How distance beween doses of two dose vaccine affects contagion and deaths in Colombia.

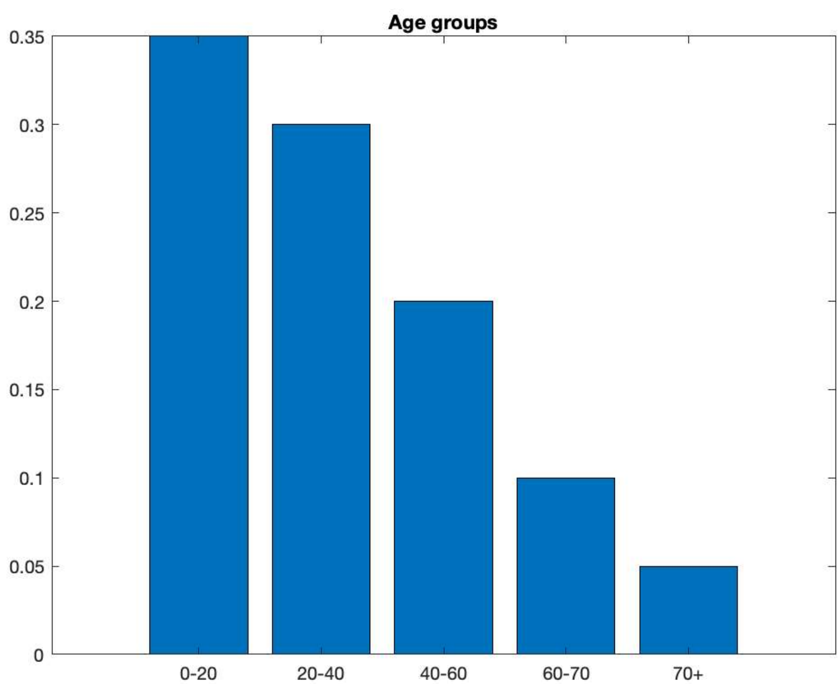
We created a Mathematical model using ordinary diferential equations to explore the effect of extending the distance between shots (in two dose vaccine) in the 20 - 40 age group in Colombia. The model

Assumptions:

1. **5 age groups. distributed as follows:**

We will work with proportions, for every variable describing the distribution of people at the different stagies of disese contagion we have the percentage of people in that group. The bar plot shows the age distrubiton for our simulations

```
age_dist = [0.35; 0.3; 0.2; 0.1; 0.05];%0-20 20-40 40-60 60-70 70+
bar(age_dist)
title('Age groups')
xticklabels({'0-20','20-40','40-60','60-70','70+'})
```



2. 11 epidemiological compartments to account for un-vaccinated and vaccinated people in all age groups.

The diagram results in a system of 11 ordinary differential equations:

$$\frac{dS_i}{dt} = -\beta_i S_i \sum \left(I_i + I_i^v\right) + \frac{R_i}{\tau_{R_i}} + \frac{R_i^v}{\tau_{R_i}} - \nu_i S_i$$

$$\frac{dI_i}{dt} = \beta_i S_i \sum \left(I_i + I_i^v\right) - \theta_H \frac{I_i}{\tau_{I_i}} - (1-\theta_H)\frac{I_i}{\tau_{I_i}}$$

$$\frac{dH_i}{dt} = (1-\theta_H)\frac{I_i}{\tau_{I_i}} - \theta_D \frac{H_i}{\tau_{H_i}} - (1-\theta_D)\frac{H_i}{\tau_{H_i}}$$

$$\frac{dR_i}{dt} = \frac{R_i}{\tau_{R_i}} + \theta_H \frac{I_i}{\tau_{I_i}} + \theta_D \frac{H_i}{\tau_{H_i}}$$

$$\frac{dD_i}{dt} = (1-\theta_D)\frac{H_i}{\tau_{H_i}}$$

$$\frac{dV_i^1}{dt} = \nu_i S_i - \xi_i^1(1-\theta_1)\frac{V_i^1}{\delta_2} - \xi_i^1(\theta_1)\frac{V_i^1}{\delta_1} - \left(1-\xi_i^1\right)\beta_i^1 V_i^1 \sum \left(I_i + I_i^v\right)$$

$$\frac{dV_i^2}{dt} = \xi_i^1(1-\theta_1)\frac{V_i^1}{\delta_2} - \xi_i^2\frac{V_i^2}{\delta_2} - \left(1-\xi_i^2\right)\beta_i^2 V_i^2 \sum \left(I_i + I_i^v\right)$$

$$\frac{dI_i^v}{dt} = \left(1-\xi_i^1\right)\beta_i^1 V_i^1 \sum \left(I_i + I_i^v\right) + \left(1-\xi_i^2\right)\beta_i^2 V_i^2 \sum \left(I_i + I_i^v\right) - \theta_H^v \frac{I_i^v}{\tau_{I_i^v}} - \left(1-\theta_H^v\right)\frac{I_i^v}{\tau_{I_i^v}}$$

$$\frac{dH_i^v}{dt} = \left(1-\theta_H^v\right)\frac{I_i^v}{\tau_{I_i^v}} - \left(1-\theta_D^v\right)\frac{H_i^v}{\tau_{H_i^v}} - \theta_D^v\frac{H_i^v}{\tau_{H_i^v}}$$

$$\frac{dR_i^v}{dt} = \theta_H^v \frac{I_i^v}{\tau_{I_i^v}} + \theta_D^v \frac{H_i^v}{\tau_{H_i^v}} - \frac{R_i^v}{\tau_{R_i}} + \xi_i^1(\theta_1)\frac{V_i^1}{\delta_1} + \xi_i^2\frac{V_i^2}{\delta_2}$$

$$\frac{dD_i^v}{dt} = \left(1-\theta_D^v\right)\frac{H_i^v}{\tau_{H_i^v}}$$

3. The distance between first and second shot has to be defined for every age group

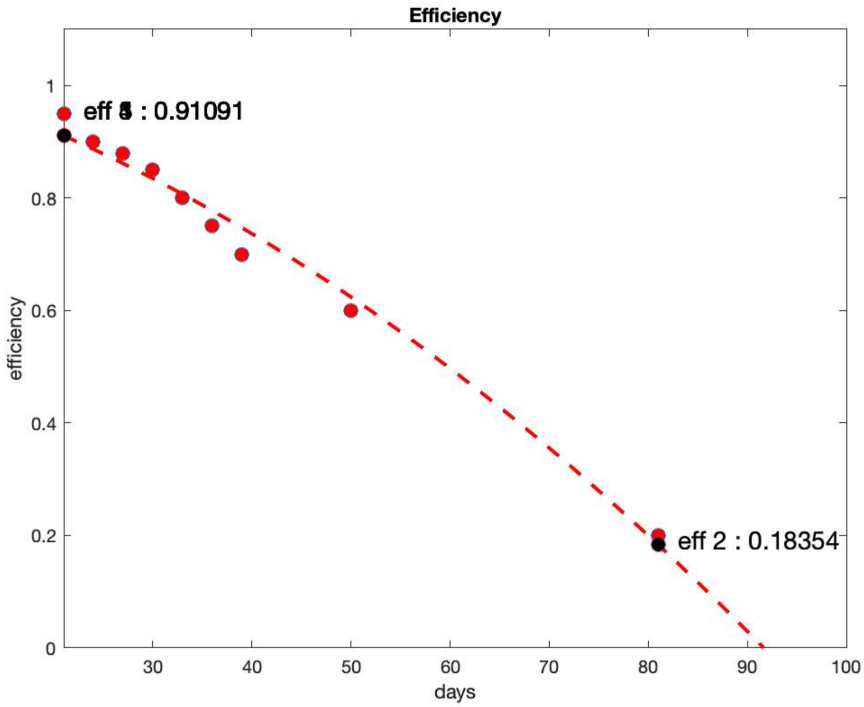
The tradeoff between vaccination pace and the application of the second dose requieres the quantification of the decrease in efficacy as the distance betwenn the two shots are applied and the adavantage of applying the first shot to more people.

```
%define distance for each age group
dist(1) = 21;%gap between shots [days] for Age  0 - 20
dist(2) = 22;%gap between shots [days] for Age 20 - 40
dist(3) = 21;%gap between shots [days] for Age 40 - 60
dist(4) = 21;%gap between shots [days] for Age 60 - 70
dist(5) = 21;%gap between shots [days] for Age 70+
```

4. With the distance between shots we have to assume how distance impacts vaccine efficiency

The assumption here is that effiency peaks at day 21 (as shown by studies) and then it slowly decreases as time between shots increases.

```
%give known efficiency points
x = [0     18   21   24   27   30   33    36    39    50     81] ;%days
y = [1   0.98 0.95 0.90 0.88 0.85 0.80  0.75  0.70  0.60   0.20] ;%efficiency
eff = find_efficacy_function(x,y,dist,1);%get effiency for each age group
```

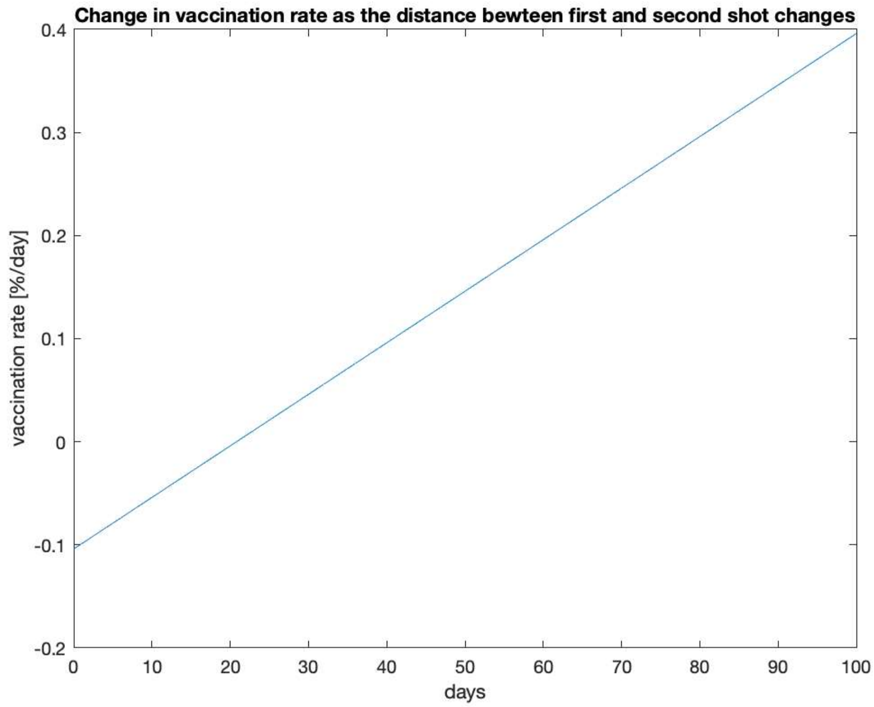


4. Define the relation between *distance between shots* and *vaccination pace*. For every day the gap is extended the vaccination pace is augmented proprotionally.

As time bewteen shots increases we can vaccinate at a faster rate (1st shot). here we assume that every day a second shot is delay afte day 21 all those doses are used for 1st shots. Here we assume enough supply for first shot rate.

```
%define baseline vaccination rates for each age group
%a vaccination rate of 100.000 people every day corresponds to 0.002
%(100.000/day/50.000.000)
vacc(1) = 0.007;%gap between shots [days] for Age  0 - 20
vacc(2) = 0.001;%gap between shots [days] for Age 20 - 40
vacc(3) = 0.001;%gap between shots [days] for Age 40 - 60
vacc(4) = 0.001;%gap between shots [days] for Age 60 - 70
vacc(5) = 0.001;%gap between shots [days] for Age 70+

%Based on the chosen distance between shots for each age group and their base line vaccination rate
% here we show the relation between these variabkes . (note that a shortage in distance between
% shots dimishes vaccines avalible for first shot as well)
%assume that V1f1 is the proportion of people in the 1st shot box that will
%get the 2nd shot, therefor the change in vaccination rate for every day
%that differs from the 21 expected is given by:
V1f1 = 0.01*0.5;%because V1 is a variable this rate changes continously in time.
vaccrates = vacc + (dist-21)*V1f1;
figure
d = 0:1:100;
plot(d,0.001 + (d-21)*V1f1)
title('Change in vaccination rate as the distance bewteen first and second shot changes')
xlabel('days')
ylabel('vaccination rate [%/day]')
```



5. The sytem parameters are as follows

The following table contais all parameters that descibe residence times, proprotions, infection rates, vaccination rates.

```
[P,IC,param_names,age_groups,variable_names] = parameters(dist,eff,vaccrates);
table(param_names,P(:,1),P(:,2),P(:,3),P(:,4),P(:,5),'VariableNames',age_groups)
```

ans = 20×6 table

	Parameters	Age 0-20	Age 20-40	Age 40-60	Age 60-70	Age 70+
1	'transmission rate …	0.50000000000…	0.300000000000…	0.300000000000…	0.200000000000…	0.2000000000…
2	'residence time in r…	100	100	100	100	100
3	'residence time in i…	6	7	8	9	10
4	'residence time in …	7	8	10	12	15
5	'proportion of infec…	0.99000000000…	0.980000000000…	0.970000000000…	0.960000000000…	0.9500000000…
6	'proportion of hosp…	0.10000000000…	0.250000000000…	0.500000000000…	0.750000000000…	0.9000000000…
7	'vaccination rate 1/…	0	0.301000000000…	1.000000000000…	1.000000000000…	1.0000000000…
8	'transmission rate …	0.60000000000…	0.300000000000…	0.200000000000…	0.150000000000…	0.1000000000…
9	'transmission rate …	0.10000000000…	0.080000000000…	0.060000000000…	0.040000000000…	0.0300000000…
10	'residence time in r…	360	360	360	360	360
11	'residence time in i…	3	5	6	7	8
12	'residence time in …	5	10	12	14	18
13	'proportion of infec…	0.99900000000…	0.990000000000…	0.980000000000…	0.970000000000…	0.9600000000…
14	'proportion of hosp…	0.05000000000…	0.100000000000…	0.200000000000…	0.400000000000…	0.5000000000…
15	'efficacy of vaccine…	0.65000000000…	0.650000000000…	0.650000000000…	0.650000000000…	0.6500000000…
16	'efficacy of vaccine…	0.91090821207…	0.183542455853…	0.910908212078…	0.910908212078…	0.9109082120…
17	'distance between …	21	81	21	21	21
18	'proportion of peop…	0.50000000000…	0.500000000000…	0.500000000000…	0.500000000000…	0.2000000000…
19	'residence time in f…	21	21	21	21	21
20	'residence time in …	30	30	30	30	30

6. The initial conditions for each variable are as follows:

Initial conditions for state variables are considered in the following table:

```
table(variable_names,IC(:,1),IC(:,2),IC(:,3),IC(:,4),IC(:,5),'VariableNames',age_groups)
```

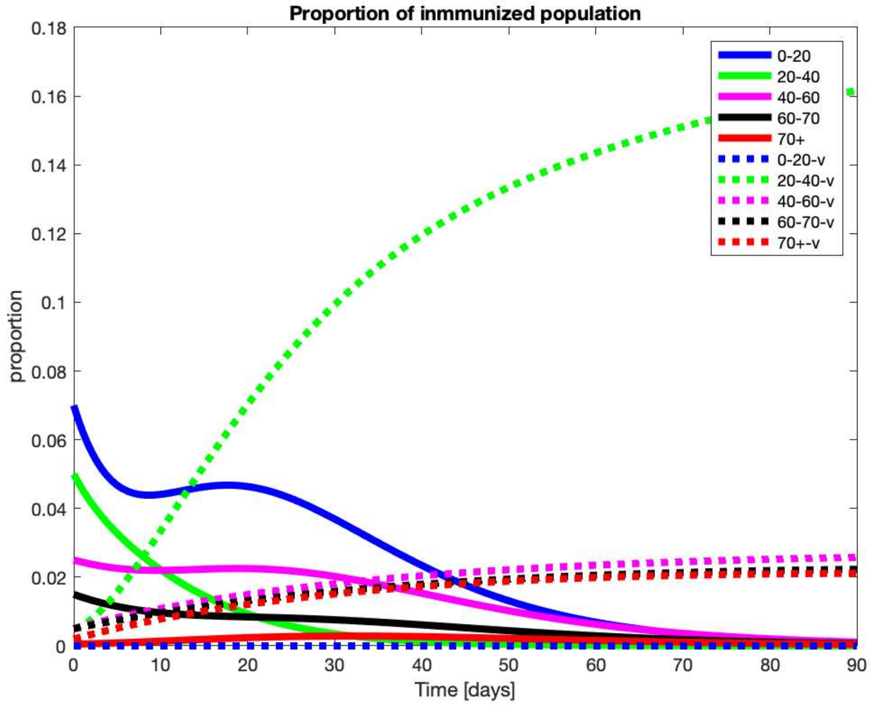
ans = 11×6 table

	Parameters	Age 0-20	Age 20-40	Age 40-60	Age 60-70	Age 70+
1	'Suceptible'	0.27000000000…	0.221890000000…	0.130490000000…	0.054090000000…	0.0218500000…
2	'Infected'	0.01000000000…	0.010000000000…	0.015000000000…	0.003000000000…	0.0010000000…
3	'Hospitalized'	0	0.000100000000…	0.000500000000…	0.000900000000…	0.0001000000…
4	'Recovered'	0.07000000000…	0.050000000000…	0.025000000000…	0.015000000000…	0.0005000000…
5	'Dead'	0	0	0	0	0
6	'Vaccinated first sh…	0	0.010000000000…	0.015000000000…	0.015000000000…	0.0040000000…
7	'Vaccinated secon…	0	0.001000000000…	0.007000000000…	0.006000000000…	0.0200000000…
8	'infected - vaccinat…	0	0.002000000000…	0.002000000000…	0.001000000000…	0.0005000000…
9	'Hospitalized - vac…	0	0.000010000000…	0.000010000000…	0.000010000000…	0.0000500000…
10	'Recovered vaccin…	0	0.005000000000…	0.005000000000…	0.005000000000…	0.0020000000…
11	'Dead - Vaccinated'	0	0	0	0	0

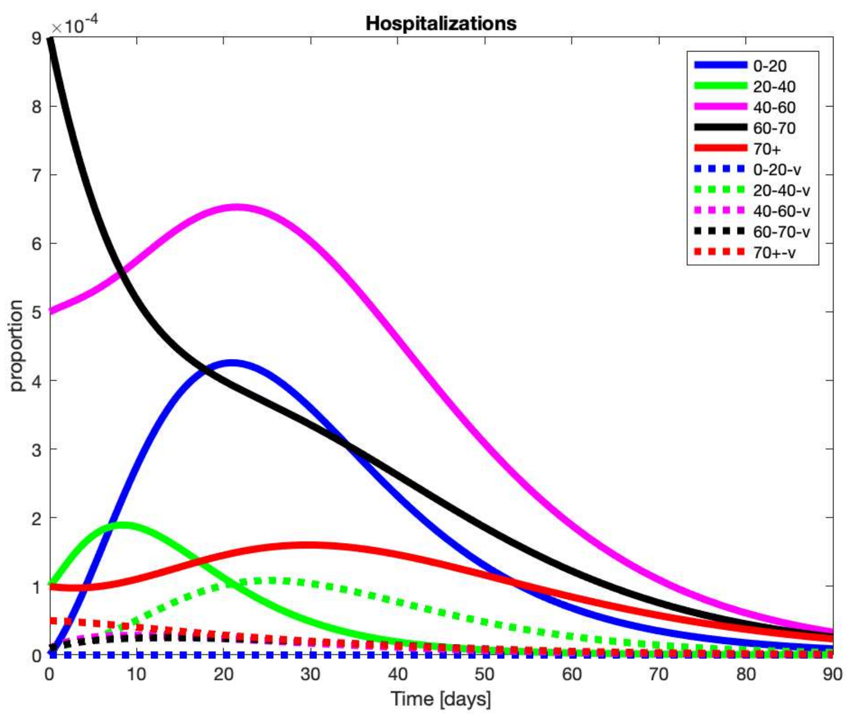
Simulations

We define a "control" a simulation with "reference" parameters and use it to compare to all perturbations. The state variables chosen to compare results are: cumulative infections, cumulative deaths, hospital demand. The model produce the folowing values for a 90 day time span with the initial conditions and parameters defined above.

```
t_span = 90; %time span for simulation
[T,Y] = run_model(IC,P,t_span);
figure%people in Vaccin1 and 2 groups
pl1 = plot(T,Y(:,4),'b',T,Y(:,15),'g',T,Y(:,26),'m',T,Y(:,37),'k',T,Y(:,48),'r',...
    T,Y(:,10),':b',T,Y(:,21),':g',T,Y(:,32),':m',T,Y(:,43),':k',T,Y(:,54),':r');
set(pl1,'LineWidth',4)
legend('0-20','20-40','40-60','60-70','70+','0-20-v','20-40-v','40-60-v','60-70-v','70+-v')
title('Proportion of inmmunized population')
xlabel('Time [days]')
ylabel('proportion')
```

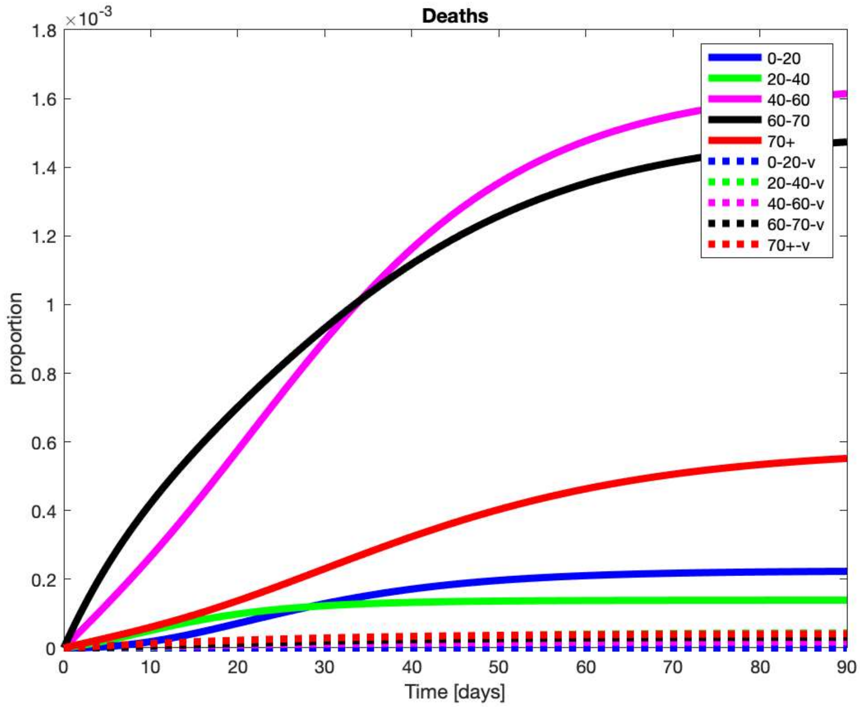



```
figure%hospitals
pl2 = plot(T,Y(:,3),'b',T,Y(:,14),'g',T,Y(:,25),'m',T,Y(:,36),'k',T,Y(:,47),'r',...
     T,Y(:,9),':b',T,Y(:,20),':g',T,Y(:,31),':m',T,Y(:,42),':k',T,Y(:,53),':r');
set(pl2,'LineWidth',4)
legend('0-20','20-40','40-60','60-70','70+','0-20-v','20-40-v','40-60-v','60-70-v','70+-v')
title('Hospitalizations')
xlabel('Time [days]')
ylabel('proportion')
```



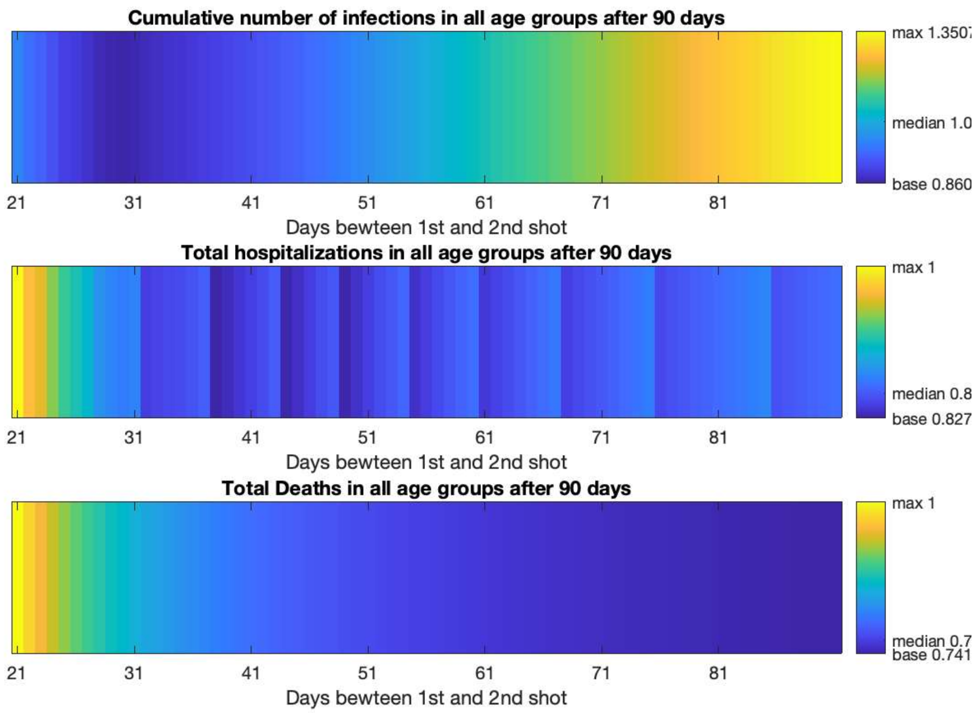

```
figure%deaths
pl3 = plot(T,Y(:,5),'b',T,Y(:,16),'g',T,Y(:,27),'m',T,Y(:,38),'k',T,Y(:,49),'r',...
     T,Y(:,11),':b',T,Y(:,22),':g',T,Y(:,33),':m',T,Y(:,44),':k',T,Y(:,55),':r');
```

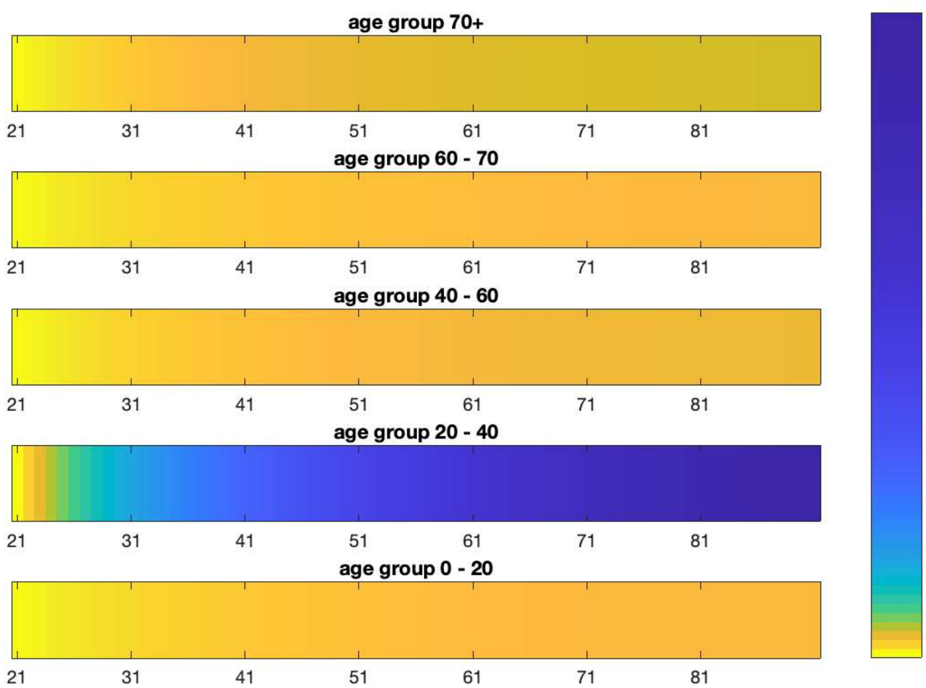
```
set(pl3,'LineWidth',4)
title('Deaths')
xlabel('Time [days]')
ylabel('proportion')
legend('0-20','20-40','40-60','60-70','70+','0-20-v','20-40-v','40-60-v','60-70-v','70+-v')
```

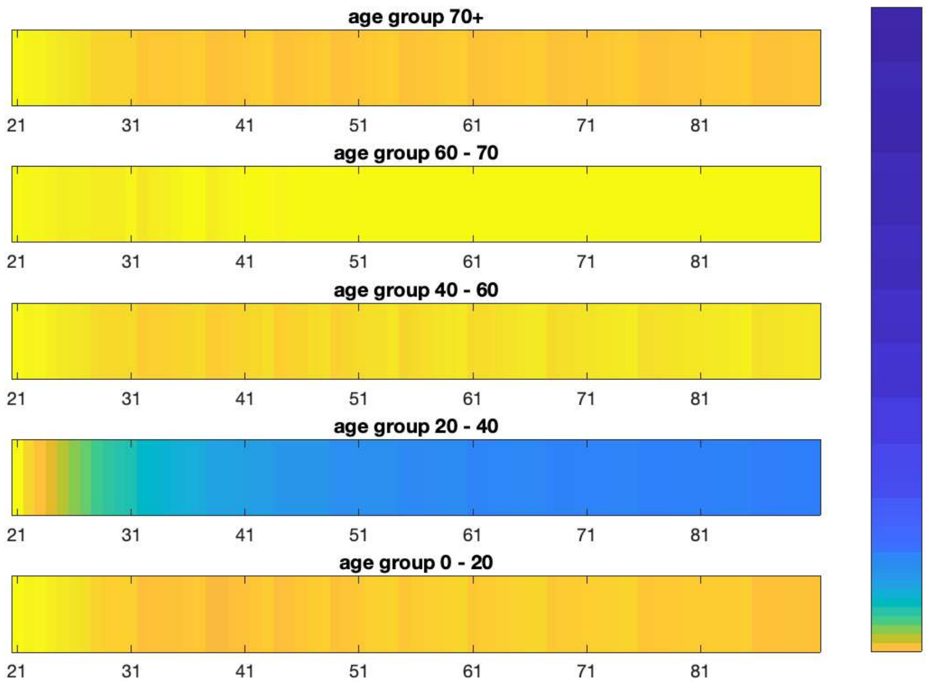


Now we investigate the effect of changing distance between shots for the age group 20-40. By selecting a window of time to study the distance between the first and second shots. simulations are run for every day of the window and sumarized in the colormaps below.

```
day1 = 21;%begging of time window for analysis
dend = 21;%end of time window for analysis
ag = 2;%chose age group for extension of window
z = change_distance(day1,dend,vacc,x,y,t_span,dist,ag);
```


Cumulative number of infections in all age groups after 90 days
max 1.3507
median 1.0
base 0.860
21 31 41 51 61 71 81
Days bewteen 1st and 2nd shot
Total hospitalizations in all age groups after 90 days
max 1
median 0.8
base 0.827
21 31 41 51 61 71 81
Days bewteen 1st and 2nd shot
Total Deaths in all age groups after 90 days
max 1
median 0.7
base 0.741
21 31 41 51 61 71 81
Days bewteen 1st and 2nd shot


age group 70+
21 31 41 51 61 71 81
age group 60 - 70
21 31 41 51 61 71 81
age group 40 - 60
21 31 41 51 61 71 81
age group 20 - 40
21 31 41 51 61 71 81
age group 0 - 20
21 31 41 51 61 71 81



Conclusions

1. If second doses are not used to suplement first doses rate of vaccination the net effect of delayig the second dose is detrimental. In other words, if shots are scarse and second doses are just used to support basal rate of vaccination (1st dose) the population as a whole will se more contagious as well as hospitalization and deaths.
2. If second doses are use on top of basal rates we less deaths and less hospitalizations. However the amount of people that gets infected increases considerabily.
3. The improvements in deaths and hospitalization are pretty robust. Even when considering low leves of effectiveness after 80 days of gap.
4. The detrimental effect in contagious only starts being significant after 50 days.