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# Challenges in integrating a complex systems computer simulation in class: An educational design research

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Complex systems are typically difficult for students to understand and computer simulations offer a promising way forward. However, integrating such simulations into conventional classes presents numerous challenges. Framed within an educational design research, we studied the use of an in-house built simulation of the coagulation network in four pharmacy undergraduate classes. Drawing upon audio recordings of small group discussions, focus group interviews, and class observations, we identified implementation challenges related to: adaptation of simulation to align with student needs; compromises to learning design; and classroom infrastructure. These findings can serve to guide teachers and staff developers on the common challenges that are likely to arise from integrating computer simulations meaningfully into realistic contexts.

## Introduction

Computational modeling technologies have expanded the boundaries of scientifically tractable problems and understanding complex systems has become increasingly important for students (Sabelli, 2006). Complex systems comprise a large number of interacting components that may not behave in a manner that is intuitively predictable. Computer simulations offer a promising way for students to make meaning of such systems (Aldrich, 2005). In this paper, we examine the core challenges faced when a complex systems simulation was integrated into a classroom.

### The system - the coagulation network

Warfarin is an anticoagulant drug used to treat and prevent blood clots. It works by inhibiting clotting factors within the coagulation network. This drug has a complex dose-response relationship in addition to large between- and within-subject variability (Pirmohamed, 2006). As a result, the relationship between the dose of warfarin and the response observed in a patient is not intuitively predictable. This poses a challenge for student learning. The most common test to determine a patient's anticoagulant needs is measuring the time it takes for a patient's blood to clot after a stimulus (expressed as the *international normalised ratio* or INR). In a clinical setting, if the INR is lower than the recommended value, there is a risk of a blood clot; if the INR is too high, there is a risk of bleeding.

We built a computer simulation based on a model of the coagulation network (Wajima, Isbister & Duffull, 2009). The simulation was built in *MATLAB* (R2008a) (MathWorks, undated), a programing environment featuring algorithm development, data analysis,

and visualisation. Using the simulation, pharmacy students were able to manipulate variables including warfarin dose, patient compliance, and genotype (patient's genetic sensitivity to warfarin). They could then run simulations for various scenarios and generate predictions of INR response over time (see Figures 1 and 2).

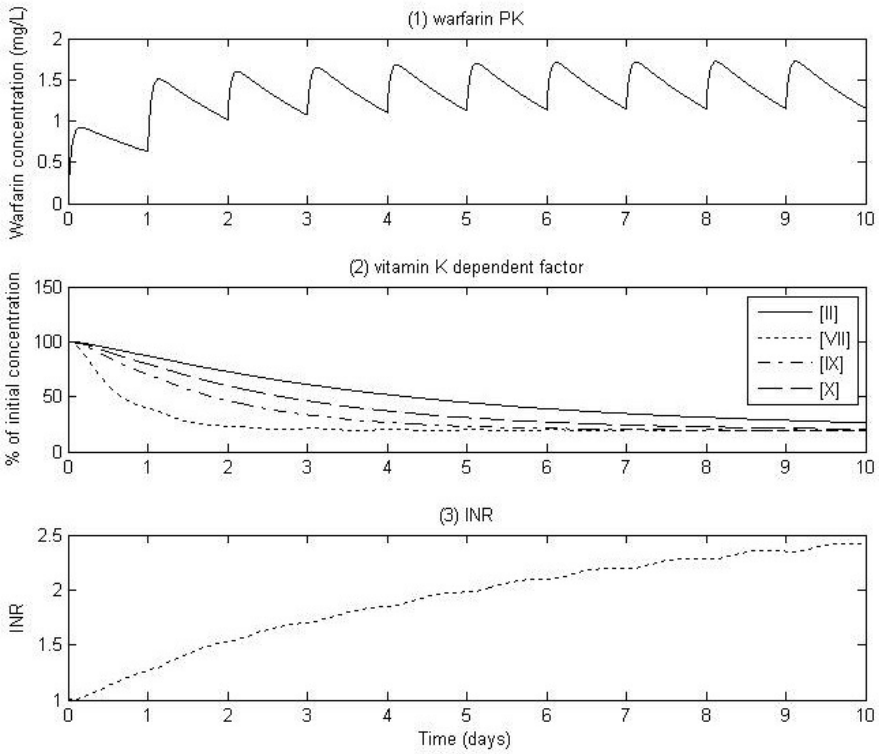


Figure 1: Simulation outputs depicting a compliant patient

Figure 1 depicts a compliant patient and Figure 2 a non-compliant patient who missed a dose on Day 5. All plots are over time with days on the x-axis. The upper panels represent the plasma concentration-time profile of warfarin, the middle panels the four main clotting factors that warfarin affects, and the lower panels the INR response.

We attempted to integrate this simulation into conventional classes to exemplify the ideals of the research-teaching nexus (Griffiths, 2004), helping students to understand the latest research findings in pharmacology and to engage in inquiry-based activities.

### Classroom integration of complex systems simulations

While many articles have lauded the potential benefits of learning with complex systems simulations (e.g., Goldstone & Wilensky, 2008; Jacobson & Wilensky, 2006; Laurillard, 1992; Riley, 2002), relatively few have examined their use by students within conventional classrooms. Among such studies, many adopted experimental research designs within controlled settings (e.g., Chang, Chen, Lin & Sung, 2008; Park, Lee & Kim, 2009). Hung's (2008) research, situated in a naturalistic setting, involved only eight postgraduate students.

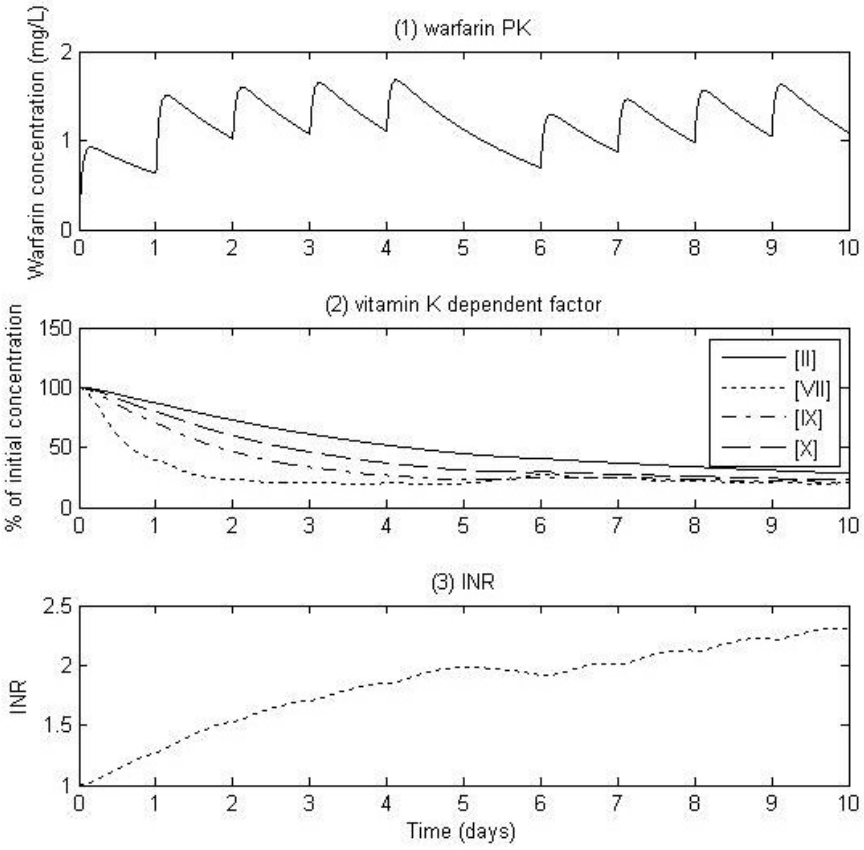


Figure 2: Simulation outputs depicting a non-compliant patient

Similarly in medical/pharmacy education, studies were often contextualised within controlled settings (e.g., Hariri, Rawn, Srivastava, Youngblood & Ladd, 2004). In a naturalistic setting, Wu-Pong and Cheng (1999) evaluated a teacher's (not students') use of a complex systems simulation (projected on screen during lectures).

## Methodology

### Research design

This study is framed within an "*educational design research*" (Reeves, McKenney & Herrington, 2011, p. 59) investigating how pharmacy students learned warfarin-dosing while interacting with a complex systems simulation in class. This type of educational research highlights practitioners and researchers jointly designing and redesigning a prototype solution to solve a teaching and learning problem. Educational design research was selected because we believe in the need to situate cognition in naturalistic contexts as well as to transform actual teaching practices (Barab & Squire, 2004).

### Participants and context

The 120 participants in this study were fourth (final) year students pursuing the Bachelor of Pharmacy. These students had just started to learn about coagulation within a clinical context (e.g., pathology of clot formation and dissolution). Faculty level ethical approval was obtained. In the past, the coagulation network was taught as a uni-directional cascade of events. Students then applied their knowledge of the cascade in a static case in a workshop. The new workshop featured an in-house built computer simulation based on a recently developed and more accurate model of the coagulation network (Wajima *et al.*, 2009).

All authors jointly designed the new workshop, with three authors taking on more specific roles: author 2 was the tutor facilitating the workshop and authors 1 and 4 were staff developers/researchers observing the workshop.

### Workshop activities

The clinical case used in the new workshop involved a virtual patient who was 58 years old, suffering from a blood clot in the leg, and being treated with daily doses of warfarin. The learning objective of this exercise was for the students to compare and distinguish the effects of (1) genetic variation and (2) non-compliance on the time course of warfarin effect (an example drug with a complex dose-response relationship). To develop their understanding, the students were tasked to articulate and verify (via the simulation) their predictions of the effects of genetic variation and treatment non-compliance on the time course.

The 120 students came from four classes and each class attended one of the four sessions of the new workshop. Each class of 30 students was further divided into groups of five or six students during each session (see Figure 3). Each group worked with a laptop running *MATLAB* and remotely connected to the School of Pharmacy's server. The four sessions were held over two days in three different classrooms within the same teaching complex.

Figure 3: Division of groups in each class

The students undertook the workshop in three parts. In part 1, the tutor introduced the case to the students (see Appendix) and invited them to execute the first run (default parameters) to find out: (a) the time the patient took to reach the desired INR; and (b) the patient's INR on Day 10. In part 2, the students selected one of five genetic markers (which indicate how sensitive a patient will be to warfarin), predicted the outcomes for (a) and (b), and ran the simulation again. The tutor made sure all five options were covered and noted the students' predictions in a *Word* document displayed to everyone. In part 3, the students picked one of five incidences of non-compliance (e.g., missing two doses, halving a loading dose), predicted the outcomes for (a) and (b), and ran the simulation.

### Data sources and analysis

In all four workshop sessions (WS1-WS4), two researchers sat with two groups to record their conversations as they participated in the learning activity (four recordings of four groups). Small group discussions are an important site for collaborative meaning-making (Cazden & Beck, 2003), notably students' assumptions behind their predictions. Field notes were also written from class observations. Lastly, audio recordings were made of two post-workshop focus group interviews (FG1-FG2), which involved four students from each workshop session (two from each group we sat with, resulting in 16 students in total).

The audio data (approximately 3 hours of classroom discourse and 45 minutes of interview data) were fully transcribed. To identify the three core challenges below, we highlighted those that impacted all four sessions in the most significant ways and that other educators would most likely encounter.

To identify students' ways of thinking about the complex phenomenon of warfarin-dosing (to support assertion #2 below), authors 1 and 4 read the transcripts independently and coded student utterances illustrating particular ways of thinking based on Jacobson's (2001) clockwork-complexity categories. These categories emerged from Jacobson's (2001) study in which complex systems experts and novices were asked how they would design a large city efficiently. Complex systems experts tended to think in terms of the following complexity categories: non-linear relationships (e.g., accepting that a small perturbation in a remote area can cause a large effect in the central business district); de-centralised interactions (e.g., construing drivers, driving patterns, and models of freeways as interacting without a centralised controlling agent); multiple causes (e.g., assuming that any perturbation is likely to be caused by multiple factors); and stochasticity (e.g., construing alternative city configurations as not being completely predictable). Complex systems novices tended to think in terms of clockwork categories (e.g., linear relationships, centralised control) which were incongruent in order to understand complex systems.

Authors 1 and 4 then met to compare and negotiate our coding. Like all forms of human intelligence, these ways of thinking are dispositional (Perkins, Tishman, Ritchhart, Donis & Andrade, 2000): the workshop sessions and focus group interviews were mere opportunities that students could seize (or dismiss) to exhibit particular ways of thinking. In other words, the appropriate instantiations of these ways of thinking were more important than their frequency (more instantiations does not imply better thinking).

The "trustworthiness" (Guba & Lincoln, 1989, p. 233) of our findings was maximised in the following ways: validity was enhanced by triangulating multiple sources of evidence (i.e., each assertion reported below is supported by evidence from both workshop sessions and focus group interviews); reliability was increased by carrying out four identical workshop sessions with four different groups; and objectivity was reinforced by maintaining both insider (tutor) and outsider (researcher) viewpoints throughout the study. Any emerging assertion was tested in the entire data corpus and negative examples were actively sought. The researchers also conducted a peer debrief between the workshop sessions to share developing understandings of the study and to re-focus follow-up observations and interviews.

## Findings and discussion

We now present the core challenges that surfaced during the classroom integration of our computer simulation: adaptation of simulation to align with student needs; compromises to learning design; and classroom infrastructure.

### Adaptation of simulation to align with student needs

The coagulation network that we had developed for the purposes of pharmacology research was too comprehensive for our students' learning needs. Hence, we designed an interface that allowed the user to interact with the model with only a reduced number of options. The goal was to emphasise: (1) warfarin-dosing; and (2) the relationship between the time course of warfarin concentration and the warfarin effect (on clotting function). The model's fidelity was not reduced in any way.

The majority of students in FG1 and FG2 did identify the relationship between dose, time of dose, measurement of clotting function, and warfarin effect as a key learning point of the workshop. However, some students expressed that the learning activity was a little beyond their understanding: "We've got no clue [what the exact duration to reach the desired INR is], we're just guessing" [WS4]; "We were only taught about the pharmacokinetics (i.e., relationship of dose to concentration) of warfarin? So… we just kind of guessed by comparing that to other drugs [e.g., antibiotics] that we know about" [FG1]. The difficulty in matching learning outcomes and simulation is well-documented (e.g., Davies, 2002; Moizer, Lean, Towler & Abbey, 2009) and is accentuated when teachers attempt to simplify the latest research findings for their students. Additional scaffolds to facilitate understanding will have to be considered for subsequent cycles of our educational design research.

### Compromises to learning design

The fixed duration of conventional classes presented the challenge of accommodating the relatively slow speed of our simulation. Given the workshop for this case was 50 minutes, the students could realistically execute only three runs (each run taking five minutes on average and time was also needed for class discussions and coordination). Many students in FG1 and FG2 felt that the learning activity could be improved with shorter runs. The relatively lengthy runs impacted the design of our learning activity in a significant way.

At the point of conception of this project, we had planned to adopt Jonassen's (1999) design principles for constructivist learning environment, positioning our computer

simulation as an example of "problem manipulation spaces" (p. 223) where students — in order to solve an authentic problem — formed and tested *their own* hypotheses and received feedback from the simulation via changes in the graphs. However, the experimentation with 'what-if' scenarios would have required an unpredictable number of runs which the time constraint did not allow. The issue of fitting more open-ended learning activities within well-defined durations is also reported in Tüzün (2007). Among the eight groups we sat with, only one managed to test out a fourth scenario on their own (to find out the threshold of missed doses before their patient's INR fell below therapeutic level) because they had started their third run earlier than the rest [WS4]. Upon reflection, many students expressed the desire to try out their own scenarios at their own time: "[Testing] what makes INR change faster" [FG1]; "Test it… until you really understood it" [FG2].

To accommodate software limitations, we redesigned the learning activity, persisting to keep "meaning open or 'performable'" (Bruner, 1986, p. 26). We asked students to predict the outcomes of one of five pre-determined scenarios and then to articulate the assumptions behind their predictions. This design decision was informed by Jacobson and Wilensky's (2006) contention that students' interactions with simulations can potentially encourage them to articulate and modify their assumptions, and by Jonassen's (1997) that students' articulation of their solutions was a good indicator of what they know.

The majority of students did appreciate that predicting made them "actively think" [FG2] and tested their understanding [FG2], without which the simulation outputs would have been "pointless" [FG1]. They also stated that they would recommend this learning activity to their peers [FG1, FG2]. In addition, two groups [WS2, WS3] articulated and modified their mistaken assumptions while interacting with the simulation (more details in the following paragraph). However, many students noticed that choosing among the five pre-determined options reduced the relevance of the activity: "Really doesn't matter which way we go" [WS3]; "We just had to choose 1 to 5. Anything [will do]" [WS1]. The mixed reactions suggest that designing a constructivist learning environment need not be an all-or-nothing undertaking: compromises to the learning design can still result in some meaningful outcomes. Working within less-than-ideal situations, we recommend the preservation of key characteristics of constructivism (student meaning-making, in our case) to maximise the potentials of our learning activity. However, we speculate that the reduction of student agency in trying out their own scenarios limited the scope in their thinking (see Table 1).

The most apparent shift in thinking happened in WS2 and WS3 where two groups we followed modified their mistaken assumptions regarding the dose-INR relationship from linear to non-linear. Their reassigning of the dose-INR relationship from a clockwork to complexity category constitutes a "conceptual change" (Chi, Slotta & de Leeuw, 1994, p. 27) through which they have begun to understand the concept "dose-INR relationship" in an *ontologically* different way. Such ontological shifts are necessary in order to understand complex systems (Jacobson, Kapur, So & Lee, 2011). Some students expressed their developing and imperfect understanding in tentative terms such as "no concentration-INR ratio" [WS2, FG1]: while they were right in that INR responses are not directly proportional to the concentration of warfarin, they had used an expression that has no meaning among pharmacists. This is characteristic of emergent words/expressions arising from local learning activities that may be

"stabilised" or "discarded" (Roth, 2005, p 123) through further interactions. Many students in FG1 and FG2 also identified this change of perspective (linear-nonlinear) as a key learning point from the workshops. Shifts in other ways of thinking about complex systems were less apparent. We speculate that if the students had been asked to test their own hypotheses, a wider range in their thinking would have surfaced.

No evidence was found of students conceptualising coagulation as stochastic. We speculate that the fidelity of the simulation had a corresponding impact on the students' thinking about complex systems. Using Sheard and Mostashari's (2009) definition of "complex systems" (p. 296), we accept that the coagulation network we had developed is not entirely complex: our model has all the elements of complex systems except stochasticity. We question the mutual exclusivity of "determinism" and "stochasticity" and affirm that, while mechanism-based models of complex biological systems are usually deterministic, the effect is often unpredictable and can appear stochastic.

Table 1: Ways of thinking about complex systems exhibited

| Ways of thinking | Clockwork | Complexity |
|---|---|---|
| Non-linear relationships | **WS2 (part 3): predicting output of non-compliance**<br>S7: Is it because you *halved it* [loading dose] so you just have to *halve whatever you have*?<br>S8: Slower [time to reach desired INR], yah.<br>S6: Yeah, it will be very slow.<br><br>**WS3 (part 2): predicting output of genetic variation**<br>(Extended dialogue from one group where they interpreted the shift of genotype from 1*1* to 2*2* as *doubling metabolism* and predicted that the duration to reach therapeutic level would approximately double from Day 5 to Day 9. After viewing the simulation's output, one student joked that they had mistaken the relationship as "*mathematical*"). | **FG1 (post-workshop)**<br>S6: When you take antibiotics, your loading dose is important, cos it just gets your plasma concentration high quickly? So halving that, logically, you'd think… your INR would take longer to increase… but it really didn't make a difference. So it shows you that there is *no concentration-INR ratio*.<br><br>**WS3 (part 3): viewing output of non-compliance**<br>S13: It's like there's a huge dip in concentration doesn't mean it'll affect its [INR].<br><br>**WS4 (part 3): viewing output of non-compliance**<br>S16: Why is there a delay in the decrease in concentration and INR? I mean how you see the concentration went down but INR didn't go down *as much*? |
| De-centralised interactions | (No utterances on centralised control: e.g., "INR is controlled by the patient's genes.") | **FG1 (post-workshop)**<br>R1: If the patient's INR keeps increasing with 7mg maintenance dose, what would you do?<br>S4: Decrease the *dose*. (…)<br>S5: Maybe the patient is changing his *diet*? (xxx)<br>S2: Check with the patient that they're taking the *right amount of pills* and stuff. (…)<br>S6: Maybe herbal stuff like *vitamins*. |

| | | |
|---|---|---|
| Multiple causes | (No utterances on single causality: e.g., "If the patient's INR keeps increasing, it's because he is overdosed.") | **WS2 (part 3): viewing output of non-compliance**<br>R1: Did you notice this drop in concentration, it's a bit different from what you had.<br>S6: Yeah. (…)<br>S8: But – why though?<br>S6: Because I guess there's *more accumulation*? Still going up?<br>S7: You *metabolise slowly*. (…)<br>S9: It really *depends on the clearance of warfarin as well*.<br><br>**FG2 (post-workshop)**<br>S20: If you double or miss a dose, then you kind of expect more effect because you know it's closely monitored? So there must a reason why it is. But *it's more because of the food and everything* which affects the enzymes [rather than the dose]. |
| Stochastic agents | **WS4 (part 3): viewing output of non-compliance**<br>S16: If you removed 1 more dose, it'd be lower than 2 *definitely*. | (No utterances on stochasticity: e.g., "INR is not completely predictable. Sometimes it varies within the same patient and we don't really know why.") |

### Classroom infrastructure

To carry out our workshop, we needed five computers with *MATLAB* installed and reliably connected to School of Pharmacy's server. The five laptops were readily acquired from the standard pool reserved for Pharmacy teaching. Care was taken to ensure the compatibility between: (1) the database in the School of Pharmacy server; (2) the version of *MATLAB* installed in all five laptops; and (3) the graphical user interface we had developed.

Even though we had scaled down our simulation, it remained resource-intensive. The teaching complex we used featured a wireless network, but having tested it, we preferred instead to use the classrooms' wired network for better reliability and performance. Although each classroom had 16 LAN points, only the one behind the teacher's desktop was activated. To activate the other LAN points, we would normally have had to wait up to two weeks and pay a fee. Because of the research support allocated to this project, we were able to go directly to our IT department to get the ports activated for our workshop quickly and at no additional cost. However, it is noteworthy that this option would usually not be available for standard teaching sessions and that classroom infrastructure has been identified elsewhere as a barrier to teaching with simulations (Moizer et al., 2009; Tüzün, 2007).

## Conclusions

We integrated a complex systems computer simulation into a workshop and encountered challenges in the following areas: adaptation of the simulation to align with student needs; compromises to learning design; and classroom infrastructure. These findings can serve to guide teachers and staff developers on the common challenges that are likely to arise from integrating computer simulations meaningfully into realistic contexts.

Despite the challenges in the three domains reported above, we noted several positive outcomes: many students came to understand that the dose-INR relationship was non-linear [WS2, WS3, FG1, FG2]; two groups articulated and modified their mistaken assumptions while interacting with the simulation [WS2, WS3]; the simulation enabled students to "visualise" warfarin's activity in humans which in turn helped them understand the reasons behind dosing regimens [FG1]; and the majority of students agreed that they would recommend this learning activity to their peers [FG1, FG2].

Given our experience, we plan to make the simulation available to students (outside of the workshop sessions) to test their own hypotheses in their own time in subsequent cycles of our educational design research. The workshop will be redesigned to exploit the students' experimentations. We also envisage the inclusion of another tutor (author 3) to facilitate the workshop with a view to sustaining the new workshop in the course.

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## Appendix: Handout for workshops

### Case 4 - Warfarin treatment simulation

Violet, 58 years, was discharged from hospital following an elective total hip replacement. She has a past history of venous thromboembolism and was positive for Factor V Leiden. Four days after being discharged, she felt pain in her left leg and noticed the leg was red and swollen. She contacted the hospital and was assessed in the emergency department.

On examination, Violet had no signs of dyspnoea, cyanosis, or fever. Her blood pressure was 120/80 mm Hg. Physical examination was normal except for swelling of the left lower leg below the knee and Homans' sign (pain on passive dorsiflexion of the foot). The operation wound was healed with no signs of inflammation or bleeding.

Violet was commenced on enoxaparin 70 mg SC BD (she weighed 70 kg) and warfarin (given once daily). She was later discharged to the care of her GP after learning how to self-administer the enoxaparin injection. Target INR is 2-3.

Use the warfarin simulation software to explore the relationship between warfarin dosage and genetic covariates on its pharmacokinetic and pharmacodynamic profiles.

Run #1 – default setting:
- 70 kg
- 10 mg (loading dose) on Days 1 and 2
- 7 mg (maintenance dose) for the remaining 8 days
- *1/*1 CYP2C9
- G/G VKORC1

Run #2 – genetic variation:
- CYP2C9 *1/*2
- CYP2C9 *2/*2
- CYP2C9 *3/*3
- VKORC1 A/G
- VKORC1 A/A

Run #3 – compliance:
- Double dose on any day
- Halve a loading dose
- Omit any dose
- Double dose on any two consecutive days
- Omit two consecutive doses

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