Teaching cardiovascular physiology with equivalent electronic circuits in a practically oriented teaching module

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Ribarič S, Kordaš M. Teaching cardiovascular physiology with equivalent electronic circuits in a practically oriented teaching module. Adv Physiol Educ 35: 149–160, 2011; doi:10.1152/advan.00072.2010.—Here, we report on a new tool for teaching cardiovascular physiology and pathophysiology that promotes qualitative as well as quantitative thinking about time-dependent physiological phenomena. Quantification of steady and presteady-state (transient) cardiovascular phenomena is traditionally done by differential equations, but this is time consuming and unsuitable for most undergraduate medical students. As a result, quantitative thinking about time-dependent physiological phenomena is often not extensively dealt with in an undergraduate physiological course. However, basic concepts of steady and presteady state can be explained with relative simplicity, without the introduction of differential equation, with equivalent electronic circuits (EECs). We introduced undergraduate medical students to the concept of simulating cardiovascular phenomena with EECs. EEC simulations facilitate the understanding of simple or complex time-dependent cardiovascular physiological phenomena by stressing the analogies between EECs and physiological processes. Student perceptions on using EEC to simulate, study, and understand cardiovascular phenomena were documented over a 9-yr period, and the impact of the course on the students’ knowledge of selected basic facts and concepts in cardiovascular physiology was evaluated over a 3-yr period. We conclude that EECs are a valuable tool for teaching cardiovascular physiology concepts and that EECs promote active learning.

OPTIMAL TEACHING of physiology to undergraduate medical students requires a fine balance between teaching facts and teaching concepts. Traditional teaching favors teaching facts over learning concepts (10), but with the wide availability of textbooks and other quality teaching material in electronic form (e.g., on the internet) this cannot be justified anymore. The passive didactic lecture style of teaching in elementary physiology courses is not the best available option to promote the learning of basic physiology concepts and their application (42). In addition, teachers tend to overestimate students’ abilities to apply their knowledge (44). Therefore, contemporary teaching should put more emphasis on teaching modules that develop the student’s ability to apply information and develop a better understanding of physiology concepts, thus ensuring the desired educational outcome for the future health professional (10). Practically oriented teaching modules that promote active learning, and are complimentary to lectures, can enhance the student’s understanding of concepts (7, 20, 21, 37)

The successful use of computer-based simulations to facilitate the retention of knowledge and promote active learning has been well documented (9, 12, 15, 18, 19, 31, 32, 34, 36, 40, 54). Also, virtual laboratories can instruct students as effectively as hands-on laboratories (9, 15, 16, 18). This article reports on the use and evaluation of a computer-based model of the cardiovascular system that uses equivalent electronic circuits (EECs) to teach undergraduate medical students some basic physiology concepts. In principle, the circuit representing the cardiovascular system can be a physical circuit (24); however, its drawback is the fact that the components, although of high quality, are still unable to perform a satisfactory simulation (e.g., leaky capacitors, input resistance of operational amplifiers not high enough, etc.). The best approach is to use computer software to draw a circuit and analyze it; thus, the components are exactly as defined. Commercial software (e.g., Micro-Cap II or Electronics Workbench) or freeware (e.g., Spice) are available for the design of EECs. In neurophysiology and cell physiology, the use of equivalent circuits is well known; they are used extensively in research as well as in teaching (2). In other fields of physiology, the use of equivalent circuits is less known. Instead, the system under study (e.g., blood circulation) is described by various sets of equations, which are then solved either for steady-state or time-dependent conditions (11, 28, 51, 56). The main advantage of a computer-based EEC model over a computer-based mathematical model of human physiology is that the knowledge of solving differential equations is not necessary; only a basic understanding of some of the physical quantities (i.e., voltage, current, resistance, charge, and capacitance) underlying the ECC is required. Thus, the undergraduate medical student can easily manipulate the model and observe the results of simulations. EEC models of selected cardiovascular, respiratory, or renal physiological and pathophysiological states have been described in detail in previous publications (6, 17, 38, 39, 45, 46, 50).

METHODS

Simulating Cardiovascular Physiology With a Computer-Based EEC

The EEC was designed with a Microsoft Windows-compatible version of Electronic Workbench software (version EWB 5.12). A detailed description of the EEC for cardiovascular physiology has been previously published (45, 46, 50); therefore, only a brief description will be given. Voltage (1 V), current (1 μA), charge (1 μAs), resistance (10 MΩ), and capacitance (1 μF) in the EEC are equivalent to blood pressure (10 mmHg), blood flow (100 ml/s), blood volume (100 ml), resistance to flow (1 unit), i.e., 100 mmHg·100 ml−1·s−1, and capacitance of vessels (100 ml/10 mmHg) in the cardiovascular system. The unit of time is 1 s. Ground potential (reference for voltage measurements) is equivalent to atmospheric pressure (reference for pressure measurements). The resistance of blood vessels is simulated by resistors; vessel capacitance (the ratio between volume and pressure...
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sure) is simulated by capacitors. An atrium or a ventricle are simulated as a section of blood vessel in which its resting capacitance (diastole) can be decreased (systole) and then returned to the resting capacitance (diastole). This was achieved by attaching a switch to the ground terminal of a suitable capacitor. By rhythmically operating the switch, the terminal of this capacitor can be connected either to ground (simulating diastole) or to the output of a suitable voltage source (simulating systole). This EEC can simulate steady-state or transient phenomena in the cardiovascular system during physiological [e.g., increased cardiac output (CO)] or pathophysiological states (e.g., heart failure). For the elective, practically oriented teaching module, we deliberately used a simple EEC model of the cardiovascular system [simulating the right ventricle (RV), pulmonary circulation, left ventricle (LV), systemic arteries, systemic arterioles, and systemic veins] that did not include contracting atria (atria were simulated as part of the venous system). The EEC can simulate changes in cardiovascular variables (venous return and CO) by adjusting the appropriate segment of the EEC that controls their physiological parameters (e.g., blood volume, capacitance, and resistance of blood vessels, contractility of the myocardium, and heart rate). A negative feedback loop, simulating the baroreceptor reflex, is also built into the EEC model of the cardiovascular system. This negative feedback loop can be switched on or off; it is also possible to simulate a delay in the negative feedback loop resulting in instability of the system and damped or maintained oscillations. With the aid of a simple and user-friendly interface, the EEC also allows for adjustments of individual cardiovascular parameters, thus enabling the study of their contribution to CO.

After the EEC is designed and thoroughly tested, it is saved for the students’ use. If it is in "run" mode (i.e., analysis executed), the effect of a parameter change (e.g., decreased contractility of the LV) on characteristic variables [aortic pressure (AoP), mean arterial pressure (MAoP), left atrial pressure (LAoP), etc.] can be readily displayed (Fig. 1, top graphs). After this, the student must calibrate the graph, i.e., to transform voltage into pressure (calibrating factor: 10) or voltage into LV volume (calibrating factor: 300; cf. Fig. 1, bottom graphs) or voltage into blood flow (CO; calibrating factor: 200). To study homeostasis, the feedback loops (controlling the venous tone, LV contractility, and heart rate) can be disconnected by operating corresponding switches.

The procedures described above are simple and straightforward and presented no problem for the students. However, if a highly motivated student requests sophisticated modifications of the EEC (e.g., to vary the time constant of a feedback loop or to vary the integration constant of MAoP calculation) it is not the student instructor but rather the teacher that explains the underlying theory and the resulting changes.

Teaching Cardiovascular Physiology With ECC in a Practically Oriented Teaching Module

Since 2001, ECCs have been used in elective pathophysiology courses for undergraduate medical students. On average, ~40 students/yr and were accepted to this practical course. The EEC course is organized within a single, elective, 4-h-long session that offers to the interested student an opportunity to enhance his/her understanding of selected concepts in cardiovascular physiology and pathophysiology during transient and steady-state conditions. These concepts (e.g., acute LV failure in the presence or absence of a negative feedback loop) have already been discussed during the preceding obligatory courses of physiology and pathophysiology. The EEC-based practical is offered at the end of the obligatory course in pathophysiology for third-year undergraduate students of medicine. Practical work is preceded with a 1-h instruction where the students are briefed on the course content, objectives, and duration and receive explicit instructions as to what study material should be studied before taking the course. The course content and execution are also available to the students in writing as a chapter in the student’s pathophysiology workbook. Students are also encouraged to bring to the practical any written material they feel would be useful to them.

Students who enrolled into the course are divided into groups of up to 16 students (2 students for each computer with an installed copy of the EEC) that attend together the 4-h-long practical course. Students were asked to take an anonymous test of 14 multiple-choice questions (MCQs) on some basic facts and concepts in cardiovascular physiology at the beginning of the course and a second MCQ test and survey on the student’s reaction to the course at the end of the session. The MCQ tests were anonymous; therefore, we could not match the pre-/posttest to the individual student. MCQs in the first and second test are similar; in the second test, the order of the MCQs is altered as well as the order of answers within each MCQ. The following are examples of questions that evaluate the student’s knowledge of facts or concepts.

Question 1: example of a question testing knowledge of facts. In an adult healthy human, the maximum velocity of ventricular contraction is about:
A. 10 m/s.
B. 2,000 mmHg/s.
C. 80 m/s.
D. 70 W.
E. 15 ml/s.

Question 2: example of a question testing knowledge of concepts. Let’s assume that after compensation of a mild acute left heart failure (via the baroreceptor reflex) the arterial blood pressure and CO are within normal limits. Compared with the values of cardiovascular parameters before acute left heart failure, one would expect:
A. Increased volume of the LV.
B. Increased end-systolic volume of the LV.
C. Increased end-diastolic volume of the LV.
D. Reduced contractility of the LV.
E. Reduced speed of contraction of the LV.

Of the 14 MCQs in the pre-/posttests, 8 questions tested knowledge of concepts and 6 questions tested knowledge of facts.

After the first MCQ test, students start to work independently on the computer-based EEC model of the cardiovascular system following a set of written instructions and questions that test the students’ understanding of the results of cardiovascular simulations (i.e., changes in cardiovascular variables after left heart failure). Essentially, students have to 1) initiate two simulations of the cardiovascular system (i.e., acute LV failure in the presence or absence of a negative feedback loop); 2) identify cardiovascular variables from graphs (Figs. 1 and 2) and observe their change over time (i.e., transient changes and establishment of a new steady state); and 3) record the observed changes as short descriptions or in tabulated form (Table 1).

The interface used is shown in Fig. 3A. Before simulation, a dialog box appears in which parameters of analysis are defined (cf. Fig. 3A1). This means that, when the simulation is started, the time course of variables (recorded at nodes 64, 79, 83, 85, 170, 249, and 270; default setting) is displayed [AoP, right atrial pressure (RAoP), LAoP, CO, MAoP, contraction of venous volume (CVV), and intrathoracic pressure (I TP); cf. the list of nodes next to Fig. 3A1] simulating cardiovascular variables before (50–70.5 s; normal conditions, normal LV contractility) and after (70.5–200 s) acute left heart failure is simulated. The default nodes are then manually removed (disabled) and node 99 is added (enabled) for the simulation of the time course of LV volume in normal conditions and after heart failure (cf. Fig. 3A2; the list of nodes is below Fig. 3A2). The time course of all variables, as seen on the computer screen before calibration, is shown in Fig. 3B. The time course of all variables, as seen on the computer screen after calibration, is shown in Fig. 3C. For correct calibration the student must know how to convert recorded variables in voltage (V) in equivalent variables (e.g., AoP, RAoP, and LAoP) using corresponding factors (e.g., factor 10 to convert voltage to pressure and factor 300 to convert charge to volume).
Students are advised that there is no specific deadline to meet when solving individual problems during the session and are also encouraged to discuss the work among them. A member of the faculty, with four student instructors, is also present at each session. They are not supposed to interfere with the students’ work and to offer advice or discuss specific issues only on the request of the individual student. The session ends with a structured group discussion lead by the faculty member where students are encouraged to discuss the results of the observed simulations on cardiovascular physiology and describe the basic physiology concept (i.e., negative feedback loop) that underlies the observed cardiovascular simulations. The relevance of computer simulations for understanding human physiology is also discussed during the EEC-based practical. Students are strongly advised to always evaluate the validity of physiological simulations by comparing the results of physiological simulations with data from in vivo measurements. We emphasize to the students that in vivo physiological measurements cannot be replaced by computer simulations. However, computer simulations can guide the development of experimental hypotheses and decrease in vivo experimentation. In addition, some measurements cannot be performed in vivo, but they can be readily performed as a simulation.

Statistical evaluation of students’ MCQ test results and answers to the survey were done with SPSS 15. Depending on the homogeneity of variances (Levene’s test), we calculated multiple comparisons with one-way ANOVA or Kruskal-Wallis test (exact test Monte Carlo with 1,000,000 samples, 99% confidence interval) and post hoc analysis ($\alpha = 0.01$) with the Bonferroni (for equal variances) or Dunnet T3 test (variances not equal). Differences among groups were considered statistically significant when $P < 0.05$. Significance of a two-tailed bivariate correlation was calculated with Kendall’s $\tau$-b test.
distribution of samples was tested with a one-sample Kolmogorov-Smirnov Z-test (99% confidence level, exact test Monte Carlo based on 1,000,000 sampled tables). Comparison of paired samples with a normal distribution of data was done with a two-tailed paired-samples t-test (99% confidence interval, exact test Monte Carlo based on 1,000,000 samples).

RESULTS

Student Perceptions of the Practically Oriented Teaching Module That Uses EEC for Teaching Cardiovascular Physiology

Aggregate student grades of the course, over the period from 2001 to 2010, are shown in Table 2. The number of undergraduate medical students that attended the workshop in this period was 346 students. The highest grade was 5 (completely agree with the statement), the lowest grade was 1 (completely disagree with the statement), and a grade of 0 was assigned to unanswered questions. The number of students that assigned a grade is shown in percentages (100% = 346 students). For example, 81.3% of students gave a grade of 5 to statement 1. For questions 1–13, the distribution of students’ grades (0–5) was compared with the Kruskal-Wallis test and post hoc analysis (α = 0.01) with the Dunnet T3 test due to significantly different variances. The distribution of grades was statistically significant for all statements (average \( P < 0.001 \) by Kruskal-Wallis test). A grade of 5 was significantly the most frequent grade for statements 1–7 and 9–12 (average \( P < 0.001 \) for multiple comparisons by Dunnet T3 test). To summarize, the majority of students were completely satisfied with the scope and organization of the course (i.e., could work independently, received an explanation when requested, and perceived the course instructors as helpful). Over 70% of the students considered the course to be useful and would recommend the course to their junior colleagues. About half of the surveyed

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Fig. 2. Changes in cardiovascular variables during normal ventricular function and acute LV failure. Students are required to identify the variables on the graphs and mark the variables with the appropriate abbreviations. ITP, intrathoracic pressure; RAP, right atrial pressure; CVV, contraction of venous volume.
students (53.3%) felt that they have received new insights into the physiology and pathophysiology of the cardiovascular system, and an additional 30.8% of students almost completely agreed with this statement (assigned the second-highest grade to this statement, a grade of 4).

Table 3 shows the average grades of statements 1–13 for each academic year from 2001 to 2010. Students graded their agreement with statements 1–13 from a grade of 5 (completely agree with the statement) to a grade of 1 (completely disagree with the statement). Over the 9-yr period, there were no significant changes \((P > 0.05)\) in the average grade for statements 2, 3, and 5–12 (two-tailed Kendall’s \(\tau-b\) correlation test). Over the same period, there was a significant increase in the average score for statements 1, 4, and 13 (two-tailed Kendall’s \(\tau-b\) correlation test). There was a significant increase in the average grade of statement 4 \((P = 0.046)\) and a significant decrease in the average grade of statements 1 \((P = 0.02)\) and 13 \((P = 0.005)\). Therefore, most of the students’ attitudes toward the course did not significantly change (did not show a significant trend) over the studied time period.

Impact of the Course on the Students’ Knowledge of Selected Basic Facts and Concepts in Cardiovascular Physiology

We compared the students’ average scores between the first and second MCQ test for the academic years of 2007–2010 (Table 4). Student scores were consistently higher in the second MCQ test for all three academic years (multiple comparisons with a two-tailed Bonferroni test, \(P < 0.001\)). The average score in the first test did not change over the three academic years (multiple comparisons with two-tailed Bonferroni test, average value of \(P = 1.0\)); the same statistical result was computed for the average scores of the second test. The students’ attrition rate (i.e., the number of students that attended the practical but did not submit or did not answer the pre-/posttest) was 0 students (0%), 9 students (18%), and 1 student (3%) for the academic years of 2007–2008, 2008–2009, and 2009–2010, respectively.

In addition to evaluating the students’ average scores of the first and second tests, we also compared the percentage of students that answered each MCQ correctly between the first and second MCQ test. Table 5 shows the proportion of students that answered each MCQ correctly given as a percentage of the number of students that attended the first and second test. For example, in the academic year of 2007–2008, the percentage of students that correctly answered question 1 was 61.5% for the first test and 86.5% for the second test. The students’ overall success rate in answering the MCQs significantly improved in the second test over the first test (two-tailed paired-samples \(t\)-test, 99% confidence interval) in each academic year for the period of 2007–2010. Questions 3–7, 10, 11, and 14 tested understanding of concepts (marked with asterisks in Table 5), and questions 1, 2, 8, 9, 12, and 13 tested knowledge of facts. We tested whether the significantly improved success rate in answering the MCQs in the second test could be observed for both types of questions when compared separately (Table 5). The success rate for questions testing the understanding of concepts improved in the second test over the first test in all three academic years \((P = 0.002, P = 0.004, \text{ and } P = 0.008)\) by a two-tailed paired-samples \(t\)-test, 99% confidence interval). However, the success rate for questions testing the knowledge of facts did not improve significantly in the second test over the first test in all three academic years \((P = 0.056, P = 0.11, \text{ and } P = 0.097)\) by a two-tailed paired-samples \(t\)-test, 99% confidence interval).

DISCUSSION

Overall, the students had a positive experience with the practical course in EEC simulations of cardiovascular physiology. A significant majority of students gave the highest
Fig. 3. A: interface displayed on the computer screen just before a simulation is started. A1: default setting of a simulation and default nodes (variables) selected to be displayed in the graph. A2: manually added (enabled) node selected to be displayed in the graph. Note the box (next to A1 and below A2) showing which variable is recorded at a single node. LVV, LV volume. B: time course of variables as seen on the computer screen before calibration. Parameter change (LV contractility decrease, ~20% of normal) occurs (set as default) at 70.5 s of simulation time. Note that the scaling of both graphs is automatic. Therefore, the scaling in the y-axes of the top and bottom graphs is different. Also, the x-axes differ in size. Therefore, there is, after the parameter change, an apparent lag in the time course of the variable shown in the bottom graph. C: time course of all variables as seen on the computer screen after calibration. For correct calibration, the student must know how to convert recorded variables in voltage (V) in equivalent variables (e.g., AoP, RAoP, and LAoP) using the corresponding factors (e.g., factor 10 to convert voltage to pressure and factor 300 to convert charge to volume). Note that after calibration both x-axes are of the same size. Therefore, after the parameter change, there is no time lag in variables shown in both graphs.
grades to the course organization (e.g., sufficient number of instructors, independent work, and sufficient time to solve individual tasks) and content (e.g., considered the practical work useful and received new insights). Seventy-five percent of the students would recommend without reservations the course to their junior colleagues. Very few students expected to attend similar practical courses in the future, consistent with the fact that there are no other similar courses available at the present.

Practical courses with computer EEC simulations improve the students’ understanding of basic concepts in cardiovascular physiology. The students’ average test score for all 14 MCQs significantly improved at the end of the course (i.e., at the second test), mainly due to the improved success rate in answering questions that tested the knowledge of concepts.

Computer-based learning enables the individualization of teaching and promotes learner-controlled instruction (LCI).

Table 3. Average student grades of the cardiovascular physiology module in the academic years of 2001–2010

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<tr>
<td>1. The scope of the workshop was appropriate.</td>
<td>4.8 ± 0.1</td>
<td>4.8 ± 0.1</td>
<td>4.8 ± 0.2</td>
<td>4.8 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.6 ± 0.1</td>
<td>4.6 ± 0.1</td>
<td>4.6 ± 0.1</td>
<td>4.7 ± 0.1</td>
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<tr>
<td>2. There was a sufficient number of instructors.</td>
<td>4.8 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>3.5 ± 0.4</td>
<td>4.8 ± 0.2</td>
<td>4.9 ± 0.0</td>
<td>4.8 ± 0.1</td>
<td>4.9 ± 0.1</td>
<td>4.8 ± 0.1</td>
<td>4.8 ± 0.1</td>
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<tr>
<td>3. The instructors were helpful.</td>
<td>4.9 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>4.8 ± 0.2</td>
<td>4.8 ± 0.2</td>
<td>4.8 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>4.9 ± 0.0</td>
<td>4.8 ± 0.1</td>
<td>4.8 ± 0.1</td>
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<tr>
<td>4. I had sufficient time to solve individual tasks.</td>
<td>3.9 ± 0.2</td>
<td>4.1 ± 0.3</td>
<td>4.5 ± 0.3</td>
<td>3.8 ± 0.3</td>
<td>4.4 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>4.6 ± 0.1</td>
<td>4.6 ± 0.1</td>
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<tr>
<td>5. I could work independently.</td>
<td>4.2 ± 0.2</td>
<td>4.8 ± 0.1</td>
<td>4.5 ± 0.3</td>
<td>4.8 ± 0.2</td>
<td>4.8 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>4.7 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.5 ± 0.2</td>
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<tr>
<td>6. I understood everything I did.</td>
<td>3.8 ± 0.1</td>
<td>4.2 ± 0.2</td>
<td>4.0 ± 0.2</td>
<td>4.4 ± 0.1</td>
<td>3.7 ± 0.1</td>
<td>4.5 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>4.2 ± 0.1</td>
<td>4.0 ± 0.1</td>
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<tr>
<td>7. I received an explanation when requested.</td>
<td>4.4 ± 0.2</td>
<td>4.9 ± 0.0</td>
<td>4.3 ± 0.2</td>
<td>4.8 ± 0.1</td>
<td>4.3 ± 0.2</td>
<td>4.9 ± 0.1</td>
<td>5.0 ± 0.0</td>
<td>4.8 ± 0.1</td>
<td>4.6 ± 0.1</td>
</tr>
<tr>
<td>8. I had the opportunity to compare the results of my simulations with those obtained in vivo.</td>
<td>4.0 ± 0.2</td>
<td>3.9 ± 0.2</td>
<td>3.4 ± 0.3</td>
<td>3.2 ± 0.3</td>
<td>3.3 ± 0.2</td>
<td>4.0 ± 0.2</td>
<td>5.0 ± 0.0</td>
<td>3.7 ± 0.2</td>
<td>3.4 ± 0.2</td>
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<tr>
<td>9. I received new insights into the physiology and pathophysiology of the cardiovascular system.</td>
<td>3.9 ± 0.2</td>
<td>4.5 ± 0.1</td>
<td>4.1 ± 0.3</td>
<td>4.3 ± 0.2</td>
<td>3.9 ± 0.2</td>
<td>4.5 ± 0.2</td>
<td>4.5 ± 0.1</td>
<td>4.4 ± 0.1</td>
<td>4.3 ± 0.1</td>
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<tr>
<td>10. The practical work at the computer workshop was useful to me.</td>
<td>4.5 ± 0.1</td>
<td>4.9 ± 0.1</td>
<td>4.6 ± 0.2</td>
<td>4.6 ± 0.2</td>
<td>4.2 ± 0.2</td>
<td>4.8 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.6 ± 0.1</td>
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<tr>
<td>11. I would recommend the computer workshop to future generations of medical students.</td>
<td>4.6 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.7 ± 0.2</td>
<td>4.6 ± 0.2</td>
<td>4.4 ± 0.1</td>
<td>4.8 ± 0.1</td>
<td>4.8 ± 0.1</td>
<td>4.6 ± 0.1</td>
<td>4.6 ± 0.1</td>
</tr>
<tr>
<td>12. The number of computer workshops of this kind in the undergraduate curriculum should be increased.</td>
<td>4.5 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.5 ± 0.2</td>
<td>4.2 ± 0.2</td>
<td>3.8 ± 0.2</td>
<td>4.6 ± 0.1</td>
<td>4.7 ± 0.1</td>
<td>4.0 ± 0.2</td>
<td>4.3 ± 0.1</td>
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<tr>
<td>13. I expect to attend similar computer workshops in the future.</td>
<td>3.0 ± 0.2</td>
<td>3.6 ± 0.3</td>
<td>3.1 ± 0.4</td>
<td>2.9 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>2.6 ± 0.3</td>
<td>2.4 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>2.3 ± 0.2</td>
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Values are means ± SE; n, no. of students.
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Table 4. Student scores on the MCQ tests in the academic years of 2007–2010

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<tr>
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<th>MCQ Test Scores</th>
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<tr>
<td></td>
<td>n</td>
<td>Test 1</td>
<td>Test 2</td>
<td>P Value</td>
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<tr>
<td>Academic years</td>
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<tr>
<td>2007–2008</td>
<td>52</td>
<td>6.5 ± 0.3</td>
<td>9.4 ± 0.2</td>
<td>&lt;0.0001</td>
<td></td>
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<tr>
<td>2008–2009</td>
<td>40</td>
<td>6.6 ± 0.2</td>
<td>9.1 ± 0.3</td>
<td>&lt;0.0001</td>
<td></td>
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<tr>
<td>2009–2010</td>
<td>33</td>
<td>6.4 ± 0.3</td>
<td>9.0 ± 0.3</td>
<td>&lt;0.0001</td>
<td></td>
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</tbody>
</table>

Values are means ± SE; n, no. of students. MCQ, multiple-choice question.

However, the study design must define clearly what the learner is controlling during a computer-based instruction (41) since learner control may or may not include control over content, control over sequence, control over pacing, context within which to learn, method of presentation, provision of optional content, or locus of control (52). Also, instructional treatments have to be of a sufficient duration to provide learners with an effective learner control experience (41), and subjects in learner control research should be engaged in learning that is personally meaningful and has real consequences for them. Two other concerns are small sample sizes and large attrition rates (41). LCI can allow learners to choose their own learning activities based on their personal needs and preferences (29), thereby promoting an internal locus of control attitude. Learners with a positive locus of control (i.e., internals) are assumed to be more perceptive to, and more ready to learn from, their learning goals (5). Internals have higher posttest achievement than externals regardless of the form of advisement given to them in a computer-based instruction session (47). Research on LCI has actually shown that it enhances learners’ motivation and involvement compared with other kinds of instruction (13, 25, 49, 55). However, LCI is often found to be less effective for learning than fixed or adaptive system-controlled instruction (25). Positive learning effects of LCI are more likely to be expected for learners with more prior knowledge (26, 33, 35, 48, 49, 53) or for learners with higher levels of metacognitive skills (3, 48) and less likely for novices (4). The variable effects of LCI on learning could be explained by differences in the learners’ ability to accurately assess their own performance (25). Therefore, learner control has to be optimized, and learner control with advisement has been recommended for computer-based instruction (8, 22). Research has shown that adaptive advisement should be used for computer-based instruction since this form of advisement resulted in a higher posttest performance than evaluative advisement when used in learner control conditions (47).

The EEC practical was designed to give the students the best possible LCI experience that could be provided (i.e., sufficient prior knowledge, control over pacing, control over sequence, and stimulation of an internal locus of control attitude). They were provided, 1 wk in advance, with all the relevant information on the selected topics in cardiovascular physiology that were discussed during this course and were also encouraged to bring their own study material should they decide that this would be necessary. The precourse study information was given in writing and during a 1-h oral briefing session that also included a demonstration of the EEC software for simulating cardiovascular physiology. The content of the EEC practical was personally meaningful to the students (i.e., gave students a better understanding of selected cardiovascular physiology topics) and had real consequences for them (i.e., the information could be applied to real patients that the students are likely to meet during clinical rotations). During this precourse briefing, the course presenter repeatedly assured the students that they will be provided with additional information during the course should they request it and that they should take advantage of this option. Students were also advised that there was no specific deadline to meet when solving individual problems during the 4-h session and were also encouraged to discuss the work among themselves. Finally, student instructors, as opposed to teaching staff instructors, were used for the individ-

Table 5. Comparison of student success rates in answering the first and second MCQ tests for the academic years of 2007–2010

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<tbody>
<tr>
<td></td>
<td>Test 1</td>
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<td>MCQs</td>
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<td>1</td>
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<td>86.5</td>
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<td>2</td>
<td>90.4</td>
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<td>3*</td>
<td>32.7</td>
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<td>4*</td>
<td>65.4</td>
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<td>5*</td>
<td>7.7</td>
<td>17.3</td>
<td>7.5</td>
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<td>6*</td>
<td>73.1</td>
<td>94.2</td>
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<td>7*</td>
<td>5.8</td>
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<td>8</td>
<td>40.4</td>
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<td>9</td>
<td>32.7</td>
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<td>10*</td>
<td>3.8</td>
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<td>13</td>
<td>86.5</td>
<td>88.5</td>
<td>95</td>
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<tr>
<td>14*</td>
<td>50</td>
<td>71.2</td>
<td>50</td>
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P values of test 1 vs. test 2 0.001 0.003 0.003
For questions on the understanding of concepts 0.002 0.004 0.008
For questions on the understanding of facts 0.056 0.11 0.097

Values are means ± SE (in %); n, no. of students. *Questions that tested the understanding of concepts.
ualization of teaching and also to further encourage the students to request information should they need it (we assumed that the students would be more comfortable consulting with their senior colleagues than with the teaching staff). On the one hand, the use of student instructors enabled the teaching staff to perform other essential work; on the other hand, student instructors have to be trained on a yearly basis by the staff since very few instructors participate in the course more than once. To optimize the computer-based instruction, adaptive advisement was practiced by the teacher and student course instructors who, during the course, had brief, focused discussions with each student about his/her progress in solving the required tasks and offered advice when requested by the student or if it was obvious that the student missed the point completely. The number of students that attended the EEC practical varied between 25% and 16% of the student body (~210 students) in the academic years of 2007–2010. However, the benefit of the EEC practical for improving the students’ understanding of selected topics in cardiovascular physiology was confirmed in three successive years by statistical analysis.

The reason for introducing the EEC-based practical module was to enhance the students’ understanding of selected concepts in cardiovascular physiology. The main advantage of this computer-based simulation is its ability to demonstrate in real time the transient cardiovascular changes as they occur and the progression to a steady state, thus offering an alternative to in vivo animal demonstrations. The use of animal models for educational purposes has been banned in Slovenia; therefore, computer simulations of cardiovascular events are the only legal alternative. We conclude that the EEC computer-based practical was well received by the students and that it also improved our students’ understanding of cardiovascular physiology. Therefore, this approach is a useful supplement to the standard course in cardiovascular physiology at our medical faculty, which does not offer the students a similar learner’s experience. However, we do not claim that the EEC computer-based instruction is better than alternative education methods; we claim that the use of EEC computer-based instruction improved our students’ understanding under the currently used curriculum.

Practical courses in cardiovascular physiology with computer-based EECs seem to be useful because they help undergraduate medical student to understand the concepts of variables, parameters, transient phenomena, and steady-state conditions. For example, venous return and CO are very often referred to as “input” and “output” of the myocardium. However, they both are variables. Under steady-state conditions they are equal, whereas during transient phenomena they may differ. However, the magnitude of both variables is dependent on parameters of the cardiovascular system (blood volume, capacitance, and resistance of blood vessels, contractility of the myocardium, heart rate, etc.). These concepts are important because clinically significant variables (blood pressure, pulse pressure, rate of ventricular pressure increase, tidal volume, concentration of solutes, etc.) are recorded (usually in steady-state conditions) to obtain data about the degree of pathological change in the basic parameter(s) of the system and then make a diagnosis. The EEC approach also allows simulation of the control of some variables (controlled variables) by negative feedback. For example, during a significant hemorrhage, the blood volume (a parameter) is decreased and MAoP (a controlled variable) is adjusted by a negative feedback by increasing contractility and contraction rate of the heart, increasing arteriolar and venous vascular tone, etc. (i.e., controlled parameters).

Some demonstration experiments are technically very difficult to perform in an animal, but they can be readily performed as a simulation. For example, the contribution of the contracting atrium to ventricular output, pressure, and blood volume over time can be clearly presented in a graph with the EEC cardiovascular model (Fig. 4).

It is well known that in humans, if resting, the majority of variables are constant, i.e., in steady state. However, if the studied person in the “resting state” (e.g., lying comfortably on a flat surface for a relatively long time) suddenly changes to an upright position, this causes many variables in his cardiovascular system (e.g., arterial pressure, CO, venous blood volume, etc.) to be temporarily disturbed (transient phenomenon) until a new steady state, characteristic for the upright position, is established. The steady-state level of these variables in the upright position is slightly different (e.g., CO is slightly decreased and venous blood volume in legs is increased from that in a human in the recumbent position).

Visualizing the time course of cardiovascular changes is extremely important in understanding the transition between two steady states. In cardiovascular pathophysiology, the transient phenomenon explains, e.g., the mechanism of acute pulmonary congestion in heart infarction. Before left-sided heart infarction, stroke volumes of both ventricles are in steady state and equal. Immediately after heart infarction, stroke volume of the RV is almost normal, whereas the stroke volume of the LV is severely decreased. This means that, for a short time span, within ~10–20 s after heart contractions, stroke volumes of both ventricles are not equal. The stroke volume of the RV is gradually decreasing, whereas the stroke volume of the LV is gradually recovering. During this relatively brief time span, as the stroke volume of the RV is larger than that of the LV, blood accumulates in the pulmonary circulation, increasing LV filling pressure. After this transient phenomenon is over, stroke volumes of both ventricles are smaller than those before infarction but equal. A new steady state has been established.

The approach to simulating cardiovascular physiology with EECs is similar to approaches described earlier, showing, e.g., the time course of arterial and LV pressure, of ventricular volume if the heart rate is changed (14), or blood pressure, CO, and venous return after sudden LV weakening (43). Recent approaches available online as free software also include negative feedback, e.g., showing the time course of renin concentration after a sudden decrease of NaCl ingestion (1, 30). However, using EECs, quite complex clinically important conditions can be qualitatively, sometimes even quantitatively well simulated (38, 39, 50, 17). Variables can be displayed not only over a relatively large time span but also within one heart cycle. The pressure-flow (voltage-current) relations are very well designed. They show how myocardial contractation is affected by the resistive/capacitive load of an attached circuit (cf. Ref. 23). This was quite explicitly shown in a recent publication (17) in which aortic and mitral flow were studied under normal conditions and in aortic and mitral regurgitation. It was shown that blood regurgitation in a mitral defect is
Fig. 4. Contribution of atrium contraction to ventricular pressure and output. *Top left and top right:* time course of ventricular pressure during one heart cycle. Atrial contraction slightly increases ventricular volume just before its systole. The net result is a more vigorous ventricular contraction; therefore, ventricular diastolic pressure is slightly lower compared with that if the atrium is not contracting. *Bottom left and bottom right:* time course of ventricular volume. Atrial contraction results in a short but pronounced ventricular volume increase; atrial contraction coincides with this presystolic ventricular volume increase. AtP, atrial pressure; EDVV, end-diastolic ventricular volume; ESVV, end-systolic ventricular volume; VP, ventricular pressure; SVV, systolic ventricular volume.
highly dependent on the capacitive component of pulmonary vessel impedance. In contrast, blood regurgitation in an aortic defect is highly dependent on the resistive component of systemic arterial impedance.

Transient states in the cardiovascular system are tradition-
ally modeled with differential equations (11, 28, 51, 56). However, this is not the best way to explain presteady-state conditions to undergraduate medical students lacking a solid background in calculus (which most of the students at our faculty do not have). In practice, the presteady state is often not extensively dealt with at our physiology and pathophysiology courses, and, as a result, there is a general lack of knowledge among our students concerning this phenomenon. The main advantage of an EEC model over a mathematical model of the human cardiovascular system is that the knowledge of solving differential equations is not necessary; only a basic understanding of some of the physical quantities (i.e., voltage, current, resistance, charge, and capacitance) underlying the ECC is required. Thus, the undergraduate medical student can quickly and easily manipulate the model and observe the results of simulations. These qualities make the computer-based EEC of the cardiovascular system suitable for teaching and learning physiology at the undergraduate level.

Conclusions

EECs present a new approach in teaching physiology to undergraduate medical students. They allow multiple possibilities for simulating basic and clinical physiological phenomena and also promote active learning. Basic concepts of steady and presteady state can be explained and understood with relative simplicity due to the many advantages that this approach can offer.

Computer-based EEC simulations of the cardiovascular system facilitate the understanding of time-dependent phenomena by stressing the analogies between EECs and physiological processes (e.g., capacitance, resistance, and time constant) and is a useful supplement to a standard course in cardiovascular physiology.

Teaching cardiovascular physiology with EECs in a practi-
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disclosures

No conflicts of interest, financial or otherwise, are declared by the author(s).

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