-learning algorithms through statistical analysis.
(5) Possibly test new machine-learning algorithms compared with those used in the reference article.

The results of this project were published as part of the *SpringerBriefs* compendium for SSCP 2023 (8). In this illustrative case, and often, project results may differ somewhat in scope from what was initially outlined. The vision and tasks presented by project advisors are goalposts designed to inspire and provide direction, with learning outcomes and the most instructive process for the group taking precedence over preconceived notions of research outputs. That said, in addition to the publication in the *SpingerBriefs* series, projects have also resulted in additional peer-reviewed publications in other venues (16).

D. Remote and hybrid capabilities

The course was originally and is currently designed to occur in person because of the small group work and hands-on learning that compose the bulk of the curriculum. However, the 2021 course was successfully conducted virtually, and in 2022, several lectures were moved to a hybrid format because of public health considerations. The resulting lectures and tutorials are now compiled in Jupyter notebooks, as referenced in the "Teaching tools" section, and are available to students through a remote server during the course.

Hands-on components of the lectures can therefore be accessed in real time by individual students in a remote setting, and instructors are additionally able to help if students are struggling via screen-share capabilities and breakout rooms. During remote teaching during the course, one to two additional teaching assistants were available during each remote video session to help the program move smoothly and to provide additional support during breakout coding sessions.

Short lectures from each of our presenters were also recorded, and the videos were provided to all students, either as material for precourse study or as a substitute for some virtual video call interactions during the remote version of the course. Students are participating from a wide range of time zones during the remote course (e.g., there is a 9-h time difference from the Pacific Time Zone on the west coast of the United States to Central European Time in Oslo). Thus, 1–2 h of prerecorded lecture, with theory and physiological background, were provided for students to watch each day, followed by a live coding video call session each evening from 5 to 8 pm (Central European Time in Oslo), which is 8:00–11:00 am (Pacific Time Zone in La Jolla).

In the virtual course, additional days were included at the beginning of the course to account for lost time during this intensive course. An example virtual syllabus can be seen in Table 4. Steps were taken to maximize time zone consolidation for project groups, which allowed group work to occur more productively during the interim period in July that year. This virtual framework was largely successful, as the student reports show (8). Our experience in SSCP can provide a useful template for conducting productive virtual workshops and courses of longer format.

Table 4. A brief version of the syllabus for part one of the virtual SSCP conducted in 2021.

Day	Format	Example lecture
	Live online	Course introduction
0	Live online	Python tutorial (optional)
1	Pre-recorded	Physical chemistry and electrochemistry
	Live online	Mass transport and membrane biophysics
2	Pre-recorded	Ion channel gating
	Live online	Simulating the action potential
3	Pre-recorded	Electrical conduction in biology
	Live online	Modelling electrical conduction in cardiac tissue
4	Pre-recorded	Quantitative aspects of calcium handling
	Live online	Calcium handling; the EMI model
5	Pre-recorded	Fundamental cardiac mechanics
	Live online	Modeling myofilament dynamics
6	Pre-recorded	Crash Course on Sobolev spaces
	Live online	The Finite Element Method/FEniCS
7	Pre-recorded	Electrophysiology modeling in FEniCS
	Live online	Mechanics applications in FEniCS
8	Pre-recorded	Machine learning in physiological systems
	Live online	Machine learning exercises
9 and 10	Live online	Branched curriculum based on project area

III. RESULTS

A. Student attendance and demographics

As expressed in the "Motivation and background" section, a key goal of the course is to ensure enthusiastic participation by Master's and PhD students from all the founding institutions. An accessory goal, accounting for applicant excellence, is to recruit widely in a broad geographical sense, both to ensure reach and equity when possible and to lend focus to the international character of the summer school. In Figure 2, the results from the first 9 years of SSCP in terms of numbers of attendees and distinct countries represented are shown.

Throughout the life of the SSCP, a general trend toward increased applicant numbers, as well as increasing numbers of attendees, has occurred. Overall, the SSCP has had a 47% acceptance rate for applicants, although in some cycles, this has been as low as 32% (2019). Of the accepted applicants, 68% have been enrolled in a PhD program, 24% have been pursuing a Master's project, and 8% are "other" (i.e., either advanced Bachelor's students or students completing a postdoctoral fellowship). Of all attendees, 47% have been female, comparing on par with recent statistics in this area from the United States (17). Approximately 40% of all attendees (87 students) attend one of the three partner institutions, but students have also attended the school from more than 70 universities worldwide, including King's College

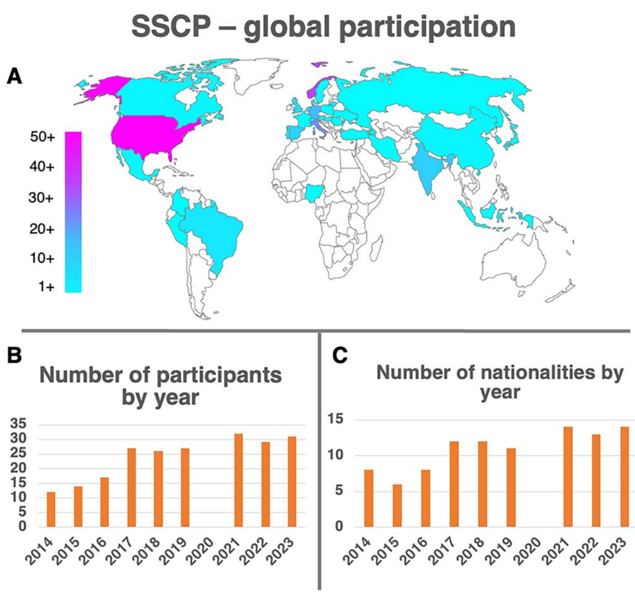

Fig 2. Increase in global reach of the SSCP, 2014–2023. (A) top: global distribution of SSCP attendees since 2014; the number of students from each nation highlighted is indicated by color. (B) bottom left: the number of SSCP attendees per year since 2014; note the steady increase in numbers of students, reflecting greater numbers of applications. (C) bottom right: the number of represented nationalities by year.

London, Karlsruhe Institute of Technology, Maastricht University, Norwegian University of Science and Technology, the University of Oxford, University of California Berkeley, and University of California Davis.

B. Student experience

1. Quantitative results

Since 2015, students have completed a full course evaluation, such that course quality and efficacy can be thoroughly assessed. Evaluations were anonymous, and results were gathered in accordance with General Data Protection Regulation guidelines. A sampling of evaluation results from recent years is highlighted in Figure 3. These specific areas of presentation relate directly to the core of the student experience, namely the course content (How valuable is the chosen content in SSCP, from the student perspective?), course organization (What sort of experience was created by the organizational choices made?), and instructor involvement and student interaction (viewed holistically across the length of the course). As presented, evaluation metrics do not distinguish individual experience or specific factors related to content, organization, and instruction; however, they do offer an overall picture of SSCP's reception by students and their overall experience as mentees. Generally, most responses for the three categories are very good or excellent (77%, 76%, and 90% for course content; 81%, 95%, and 95% for course organization; and 71%, 82%, and 94% for instructor involvement and interaction with students for 2021, 2022, and 2023, respectively).

2. Qualitative results

In addition to the immediate annual course evaluations presented in brief in the previous section, feedback was very recently requested from all SSCP alumni from 2014 through 2023 in the form of an anonymous online survey for the advent of the 10-year anniversary of the SUURPh program and SSCP. Of the 14 individuals who have responded to date, six took the course in 2023, three in 2022, two in 2021, two in 2015, and one in 2018. Although this initial response to the available survey is relatively sparse in comparison with the numbers trained, the survey offers key qualitative insight on course attitudes and outcomes.

On a scale of 1–5 (low to high) rating the likelihood that the participant would recommend SSCP to a colleague, 21.4% chose a rating of 4, and 78.6% chose a rating of 5, corresponding to all respondents saying that they would be likely or highly likely to recommend SSCP. Furthermore, although many respondents were unsurprisingly still in training, others currently work or have worked in diverse sectors (Fig 4).

Both in the all-alumni survey and in annual course evaluations, opportunities are available for respondents to weigh in with stories about how SSCP may have benefited their research and careers. This input is frequent and includes the following testimonial feedback:

(1) "The Simula summer school was a valuable experience for me. The comprehensive training in Oslo, paired with the engaging project work in San Diego, has greatly enhanced my

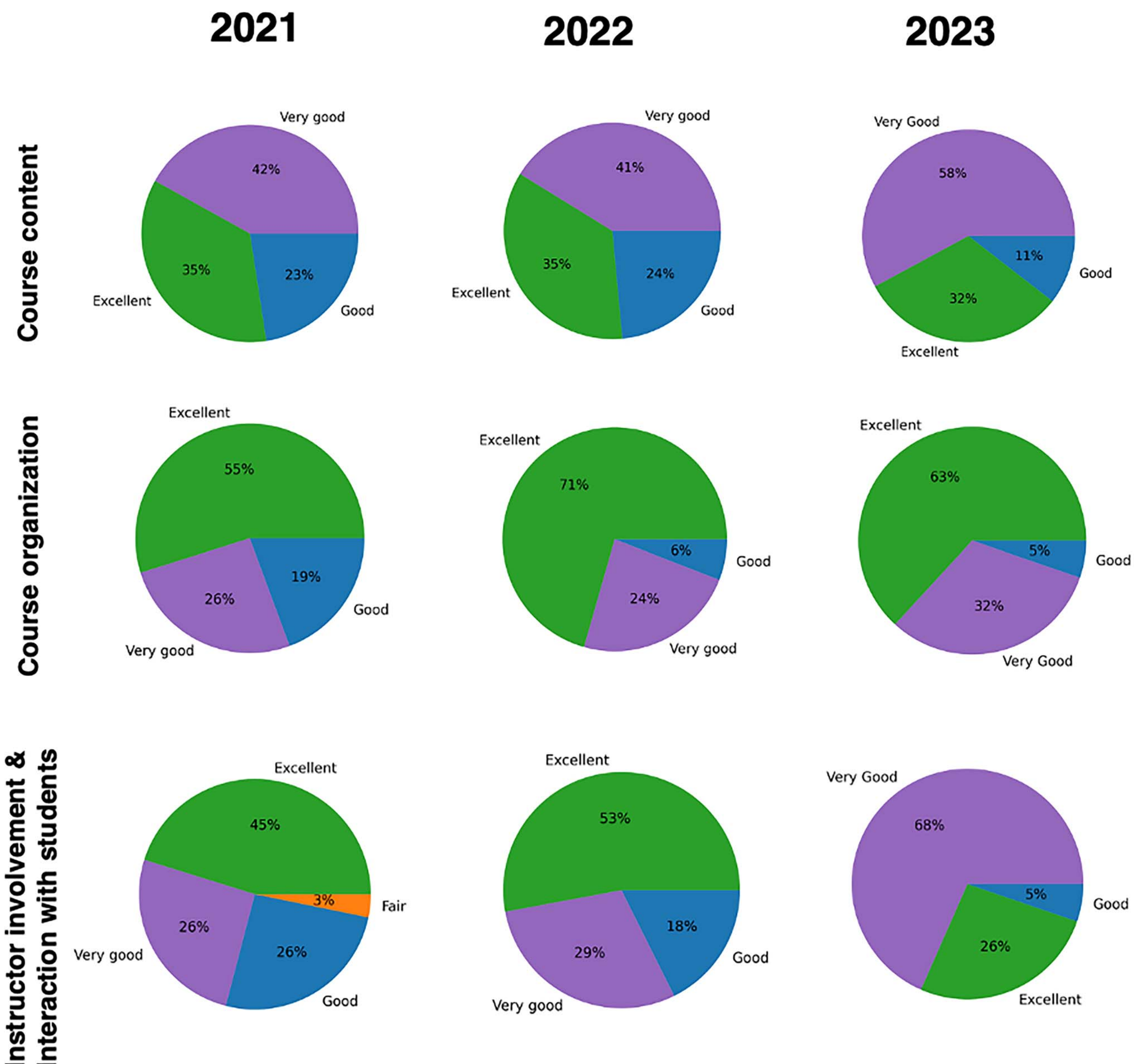

Fig 3. Partial results from the SSCP student course evaluations for recent years, 2021–2023. Top row: course content; middle row: course organization; bottom row: instructor involvement and interaction with students.

learning journey. Interacting with exceptional individuals and establishing new connections has been incredibly rewarding. I am grateful for the wonderful moments and the knowledge gained during this valuable opportunity provided by Simula."

(2) "SSCP was a great experience. Very good educational content, and a great way to get to know other researchers and students working with computational physiology across the globe."

(3) "I think that everything went very smoothly and we got to connect with our supervisors as a whole, and also get to do a bit of independent research. I really appreciated the fact that our supervisors were always interested in listening to our new ideas, and discussing it with us in depth. All in all, a great experience and I feel very lucky to have been a part of this summer school!"

(4) "[My advisor] was a great mentor. He always helped us when we were stuck and

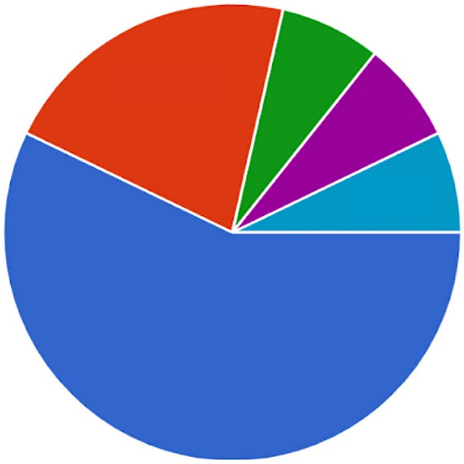

Fig 4. Initial results from the SSCP 2014–2023 alumni survey, indicating the potentially diverse career paths chosen by trainees.

motivated us. I also had a great learning experience with my teammates. Everyone was involved and motivated to contribute to the project. Even though I work in cardiac research and not pancreatic beta cells, the modeling techniques and tools I learnt and applied are equally applicable to my research."

C. Funding

As mentioned in the "Introduction," the Norwegian government (specifically KD) has provided major and direct funding for the SSCP since the school's inception in 2014. Without this sustained support, neither the SSCP nor the parent SUURPh program would be possible, let alone have become well-recognized and stable mechanisms of training and collaboration. Additional funding from adjacent groups within Norwegian and European research environments has also provided opportunities for complementarity over the years. Notably, the SSCP has consistently partnered with Digital Life Norway (DLN) since the latter's inception in 2016. DLN is a major initiative of the Research Council of Norway (RCN) to foster cross-disciplinary science that couples digital technologies with life science research. The commonality of mission between SSCP and DLN has made for easy involvement (and support) of DLN students in the SSCP, who have, in turn, enriched and expanded the school.

Given the international nature of the SSCP, it has also been a natural fit to partner with major internationalization initiatives. The RCN funds the International Partnerships for Excellent Education, Research and Innovation (INTPART) program to foster long-term international cooperation and training. To date, three INTPART financial awards have been collaborated with SSCP awards to provide domain-specific training in computational physiology. Namely, NeuroComp (the Trans-Atlantic Consortium in Computational Neuroscience), SiMent (Simulating the Multiscale Physiology of Mental Illness), and SIMBER (the Simula-Berkeley Education and Research Collaboration). In each case, the awards have supported SSCP involvement for several students and exchange of trainees between students based in Oslo and North America. Finally, the SSCP has also combined with major European training awards in computational cardiac physiology, first with the Atrial Fibrillation Training Network (a Marie Skłodowska-Curie award from EU Horizon 2020, 2016–2019). In 2024 the SSCP will partner with the MicroCard project, a consortium for high-performance computing in cardiology cofunded by EuroHPC and the RCN.

It is through this broad range of collaborations (and shared funding) involving Norway, the United States, and Europe that the SSCP has become a mature, diverse, and well-regarded international training mechanism; however, the crucial, stable funding that the KD has provided to this end must be stressed. With that reliable and invaluable support, it has been possible to consistently offer the school's opportunities to students year after year, relatively insulated from the broader fluctuations in economics and international sentiment. That consistency has been essential for progressively building the curriculum and student experience as it is today.

D. Perspectives

It is, of course, relevant to acknowledge the challenges that have presented themselves in developing the SSCP. It is an ambitious school that accepts students of diverse educational, linguistic, and cultural backgrounds and asks them to learn actively from start to finish.

A major focus over the first few years was to develop a clear trajectory through the curriculum—spanning molecular biophysics to tissue- and organ-level phenomena—which is generally taught by specialists in each area. To do this, the focus has been on establishing a common lineage of practical exercises that more explicitly links the topics and makes extensive use of the Jupyter framework.

As mentioned, a second major evolution has been to implement remote and hybrid approaches that have served to make the school and student experience much more flexible. This has broadly improved learning outcomes and allowed students to preemptively search for the material that is new for them and a posteriori engage with topics and exercises they found challenging.

Finally, an ongoing challenge for the SSCP is to balance the breadth of the material and varied student backgrounds. In part, this issue is addressed by carefully selecting the student cohort each year, and, to the extent it is possible, the projects are tailored to the students' backgrounds. For the lectures, it was clear that to properly serve certain topics, it was necessary to allow students to separate into streams of specialization over the latter portions of the curriculum.

These changes have all been adaptive in response to the feedback received from students or from the changing environment in which it is conducted. It is expected that this process will be ongoing and intended so that the school will continue to evolve in the years to come, thereby better serving the students and scientific communities.

Several other high-quality summer schools and workshops exist in the general space of computational physiology. Some examples are the Institute of Electrical and Electronics Engineers, Engineering in Medicine and Biology Society International Summer School on Computer Modeling in Medicine, the CNeuro Theoretical and Computational Neuroscience Summer School, the European Brain Research Infrastructures Baltic-Nordic Summer School on Neuroscience and Neuroinformatics, and the University of Graz Summer School on Biomechanics and Modelling in Mechanobiology. These courses generally occur in a 1–2-week period, have varying registration fees, change specific topics from year to year, and focus mostly on lectures and tutorials. The SSCP stands out as a separate and valuable contribution to the field of graduate education in computational physiology because of the following: (1) specific course material in multiscale modeling of excitable tissues from both EP and mechanics perspectives; (2) research projects related to student backgrounds and grounded in ongoing research, with the potential for future collaboration with project advisors; (3) 18 days of in-person instruction, split across two campuses; (4) the ability for students to earn 10 credits within the European Credit Transfer and Accumulation System by completing both the lecture and project portions of the course; (5) the lack of registration fee or costs related to accommodation and travel; and (6) ongoing funding, allowing for growth and continuity on a 10-year time frame and beyond.

IV. CONCLUSION

Over the past 10 years, the SSCP has grown to become a major international training mechanism for PhD students in computational physiology, bioengineering, applied mathematics, and medicine. In that time, it has educated 217 students from 38 countries, including 41 Norwegian PhD students. In addition to fundamental student training and fostering student exchange across borders, SSCP has served as a vital means of recruiting talented young scientists both to Norwegian research and to our U.S.-based SUURPh partner institution, UCSD. Through a combination of hands-on teaching, real-world problem solving, and a sustainable funding source, the SSCP can serve as a helpful guide for others wanting to foster scientific collaboration and cutting-edge research through targeted mentorship.

AUTHOR CONTRIBUTIONS

KJM designed research, performed research, and wrote the paper. NF performed research, contributed analytic tools, and analyzed data. AGE designed research, performed research, and contributed writing to the paper. MMM designed research, performed research, analyzed data, and wrote the paper.

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