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Analysis of Physiological Systems
Assignment on Properties of the Hodgkin-Huxley Equations

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Submitted in partial fulfillment of the requirements for the module
BM2102 - Modelling and Analysis of Physiological Systems

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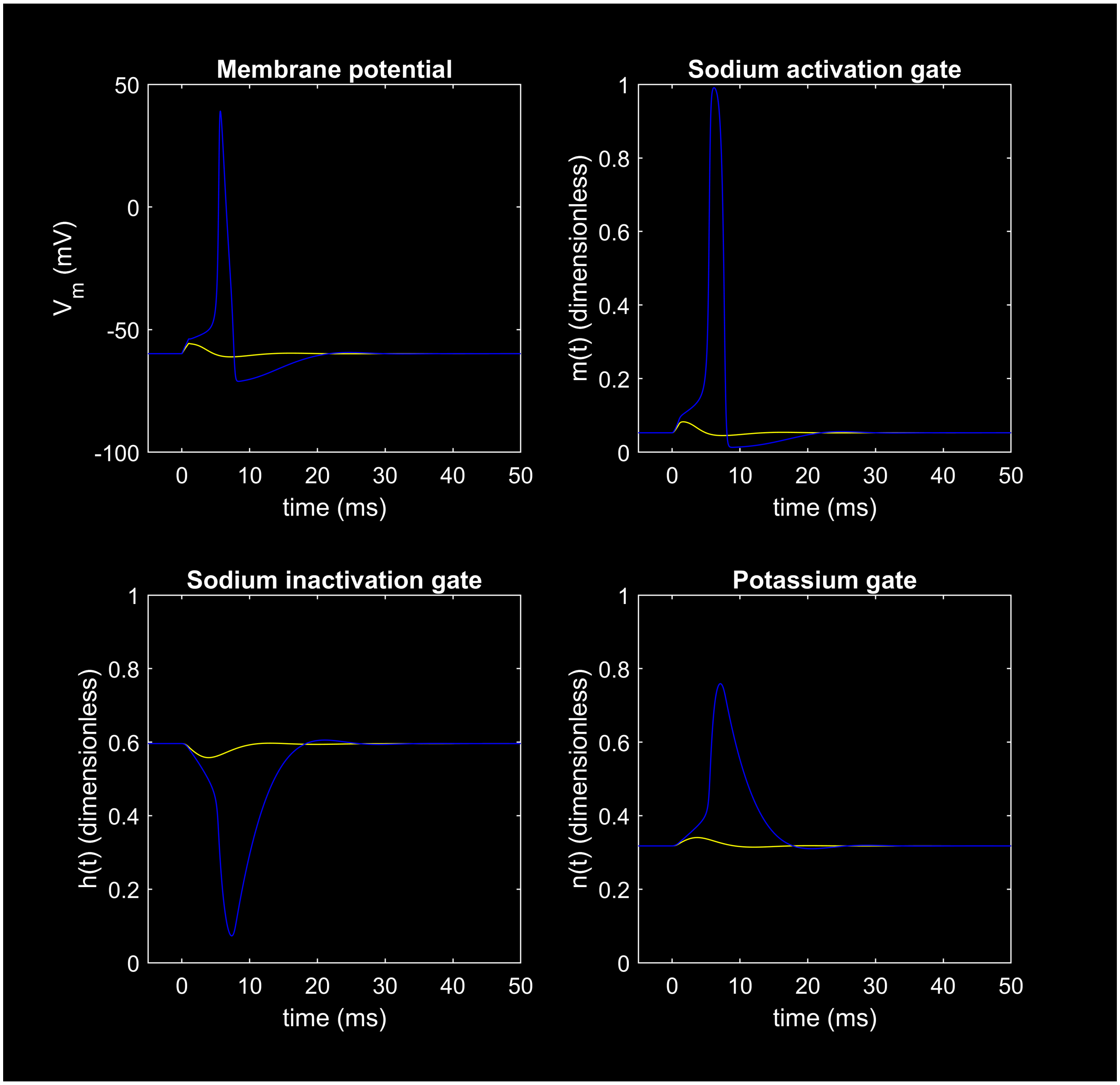
Threshold

```
hhconst
ampl = 6;
width1 = 1;
hhmplot(0,50,0);
amp1 = 7;
hhmplot(0,50,1);
```

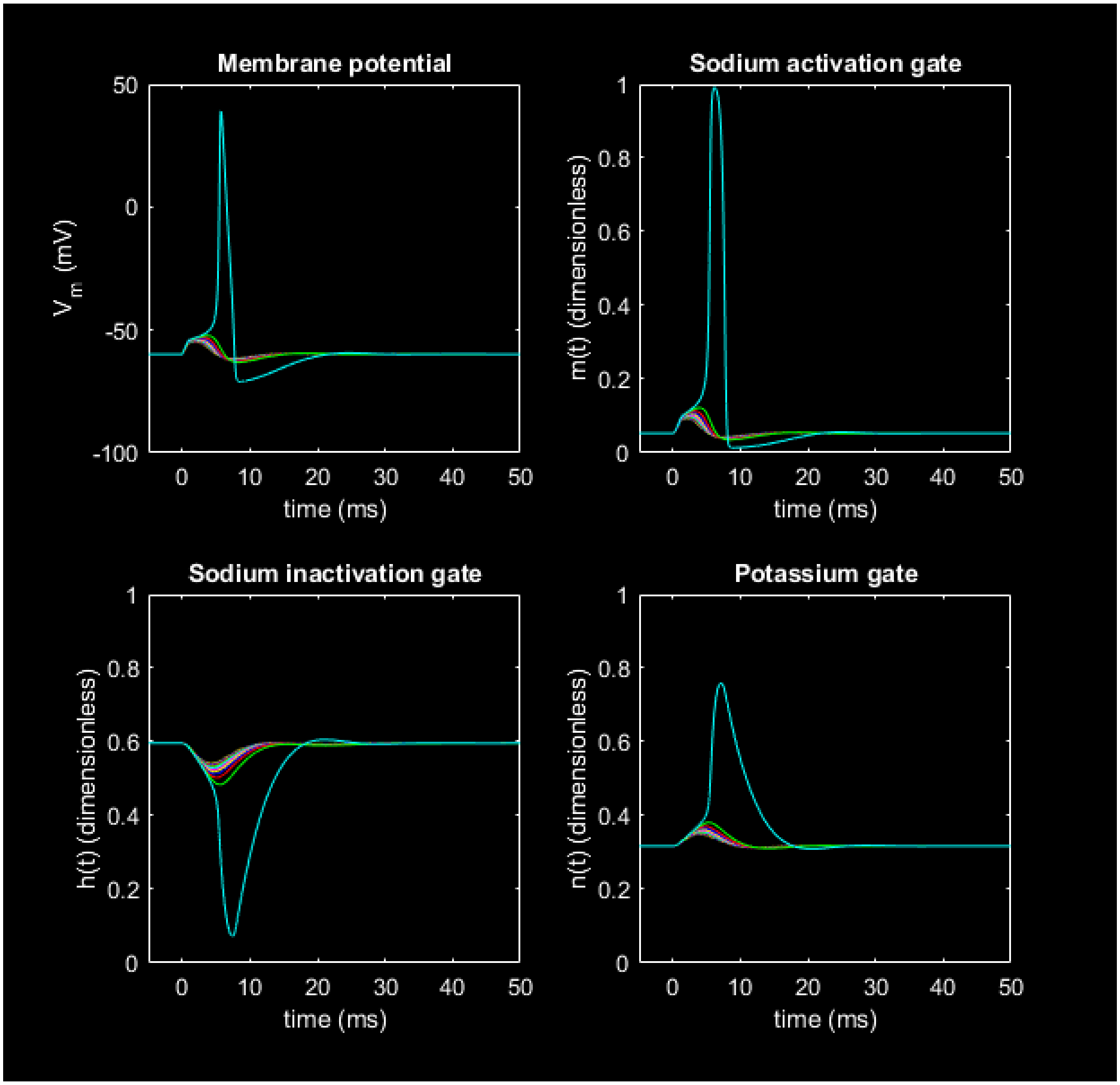


As there are no action potentials (AP) when the amplitude is $6\,\mu\mathrm{A\,cm^{-2}}$ but there are action potentials when the amplitude is $7\,\mu\mathrm{A\,cm^{-2}}$, the threshold should be between $6\,\mu\mathrm{A\,cm^{-2}}$ and $7\,\mu\mathrm{A\,cm^{-2}}$.

Question 01

```
pause on
hhconst;
amp1 = 6;
```

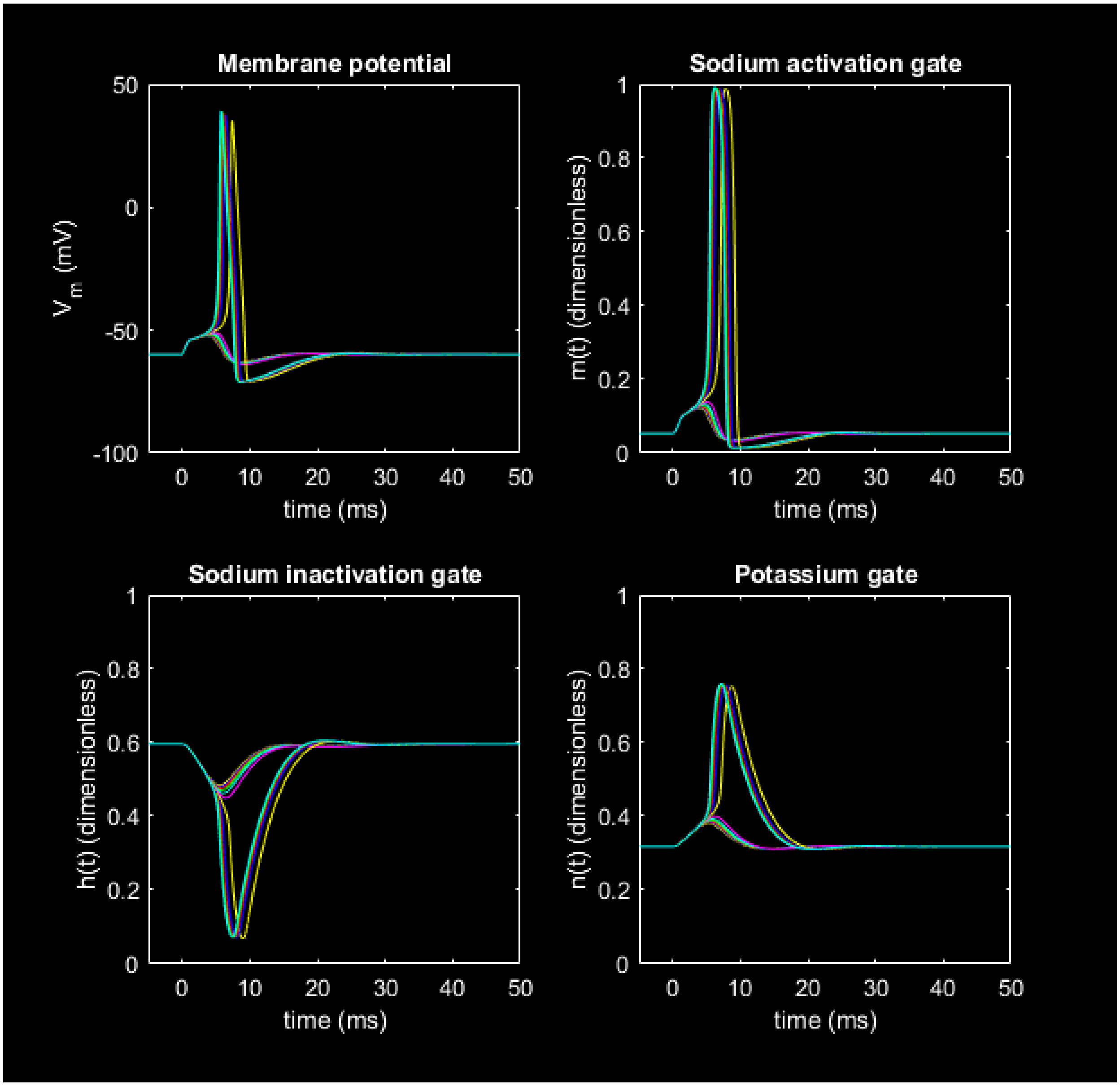
```
width1 = 1;
hhmplot(0,50,0);
for i = 1:10
 amp1 = amp1+0.1;
 hhmplot(0,50,i);
 pause(1);
end
```



As there are no action potentials (AP) when the amplitude is 6.9 $\mu\mathrm{A\,cm^{-2}}$ but there are action potentials when the amplitude is 7 $\mu\mathrm{A\,cm^{-2}}$, the threshold should be between 6.9 $\mu\mathrm{A\,cm^{-2}}$ and 7 $\mu\mathrm{A\,cm^{-2}}$.

```
pause on
hhconst;
amp1 = 6.90;
width1 = 1;
hhmplot(0,50,0);
for i = 1:10
```

```
  amp1 = amp1+0.01;
  hhmplot(0,50,i);
  pause(1);
end
```

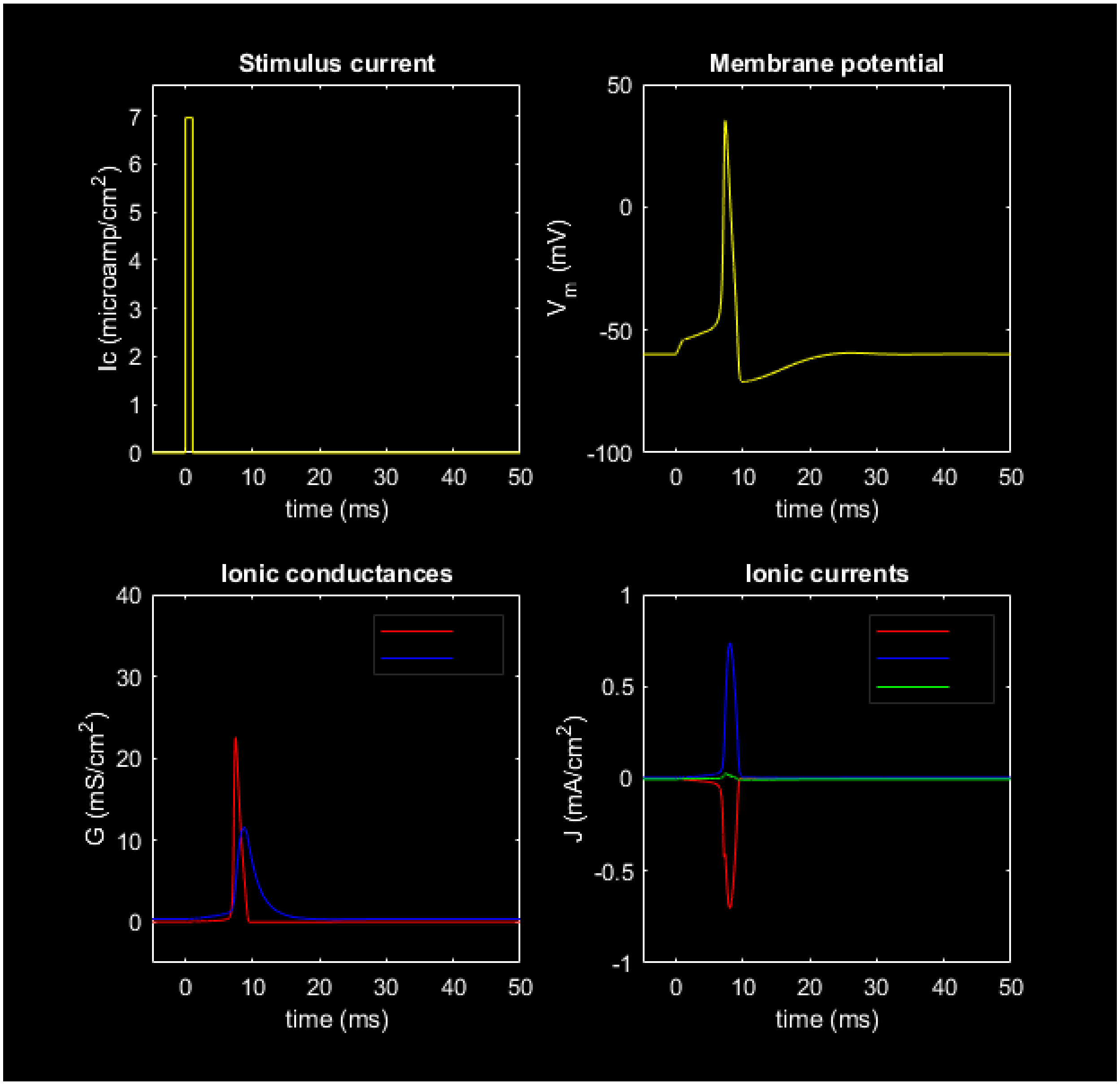


As V_m shows an AP in 6.96 $\mu\mathrm{A\,cm^{-2}}$ we can select it as the threshold stimulating current amplitude.

Question 02

For Amplitude= 6.98 $\mu\mathrm{A/cm^2}$

```
amp1 = 6.96;
[qna,qk,ql]=hhsplot(0,50);
```



$$\int_{t_0}^{t_f} \sum_k J_k dt = qna + qk + ql$$

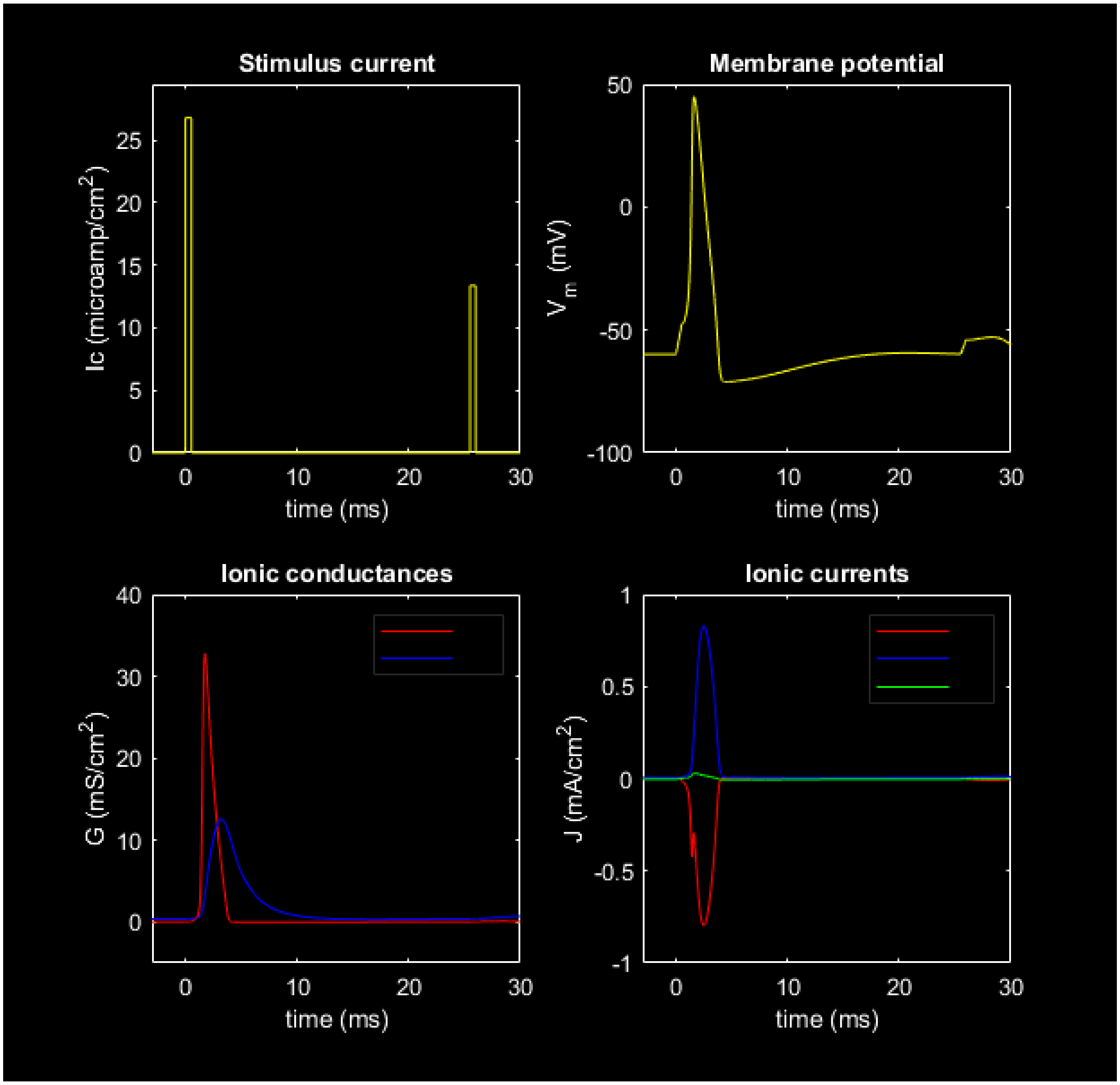
```
qna+qk+ql
```

```
ans = 6.9620
```

The expected result is $\int_{t_0}^{t_f} \sum_k J_k dt = \int_{t_0}^{t_f} J_e dt$

Refractoriness

```
amp1 = 26.8;
width1 = 0.5;
delay2 = 25;
amp2 = 13.4;
width2 = 0.5;
hhsplot(0,30);
```

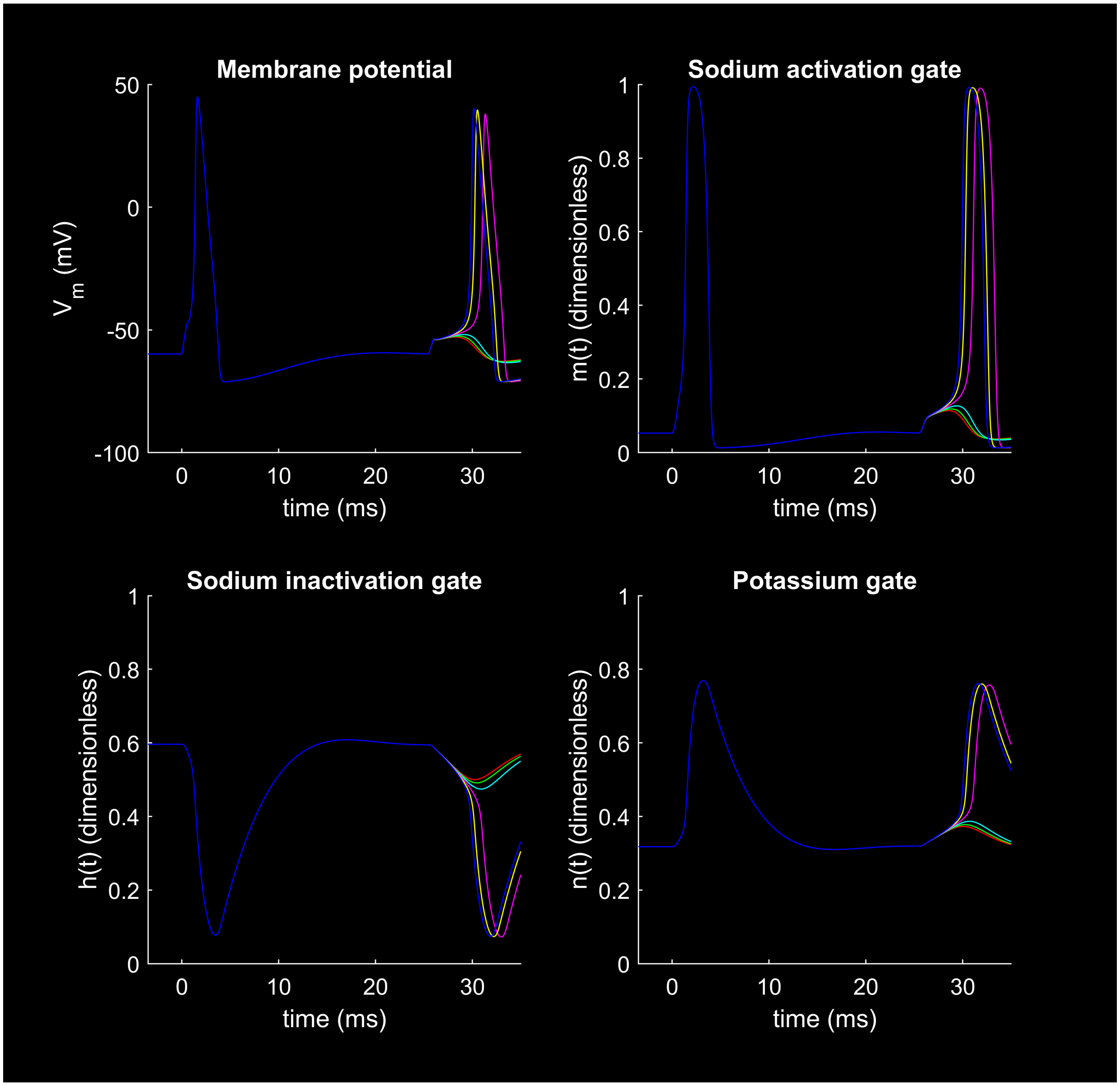


Question 03

For delay 25

```
close;
amp2=13.4;
amp1 = 26.8;
width1 = 0.5;
delay2 = 25;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

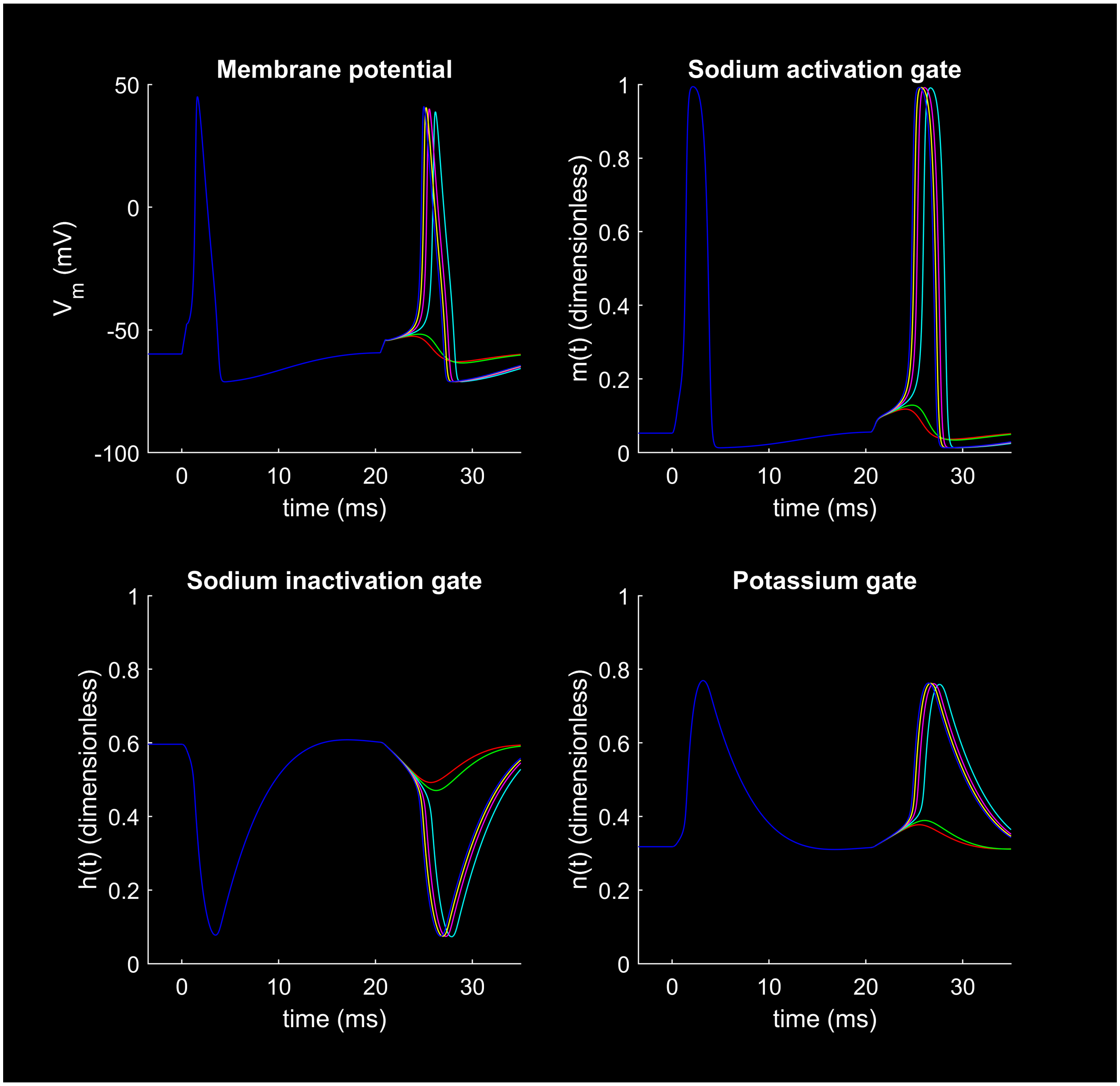


As the plot for the delay 25ms, 13.7 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 20

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 20;
amp2 = 11.4;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

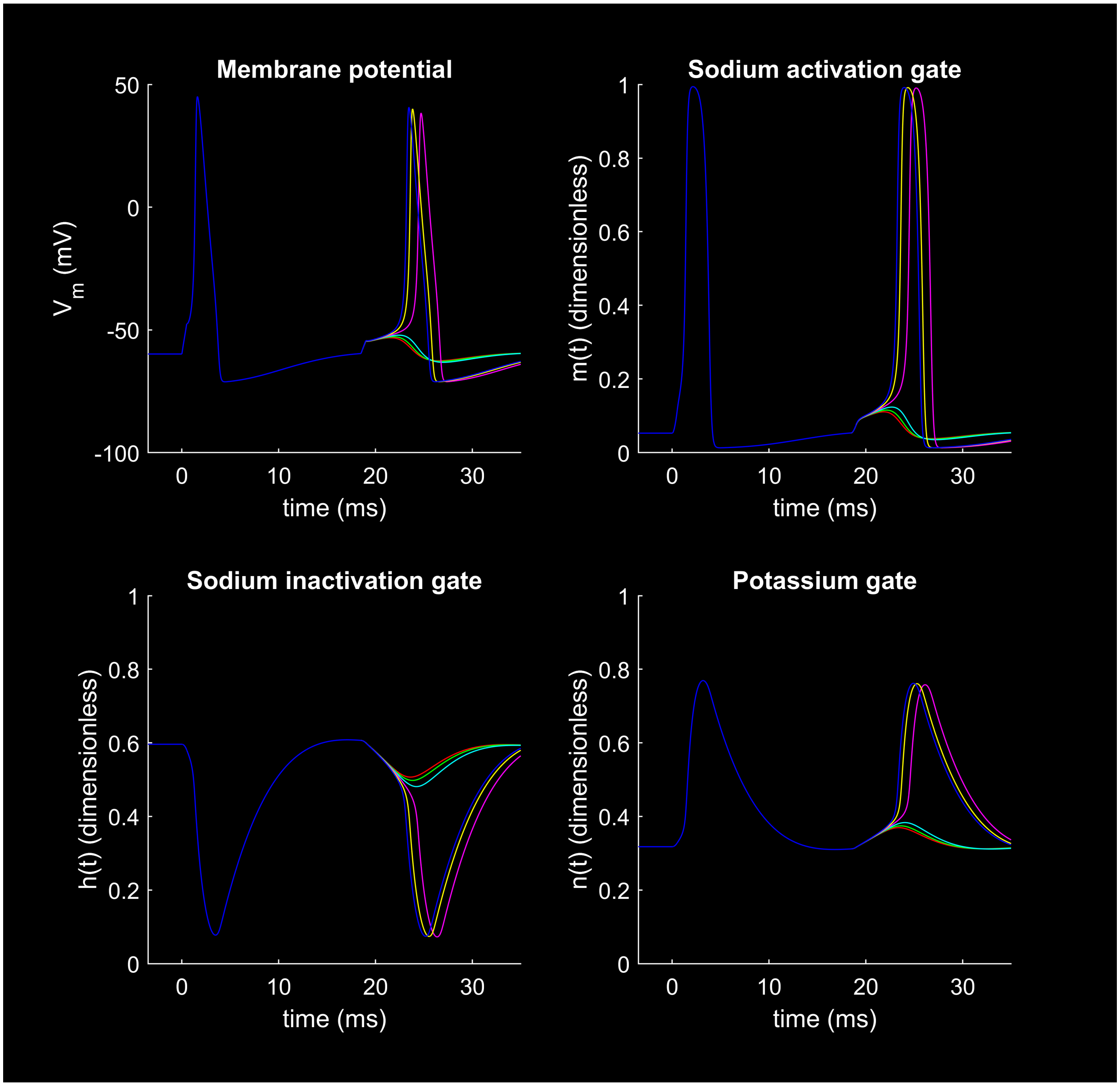


As the plot for the delay 20ms, 11.6 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 18

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 18;
amp2 = 11;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

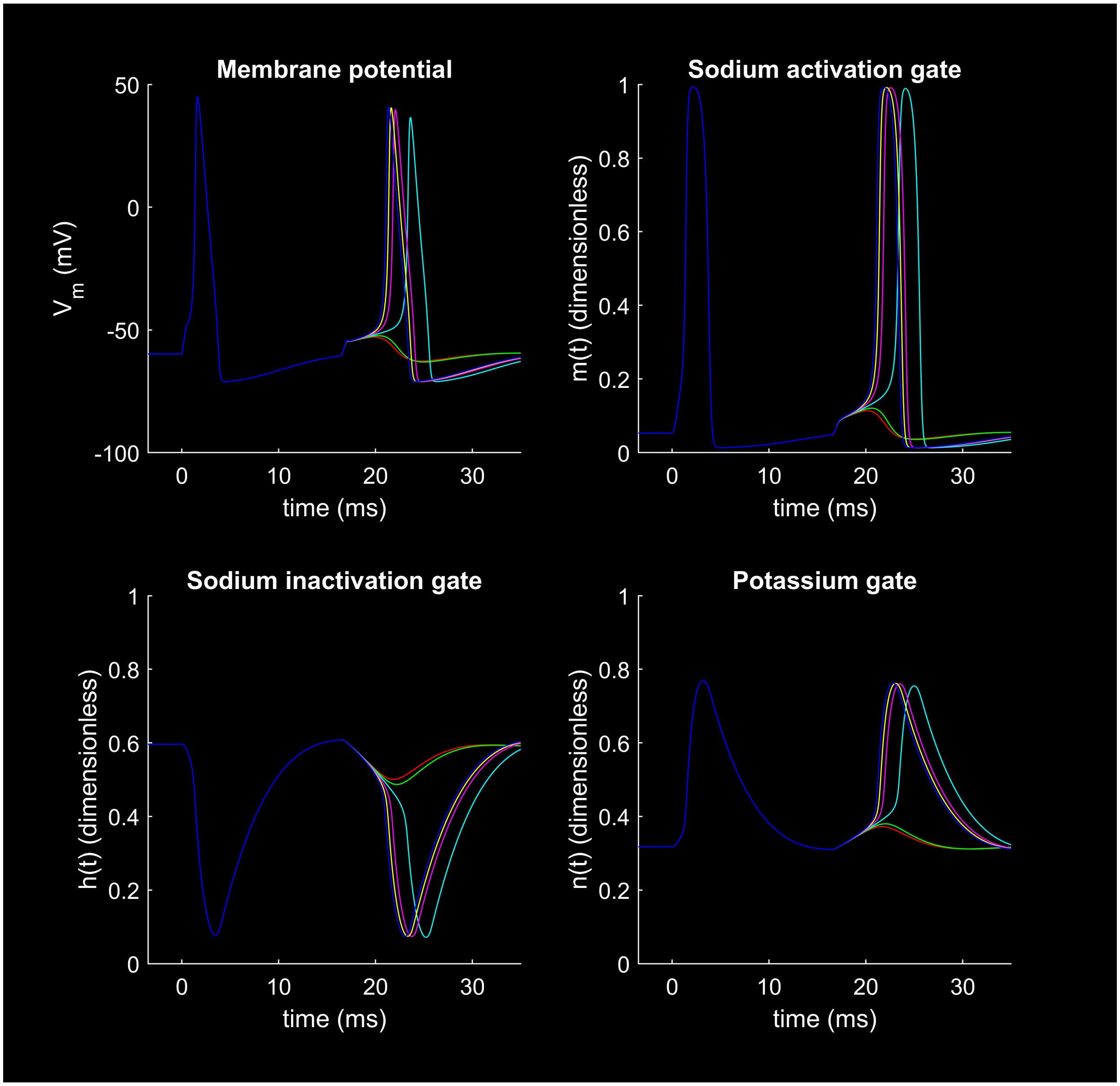


As the plot for the delay 18ms, 11.3 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 16

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 16;
amp2 = 12.5;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

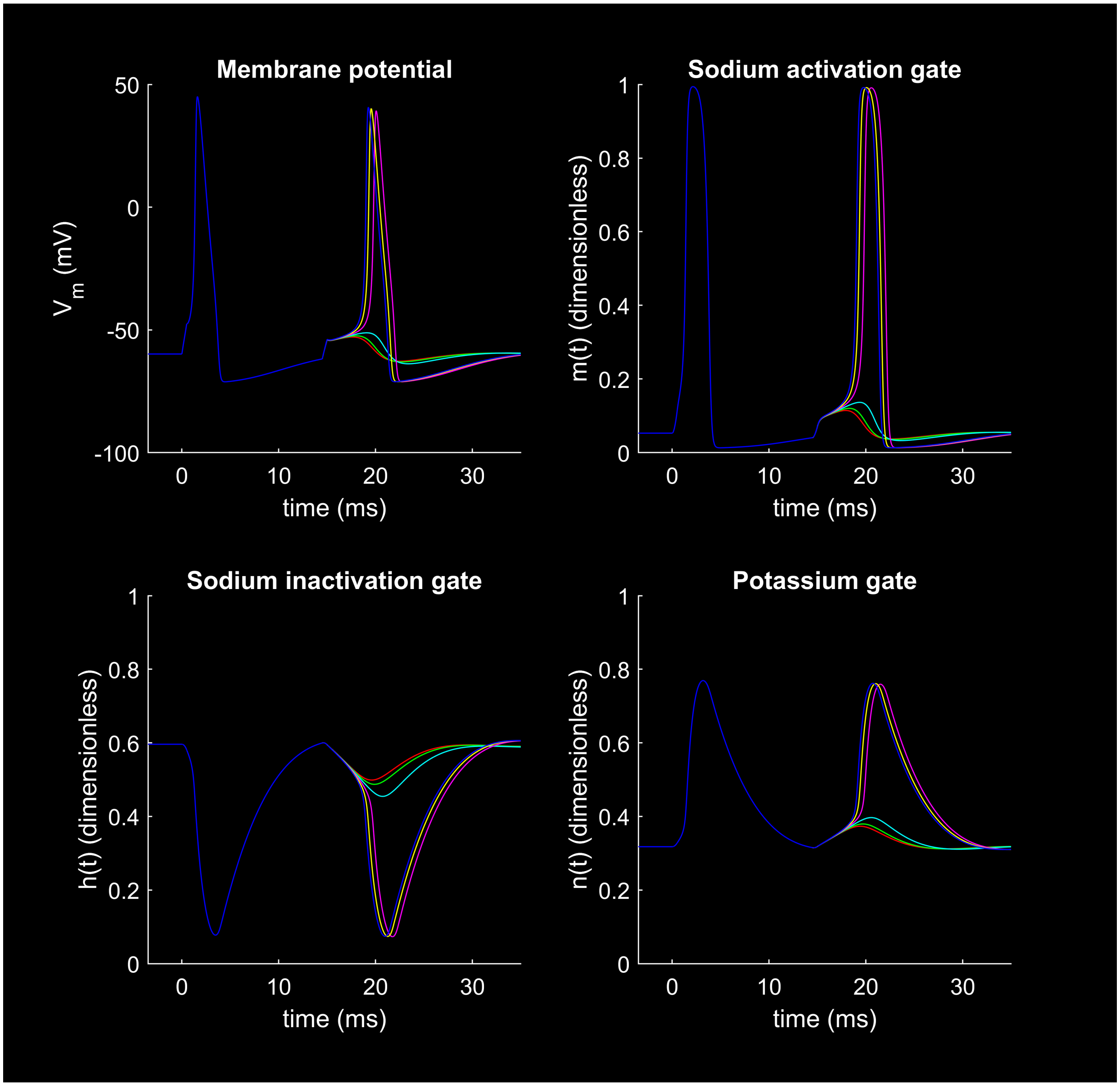


As the plot for the delay 16ms, 12.7 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 14

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 14;
amp2 = 16.7;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

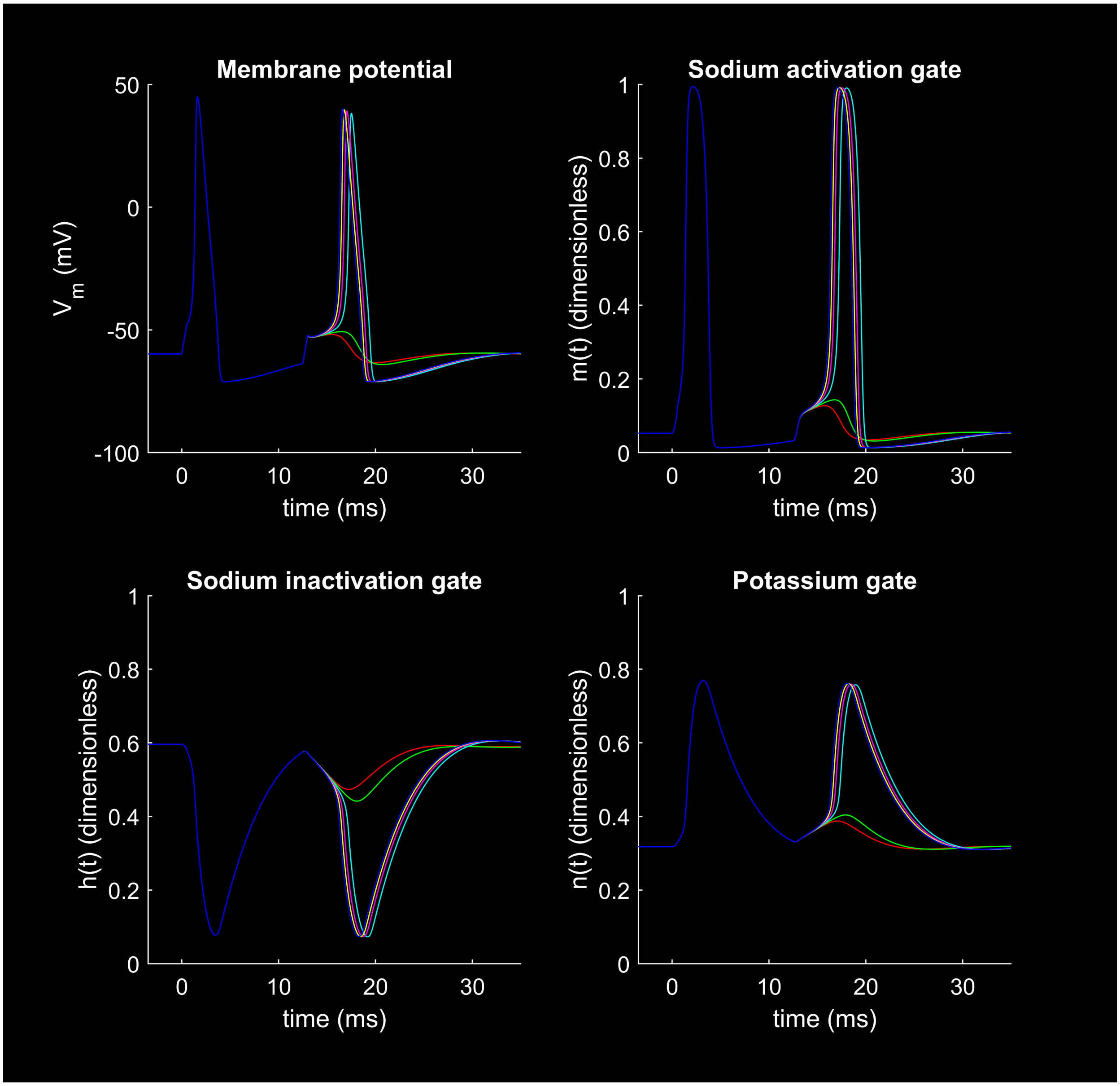


As the plot for the delay 14ms, 17.0 $\mu\mathrm{A}\,\mathrm{cm}^{-2}$ of second impulse is needed to elicit an AP.

For delay 12

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 12;
amp2 = 25.3;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

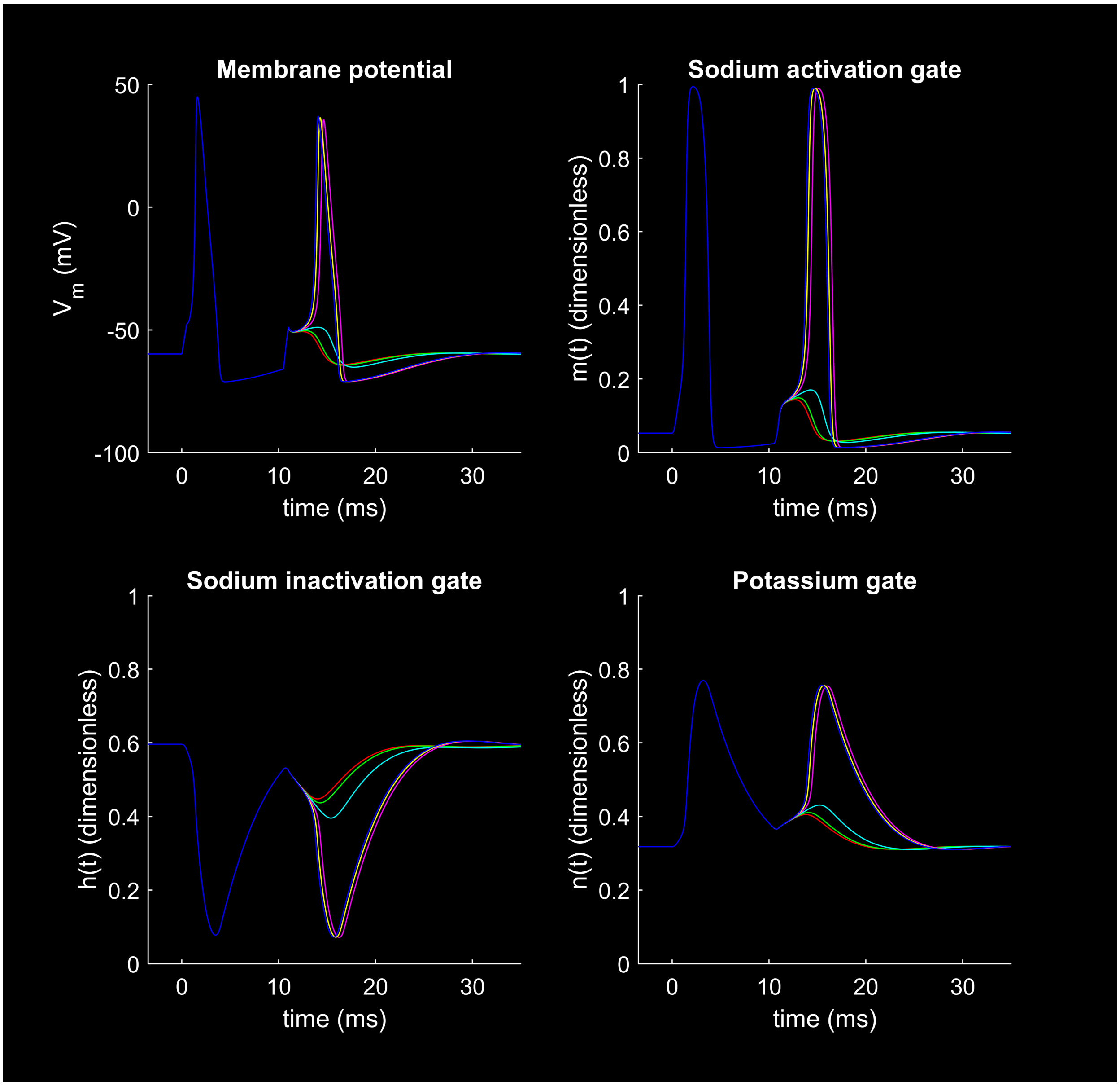


As the plot for the delay 12ms, 25.5 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 10

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 10;
amp2 = 40.5;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

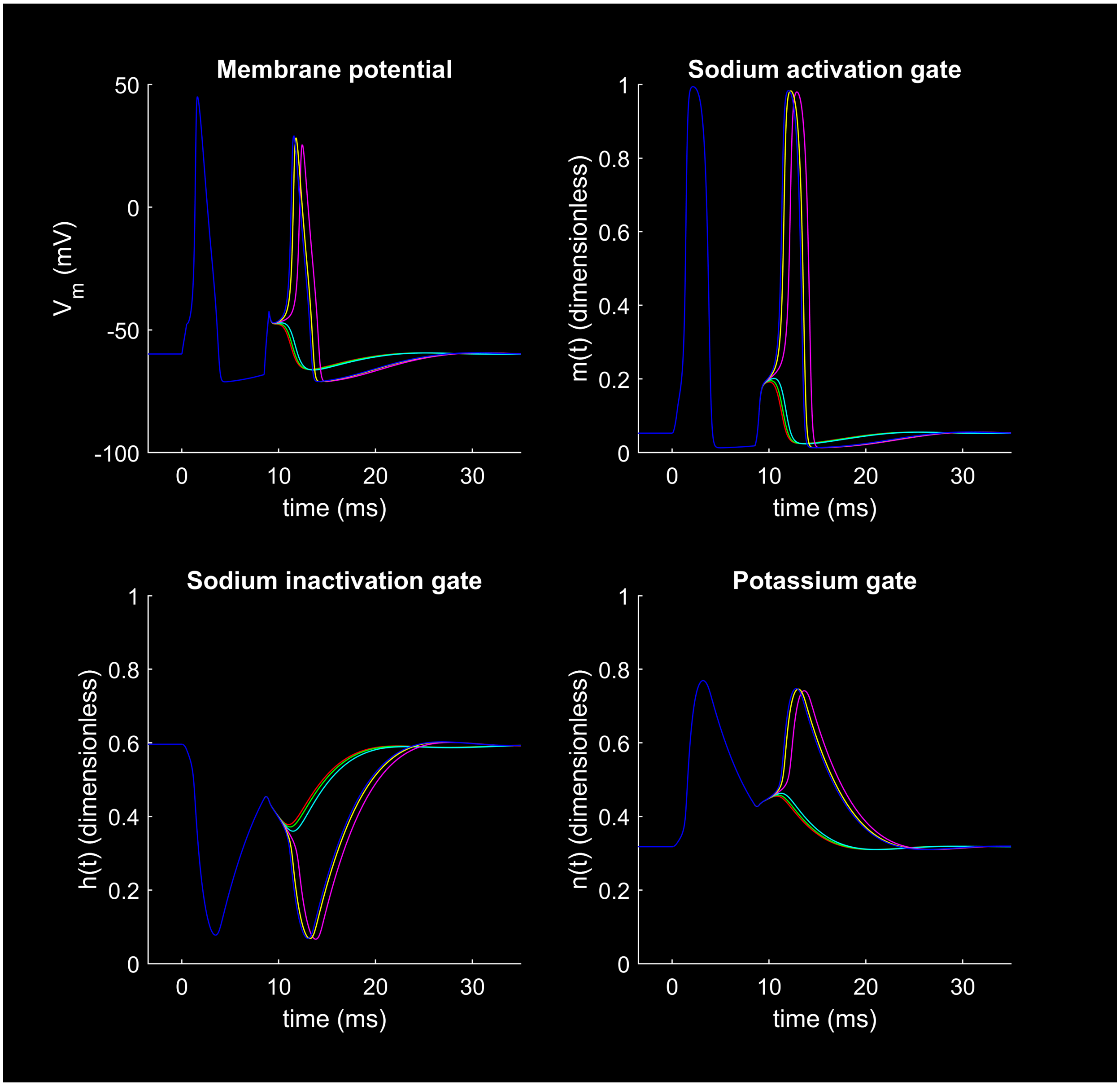


As the plot for the delay 10ms, 40.8 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 8

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 8;
amp2 = 69.8;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

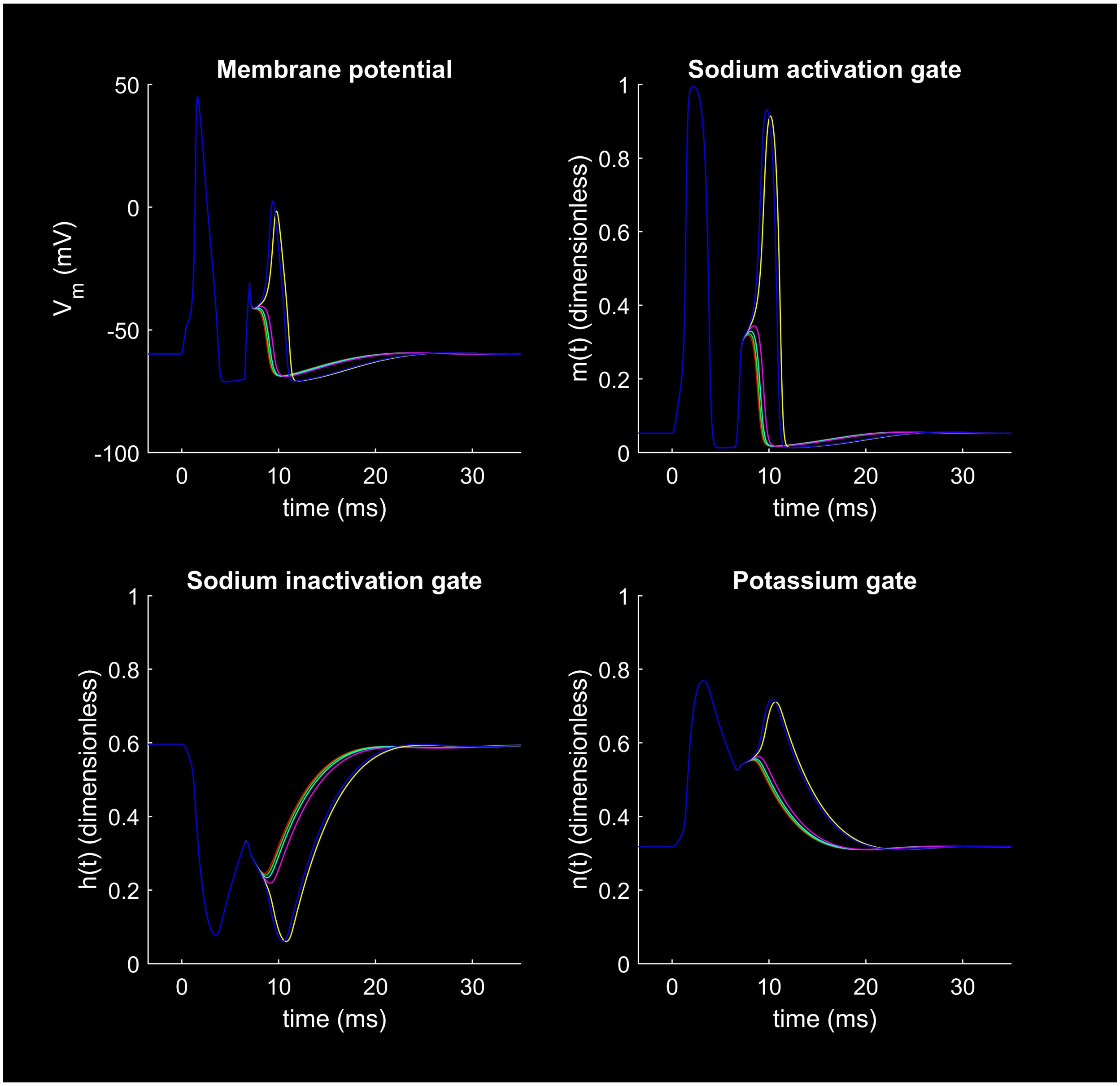


As the plot for the delay 8ms, 70.1 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

For delay 6

```
close;
amp1 = 26.8;
width1 = 0.5;
delay2 = 6;
amp2 = 144.8;
width2 = 0.5;
```

```
for i = 1:6
 hhmplot(0,35,i);
 amp2 = amp2+0.1;
end
```

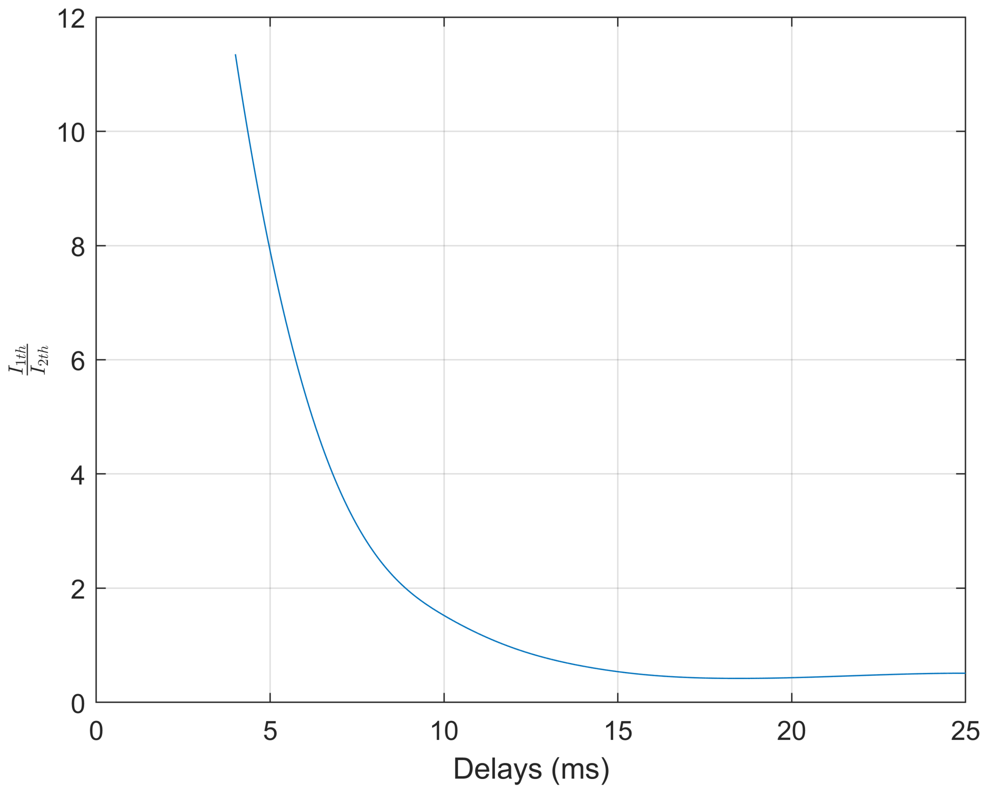


As the plot for the delay 6ms, 145.2 $\mu\mathrm{A\,cm^{-2}}$ of second impulse is needed to elicit an AP.

Question 04

```
close;
I2 = [145.2, 70.1, 40.8, 25.5, 17.0, 12.7, 11.3, 11.6, 13.7];
I1 = 26.8;
I1DivI2 = I2 / I1;
delay = [6, 8, 10, 12, 14, 16, 18, 20, 25];
x_values = linspace(4, 25, 10000); % Points to evaluate the smooth curve
fx = spline(delay, I1DivI2, x_values);
plot(x_values, fx);
```

```
xlabel('Delays (ms)');
ylabel('$\frac{I_{1th}}{I_{2th}}$', 'Interpreter', 'latex');
grid on;
```

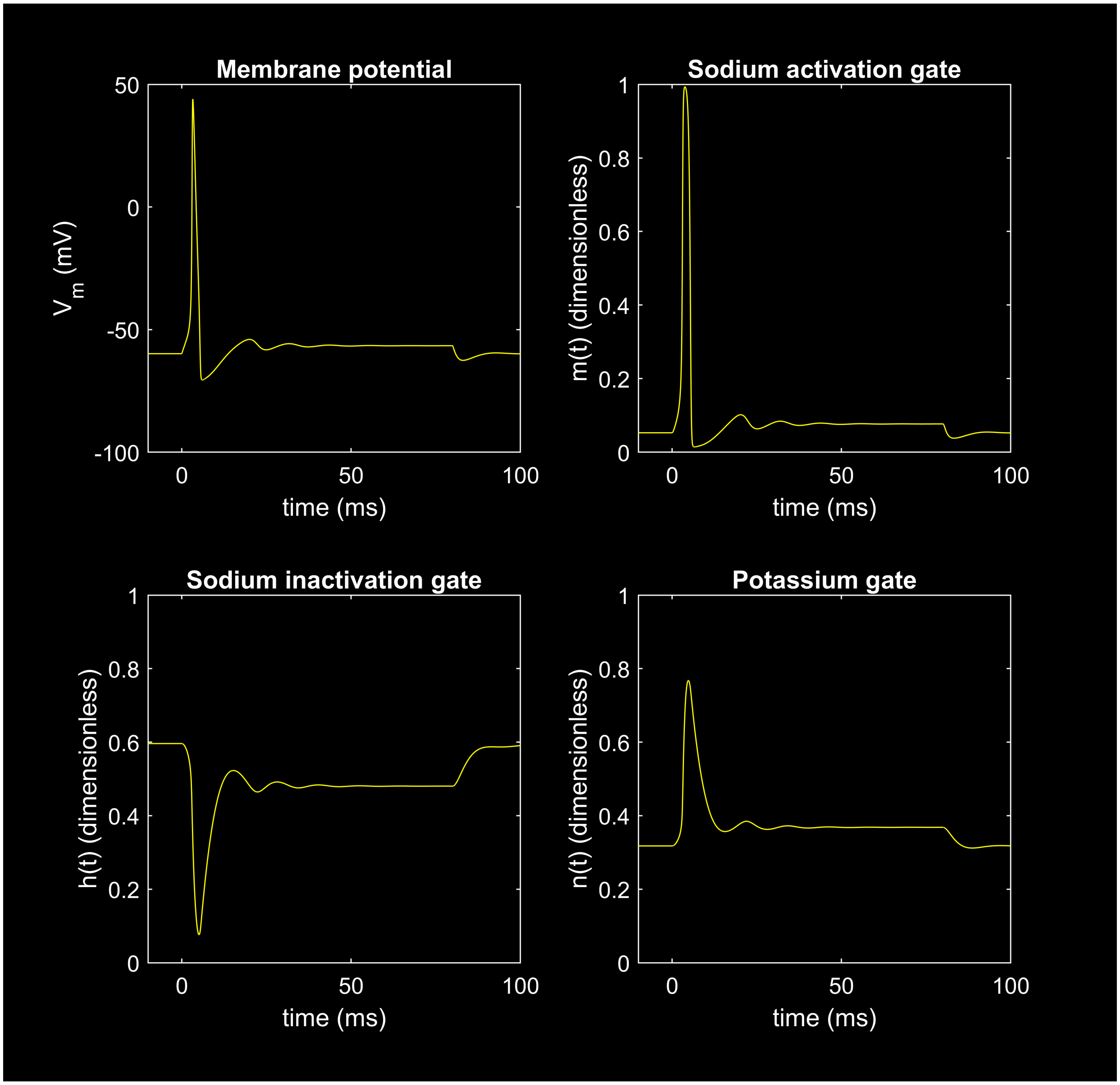


As the graph shows, it's clear that for delays of less than 5 ms, the $I_{2\text{th}}$ � must be more than 10 times greater than the $I_{1\text{th}}$ �. Thus, the absolute refractory period is less than 4 ms (normally 2-3 ms). The relative refractory period follows this. We can see that after a 12 ms period from when the 1*hI*1*th*� occurs, even for a pulse that is more than the threshold stimulating current, as long as $I_{2\text{th}}<I_{1\text{th}}$ �, an action potential (AP) can occur. Therefore, the relative refractory period is 13-16 ms.

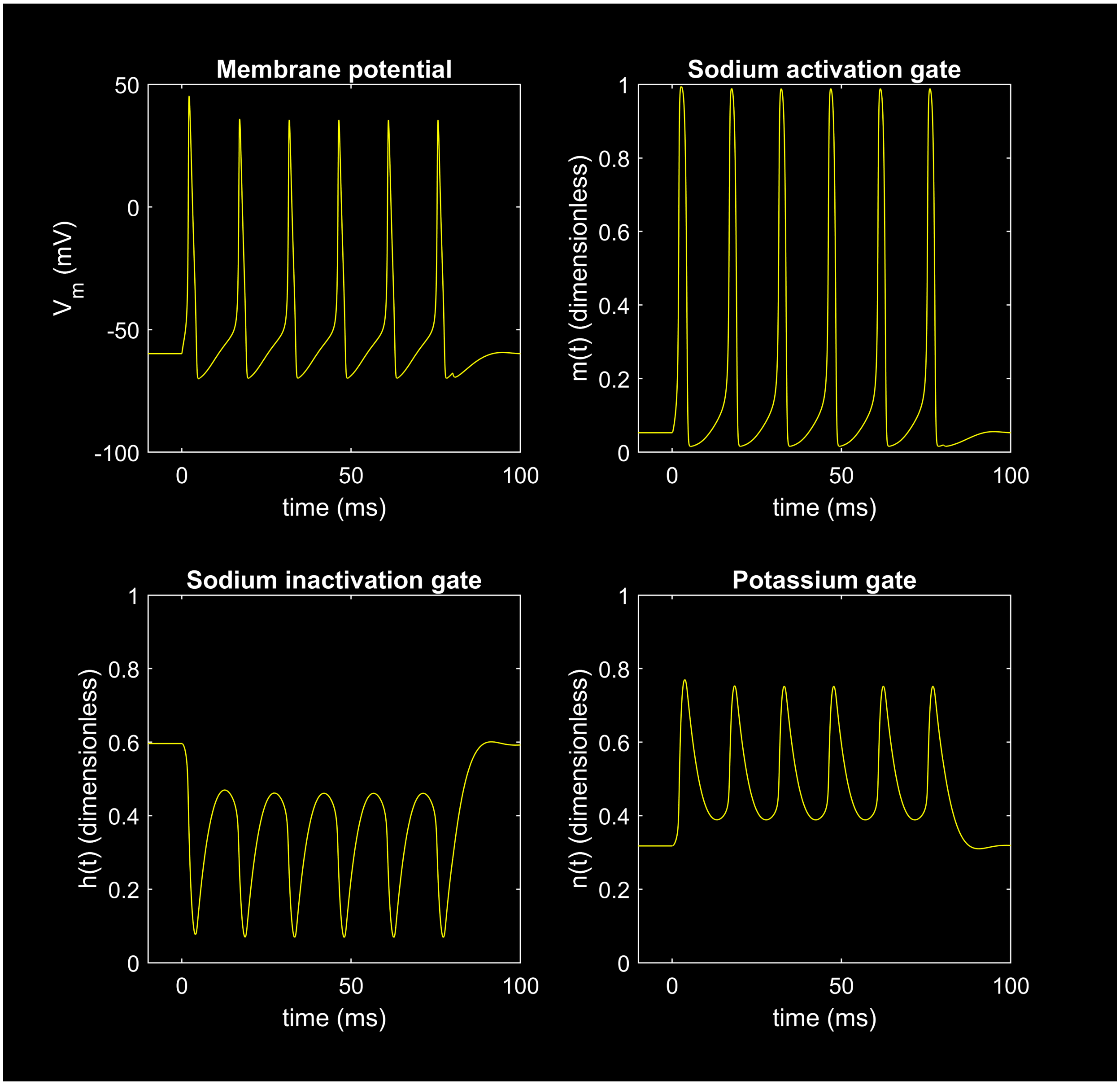
Repetitive activity

Question 05

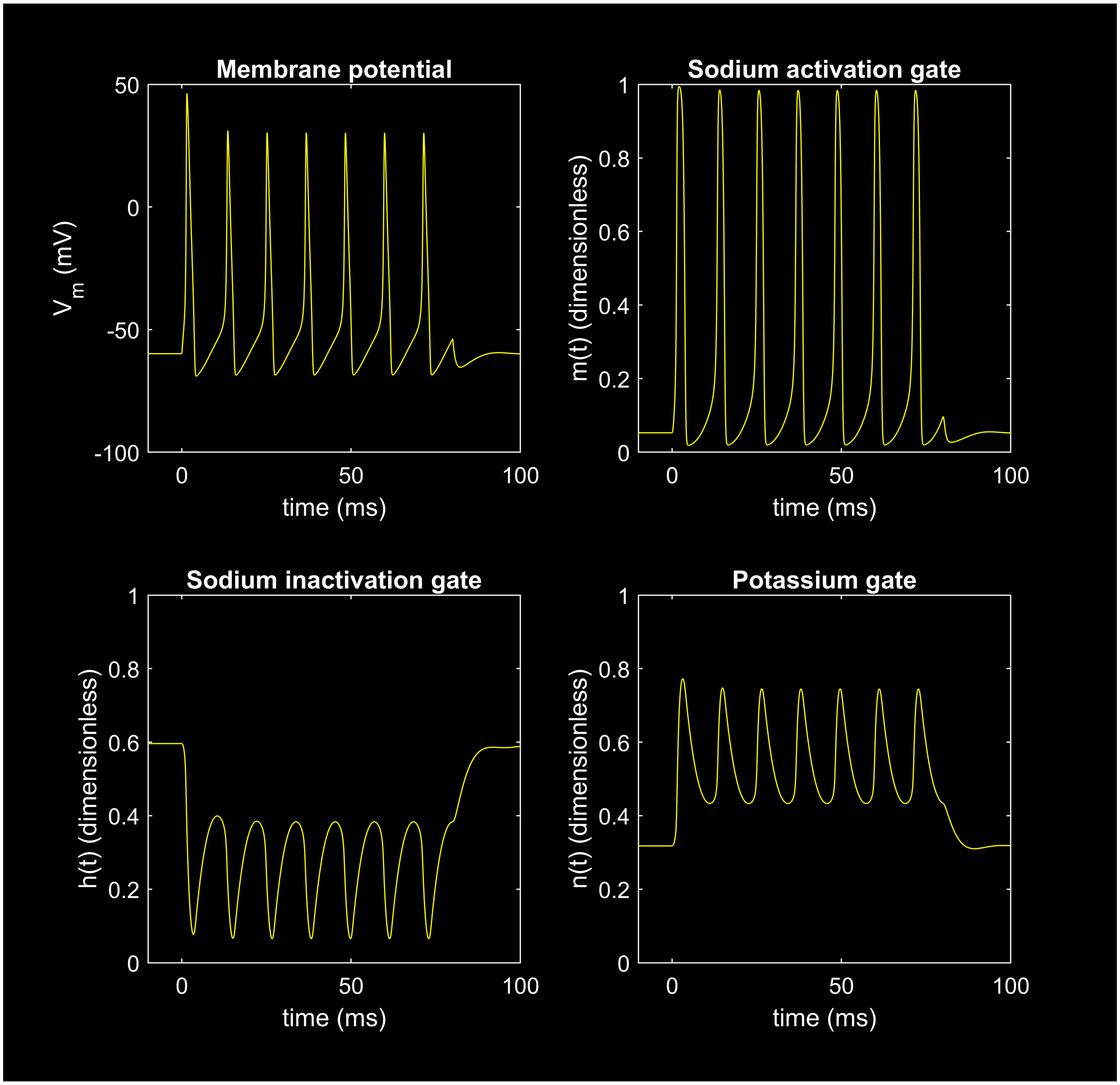
```
% Plot for amp1 = 5
close;
amp1=5;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
amp2 = 0;
hhmplot(0,100,0);
```



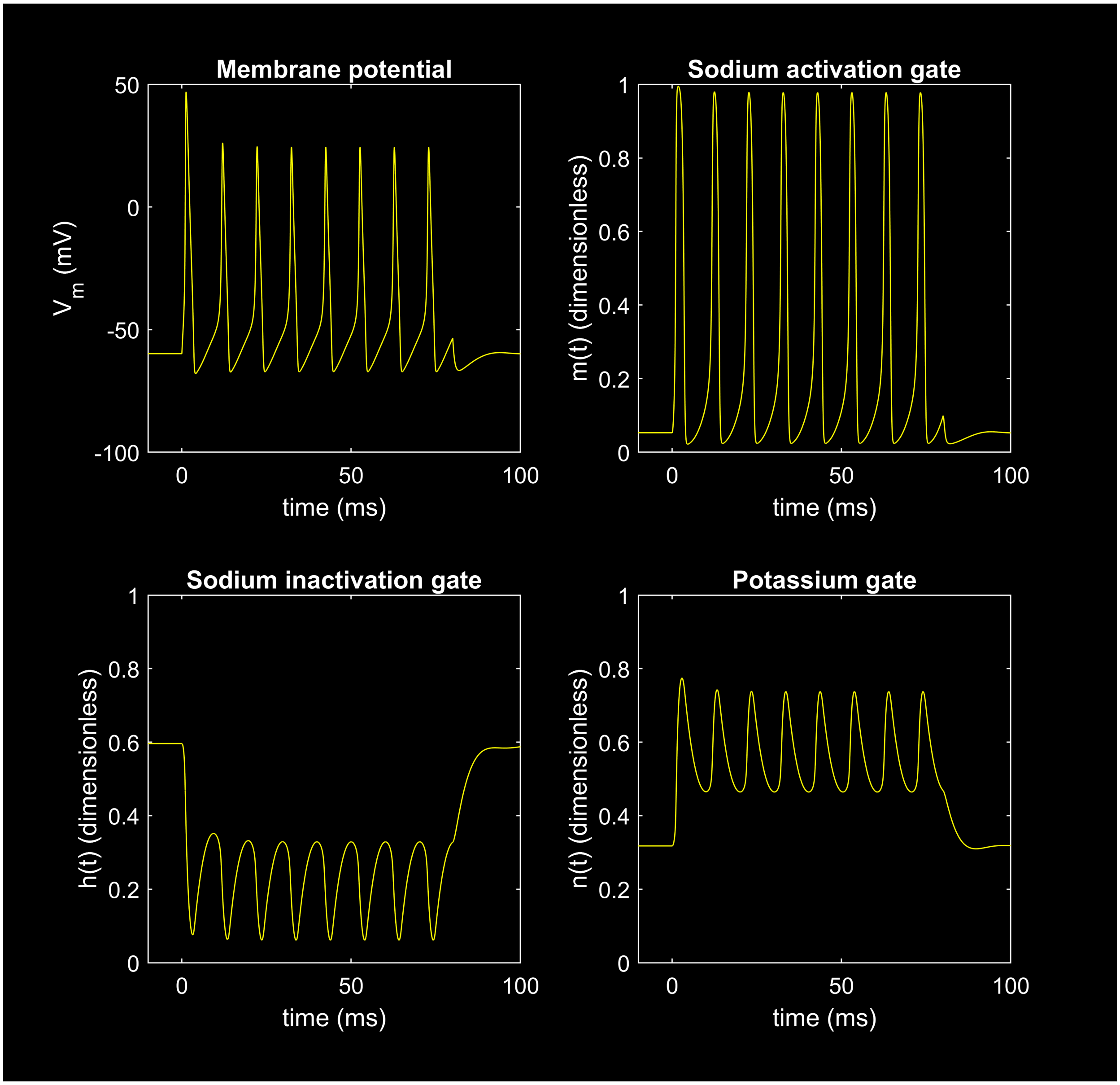

```
% Plot for amp1 = 10
close;
amp1 = 10;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```



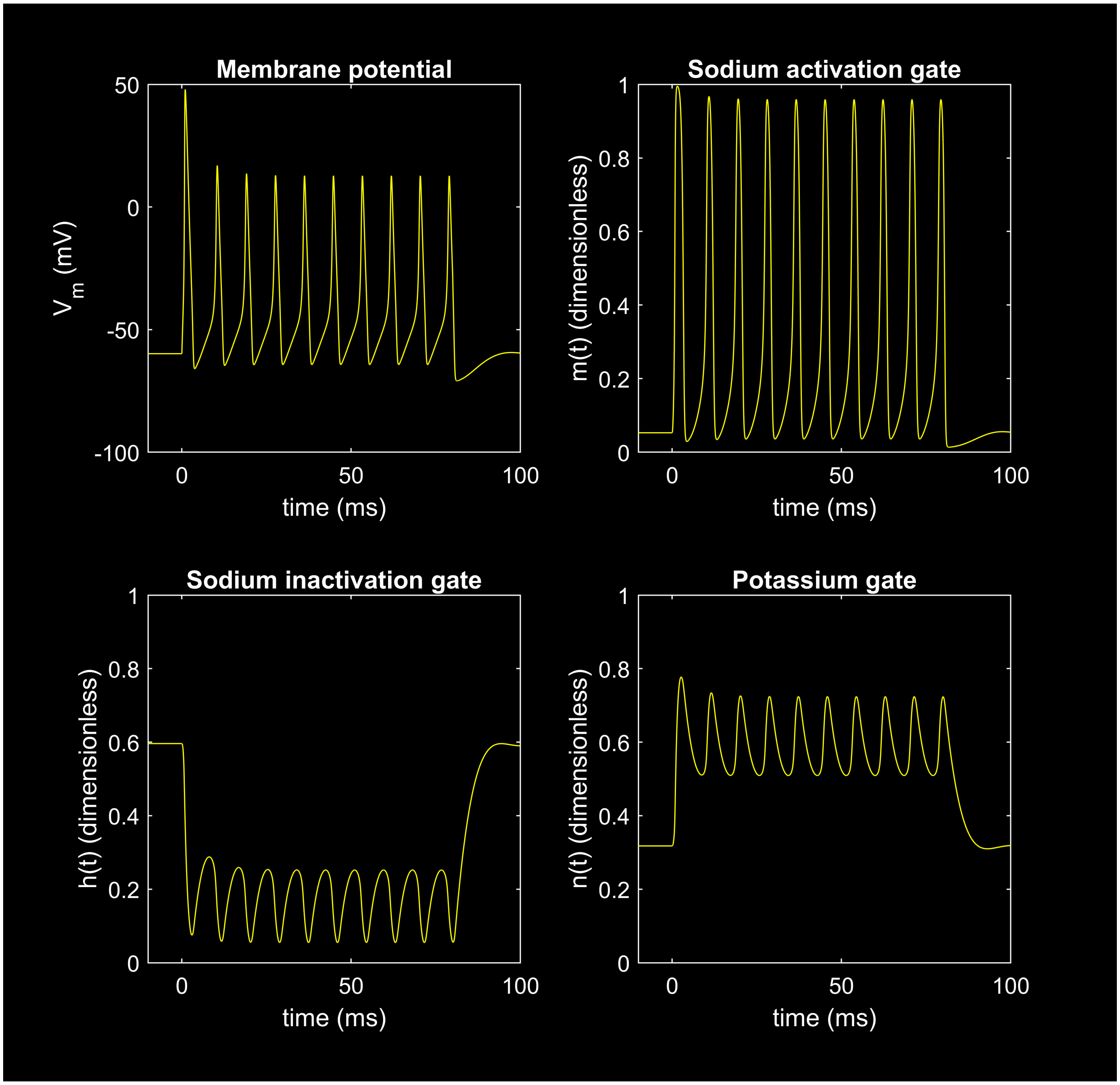

```
% Plot for amp1 = 20
close;
amp1 = 20;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```



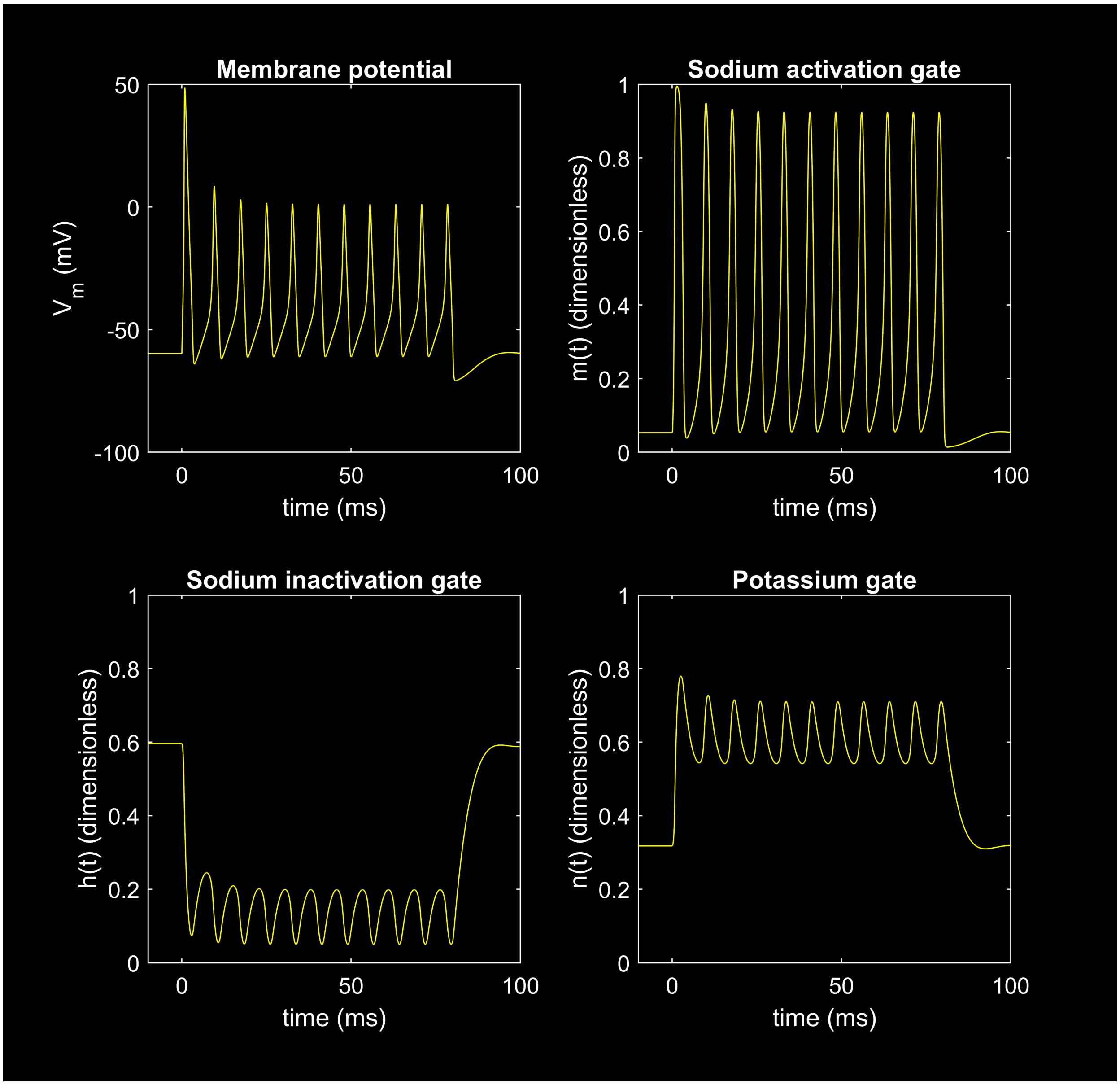

```
% Plot for amp1 = 30
close;
amp1 = 30;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```



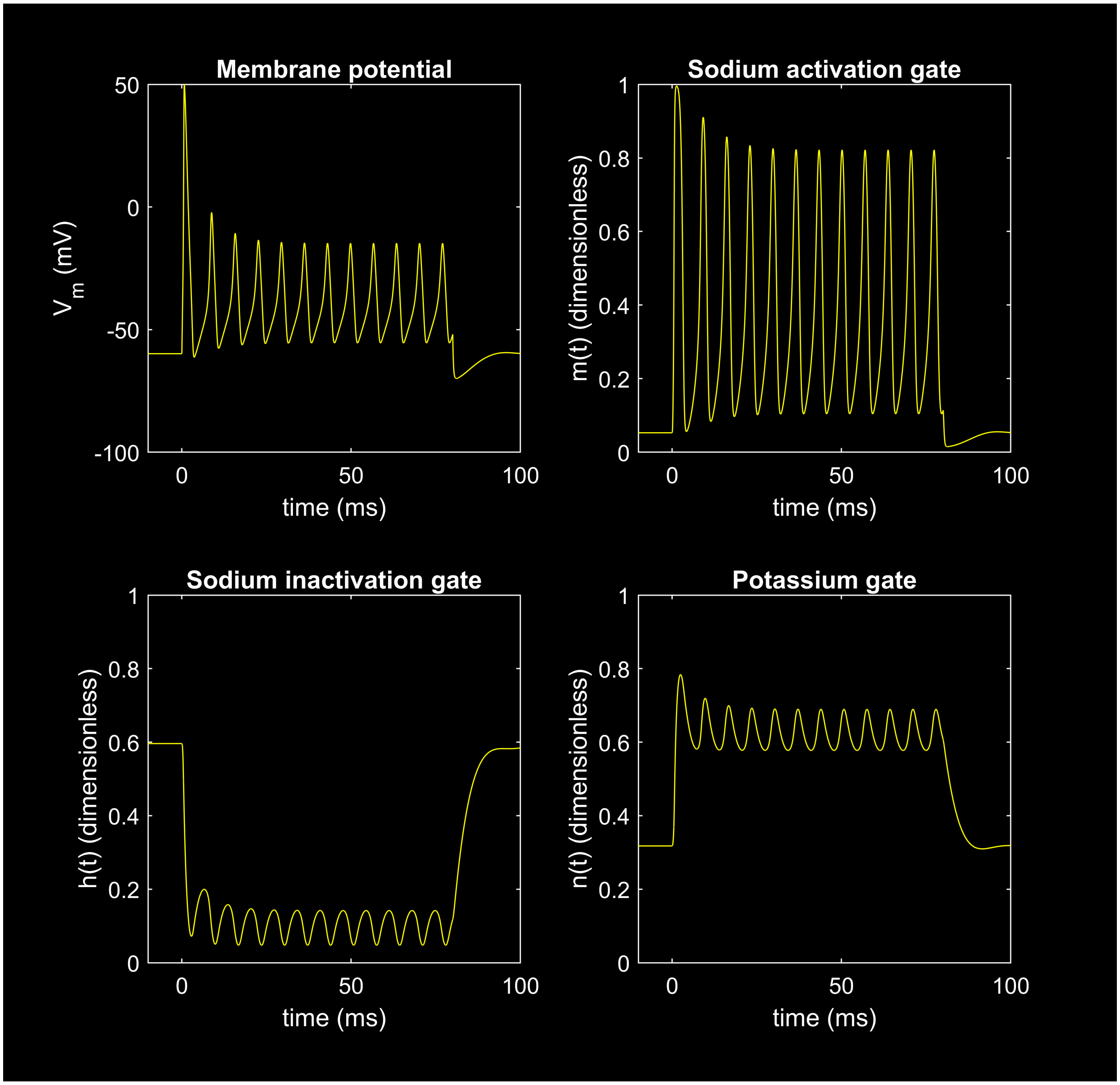

```
% Plot for amp1 = 50
close;
amp1 = 50;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```



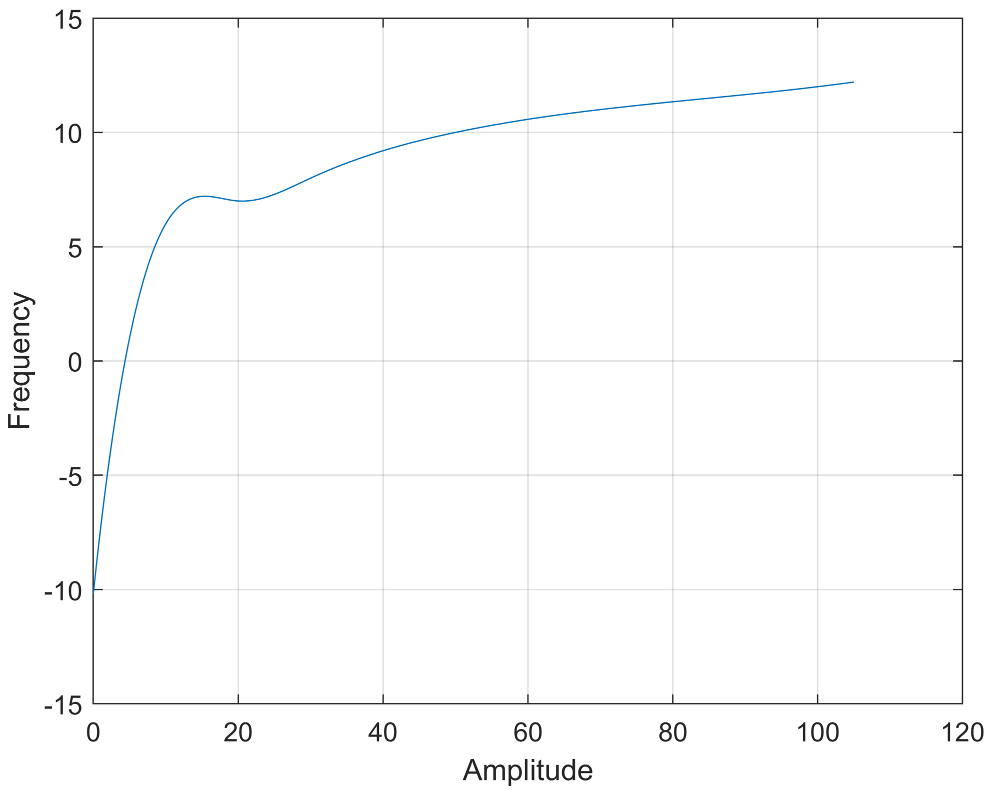

```
% Plot for amp1 = 70
close;
amp1 = 70;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```




```
% Plot for amp1 = 100
close;
amp1 = 100;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```



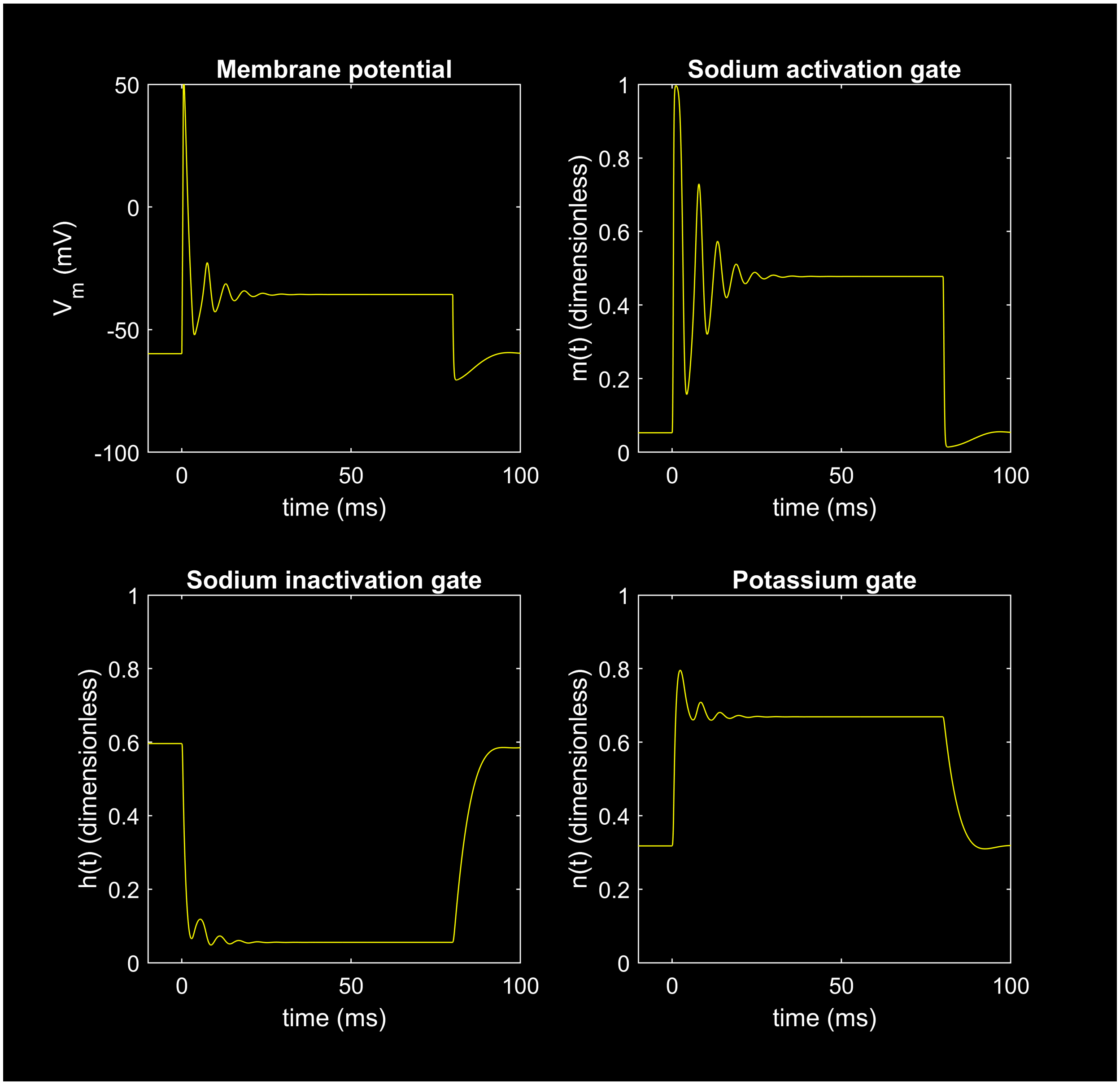

```
close;
amp = [5,10,20,30,50,70,100];
freq = [1,6,7,8,10,11,12];
x_values = linspace(0, 105, 1000); % Points to evaluate the smooth curve
fx = spline(amp, freq, x_values);
plot(x_values, fx);
xlabel('Amplitude');
ylabel('Frequency');
grid on;
```



The frequency increases with the amplitude. Initially, there is a rapid increase at small amplitudes, followed by a gradual decrease in the rate of increase. However, as the frequency rises, the amplitude of the stimulus intensity decreases.

Question 06

```
close;
amp1 = 200;
width1 = 80;
delay2 = 0;
amp2 = 0;
width2 = 0;
hhmplot(0, 100, 0);
```



Observation: The frequency of the stimulus is high, and the stimulus intensity amplitudes are decaying rapidly. As both the amplitude and the frequency are very high, the stimulus intensity amplitude continues to decrease.

According to the Hodgkin-Huxley model, the factors h and regulate membrane excitability by quickly transitioning to inactive states at high depolarized potentials. Voltage-dependent sodium and potassium conductances are essential for the strength of the action potential.

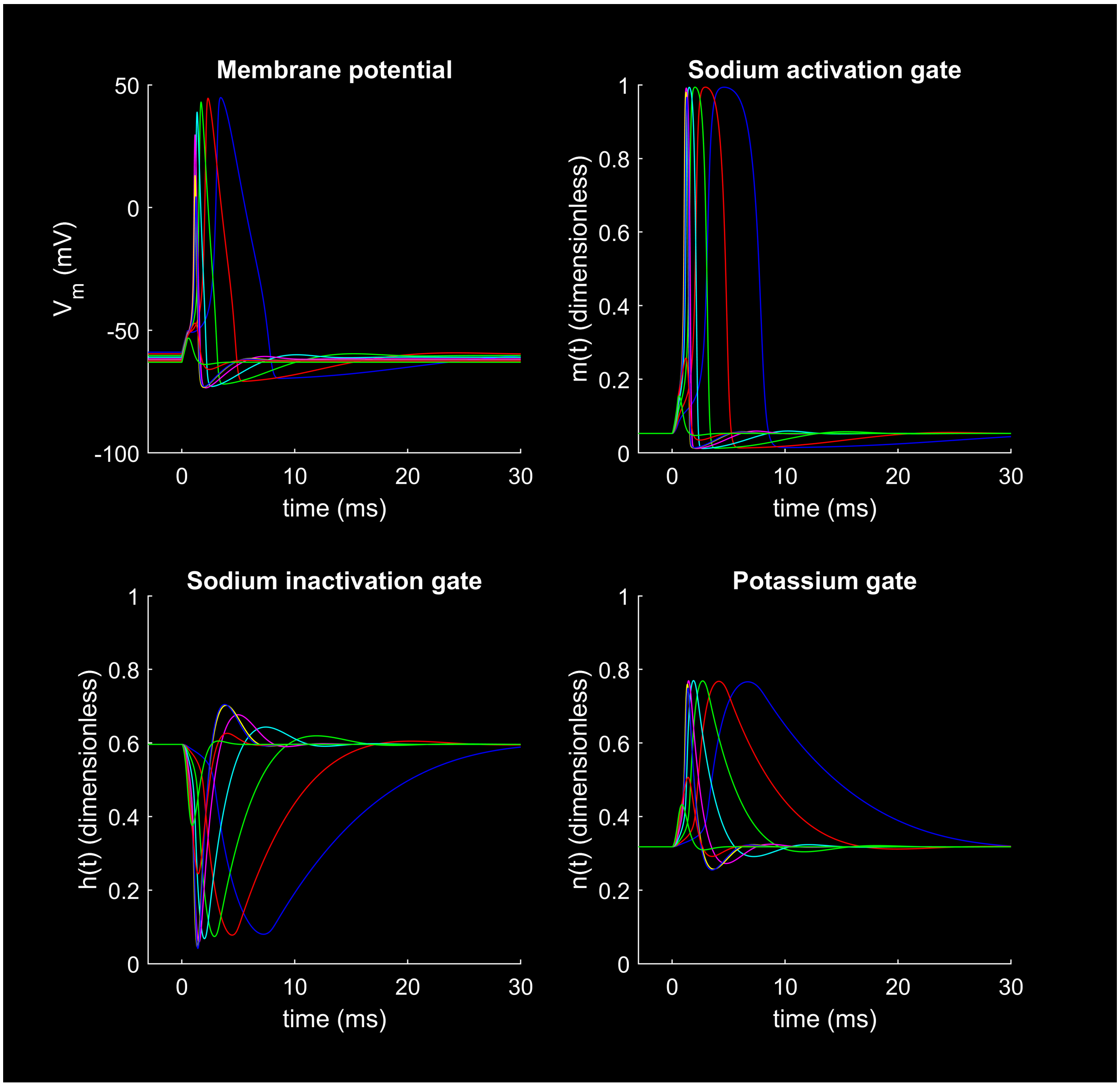
Sodium channels (and h) open more with increased depolarization, resulting in a greater inward sodium current during the upstroke. As the stimulus magnitude increases, the action potential amplitude tends to decrease.

On the other hand, potassium channels () become more active with membrane depolarization. However, if potassium conductance does not adequately counterbalance the increased sodium influx, it can negatively affect the action potential amplitude.

Temperature dependence

Question 07

```
close;
vclamp = 0;
amp1 = 20;
width1 = 0.5;
temp=[0, 5, 10, 15, 20, 24, 25, 26, 30];
for i =1:9
 tempc = temp(i);
 hhmplot(0,30,i);
end
```



1. Higher temperatures significantly increase the conduction velocity of action potentials along axons.

2. Increasing temperature shortens both absolute and relative refractory periods.
3. At higher temperatures, the resting membrane potential may decrease.
4. Faster opening and closing of voltage-gated ion channels at higher temperatures lead to quicker ion movement, resulting in increased action potential amplitude and decreased duration.
5. Elevated temperatures promote higher rates of vesicular fusion, enhancing postsynaptic responses and synaptic transmission.