UNIVERSIDAD NACIONAL DE ROSARIO

Facultad de Ciencias Económicas y Estadística



Análisis de temperatura corporal postmortem utilizando modelos lineales bayesianos

Estadística Bayesiana - Trabajo Práctico ${\rm N}^{\rm o}3$

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Introducción

La tanatocronología, derivada de las palabras griegas "thanatos" (muerte) y "chronos" (tiempo), es un subcampo de la medicina forense que se centra en determinar el intervalo postmortem, es decir, el tiempo transcurrido desde la muerte hasta el descubrimiento del cadáver. ¹

Desde el momento de la muerte, comienza en el cuerpo humano una serie de procesos químicos y físicos que se conocen como fenómenos cadavéricos. Uno de ellos es el enfriamiento del cuerpo (enfriamiento postmortem o algor mortis). En este proceso, la temperatura del cadáver desciende hasta igualarse con la temperatura ambiente. Este descenso ocurre más rápido en las primeras horas después de la muerte.

El objetivo de este trabajo es averiguar la hora de muerte de Sergio Contreras, un hombre que fue hallado muerto desangrado, producto de una herida punzante recibida en el bazo, en su casa en la localidad cordobesa de Salsipuedes. Para resolver este acertijo, se cuenta con la siguiente información sobre la temperatura del cuerpo sin vida del hombre:

- 5:33 hs El Centro de Atención de Emergencias 911 recibe un llamado de Lidia Benegas, alertando sobre ruidos extraños en la vivienda de su vecino en la localidad de Salsipuedes.
- 6:00 hs La policia arriba al lugar y se constata la presencia de un cuerpo tendido en el suelo.
- 6:45 hs Arriba la policía científica al lugar del crimen, se determina la ausencia de signos vitales en el cuerpo de Sergio y el médico forense informa una temperatura corporal de 32.8 °C.
- 8:15hs Finalizados los procedimientos legales y técnicos, se coloca el cuerpo en la bolsa de óbito para ser trasladado a morgue judicial. El termómetro registra que la temperatura del cadáver es de 30.5 °C.
- 13:30 hs Comienza la autopsia. El cadáver se encuentra a 23.7 °C.

Sección con nombre????

Como el ritmo con el cual el cuerpo pierde temperatura no es constante, se puede pensar que la derivada de la temperatura respecto al tiempo varía con el tiempo. En este caso, la temperatura del cadáver satisface la siguiente ley:

$$\frac{dT(t)}{dt} = r[T_{\rm amb} - T(t)] \tag{1}$$

donde T_{amb} es la temperatura ambiente (un valor fijo y conocido), r es una constante y T(t) es la función (por ahora desconocida) que describe la temperatura del cuerpo en función del tiempo.

Una posible función T(t) es:

$$T(t) = T_{\text{amb}} + (T_i - T_{\text{amb}}) \cdot e^{-rt}$$

siendo T_i la temperatura a la que está inicialmente el cuerpo.

La misma satisface la ecuación (1) ya que:

$$\frac{dT(t)}{dt} = (T_i - T_{amb}) \cdot (-r) \cdot e^{-rt} =$$

$$= -r \cdot [(T_i - T_{amb}) \cdot e^{-rt}] =$$

$$= -r \cdot [-T_{amb} + T_{amb} + (T_i - T_{amb}) \cdot e^{-rt}] =$$

$$= -r \cdot [-T_{amb} + T(t)] =$$

$$= r \cdot [T_{amb} - T(t)]$$

¹Fuente: Diccionario Médico: tanatocronología - Clínica Universidad de Navarra

Se grafica a continuación la función T(t) para distintos valores de la constante r, considerando una temperatura inicial del cuerpo de 37 C° y una temperatura ambiente de 23 C° .

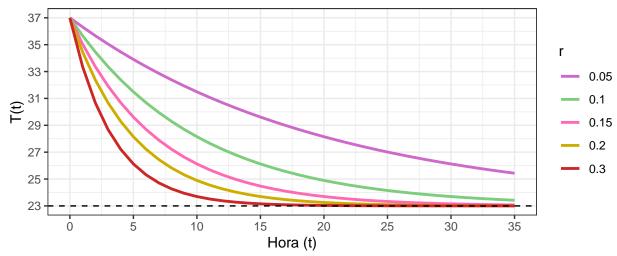


Figura 1: Gráfica de la función de descenso de la temperatura corporal T(t) para 2 valores de la constante r, con una temperatura inicial del cuerpo de 37 Cº hasta alcanzar una temperatura ambiente de 23 Cº

r es una constante que representa la conductividad entre el cuerpo y la superficie de contacto. A valores más altos de r, más rápido será el descenso de la temperatura corporal.

Los órganos abdominales pueden mantener el calor por al menos 24 horas. En las primeras 12 horas se va perdiendo el calor de 0.8 a 1.0 grado centígrado por hora y en las siguientes 12 horas de 0.3 a 0.5 grados centígrados.²

Teniendo en cuenta esta información y lo observado en la Figura 1, se puede considerar que un valor razonable para r se encuentra entre 0.1 y 0.2.

Postulación del modelo

Para mayor simplicidad a la hora de construir un modelo, en lugar de trabajar con la temperatura del cuerpo se decide utilizar la diferencia entre la temperatura del mismo y la temperatura ambiente $T(t) - T_{\rm amb}$. Además, se define $T_{\rm diff} = T_i - T_{\rm amb}$; por lo que se obtiene finalmente que $T(t) - T_{\rm amb} = T_{\rm diff} \cdot e^{-rt}$.

Se demuestra a continuación un resultado que será de vital importancia para la construcción de un modelo: el logaritmo natural de la nueva variable $T(t) - T_{\rm amb}$ es una función lineal de t.

$$\ln(T(t) - T_{\text{amb}}) = \ln(T_{\text{diff}} \cdot e^{-rt}) = \ln(T_{\text{diff}}) + (-rt) \cdot \ln(e) = \ln(T_{\text{diff}}) - rt = \beta_0 + \beta_1 \cdot t \tag{2}$$

Se puede interpretar a β_0 como el valor del $\ln(T(t) - T_{amb})$ cuando t = 0. Al exponenciar ambos miembros se obtiene que

$$T(t=0) - T_{\rm amb} = e^{\beta_0}$$

Si se toma como tiempo cero el momento de la primera medición, entonces la temperatura del cuerpo en ese momento es igual a $e^{\beta_0} + T_{\rm amb}$

 β_1 es el opuesto de la constante de conductividad. Representa el cambio en el logaritmo de la diferencia entre la temperatura corporal y la temperatura ambiente por cada hora transcurrida.

²Fuente: Fenómenos cadavéricos - Valentina Gómez Hernández

Para determinar la hora de muerte de Sergio, se trabajará con un modelo lineal bayesiano; se determinarán creencias a priori para los parámetros desconocidos para luego actualizarlas con las mediciones de temperatura que se realizaron al cuerpo del hombre. Para este proceso, se considera que la temperatura ambiente (constante a través del tiempo) es de 22°C.

El modelo propuesto incompleto, porque faltan las distribuciónes a priori de sus parámetros, es el siguiente:

$$\begin{cases} \ln(T(t) - T_{\text{amb}}) \sim \mathcal{N}_{(\mu,\sigma)} \\ \mu = \beta_0 + \beta_1 \cdot t \end{cases}$$

Se asignarán distribuciones a priori para los parámetros desconocidos β_0 , β_1 y σ . Si bien μ también es desconocido, no se le asigna un prior propio ya que su valor depende exclusivamente de β_0 y β_1 , de forma que una vez asignados valores para estos dos parámetros, μ queda definido.

Como se menciona en la ecuación (2), β_0 es el $\ln(T_{\rm diff}) = \ln(T_i - T_{\rm amb})$. Se sabe que la temperatura ambiente es de 22°C, mientras que la temperatura inicial del cuerpo se encuentra entre 36,5°C y 37,5°C (temperatura habitual del cuerpo humano). Con esto se puede decir que el valor mínimo para β_0 es $\ln(36,5^{\circ} - 22^{\circ}) = \ln(14,5^{\circ}) = 2,67^{\circ}$, y el máximo es $\ln(37,5^{\circ} - 22^{\circ}) = \ln(15,5^{\circ}) = 2,74^{\circ}$.

Con este rango de valores, se puede suponer a priori una distribución normal para β_0 , de media $\mu_{\beta_0} = \frac{2.74 + 2.67}{2} = 2.705$ y desvío $\sigma_{\beta_0} = \frac{2.74 - 2.705}{3} = 0.012$, quedando así definido su *prior*.

Para definir una distribución para β_1 , se puede utilizar la Figura 1; si bien el gráfico se realizó para una temperatura ambiente 1°C más alta que la actual, las conclusiones son las mismas. Entonces, si un valor razonable para r se encuentra entre 0.1 y 0.2, se puede decir que $\beta_1 = -r$ toma valores entre -0.2 y -0.1.

Si nuevamente se utiliza una distribución normal, se obtiene que $\beta_1 \sim \mathcal{N}(\mu_{\beta_1}, \sigma_{\beta_1})$, con media $\mu_{\beta_1} = \frac{-0.2 - 0.1}{2} = -0.15$ y desvío $\sigma_{\beta_1} = \frac{-0.1 + 0.15}{3} = 0.017$.

Por último, sigma es el desvío del $\ln(T(t) - T_{\rm amb})$. La diferencia máxima entre la temperatura ambiente (22°C) y T(t) se da cuando T(t) es máxima (37,5°). En ese caso, $\ln(37.5-22)=2.74$. La diferencia mínima es de cero grados, y se da cuando la temperatura del cuerpo alcanza la temperatura ambiente, pero ahí el logaritmo no existe.

Como el desvío de una distribución es estrictamente positivo, se propone para el mismo una distribución Half-normal, con desvío $\sigma_{\sigma} = \frac{2.74}{3} = 0.91$.

Por lo tanto, si se consideran independientes los parámetros entre sí, el modelo con las distribuciones a priori propuestas es:

$$\begin{cases} \ln(T(t) - T_{\text{amb}}) \sim \mathcal{N}_{(\mu,\sigma)} \\ \mu = \beta_0 + \beta_1 \cdot t \end{cases}$$

$$\begin{cases} \beta_0 \sim \mathcal{N}_{(2.705,0.012)} \\ \beta_1 \sim \mathcal{N}_{(-0.15,0.017)} \\ \sigma \sim \mathcal{N}_{(0.91)}^+ \end{cases}$$

Se realizan pruebas predictivas a priori para este modelo.

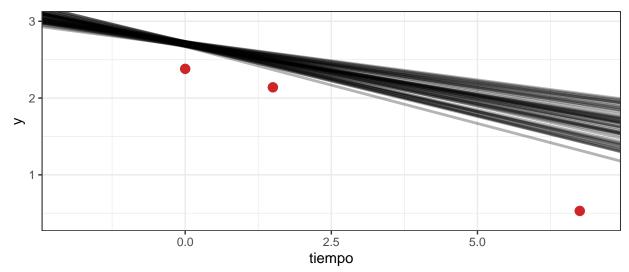


Figura 2: rectas predictivas a priori

Se puede ver que el prior no es tan compatible con las observaciones. La pendiente parece estar bien, pero el β_0 es muy alto.

Primer observación

Se actualiza el modelo con el primer dato observado: la temperatura del cuerpo de Sergio en la primer medición (6:45hs) fue de $32.8^{\circ}C$.

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## Chain 1:
## Chain 1: Elapsed Time: 0.049 seconds (Warm-up)
## Chain 1:
                           0.051 seconds (Sampling)
## Chain 1:
                           0.1 seconds (Total)
## Chain 1:
##
## SAMPLING FOR MODEL 'modelo' NOW (CHAIN 2).
## Chain 2:
## Chain 2: Gradient evaluation took 0 seconds
## Chain 2: 1000 transitions using 10 leapfrog steps per transition would take 0 seconds.
## Chain 2: Adjust your expectations accordingly!
## Chain 2:
## Chain 2:
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## Chain 2:
             Elapsed Time: 0.217 seconds (Warm-up)
## Chain 2:
                             0.058 seconds (Sampling)
## Chain 2:
                             0.275 seconds (Total)
## Chain 2:
## SAMPLING FOR MODEL 'modelo' NOW (CHAIN 3).
## Chain 3:
## Chain 3: Gradient evaluation took 0 seconds
## Chain 3: 1000 transitions using 10 leapfrog steps per transition would take 0 seconds.
## Chain 3: Adjust your expectations accordingly!
## Chain 3:
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## Chain 3:
## Chain 3:
             Elapsed Time: 0.088 seconds (Warm-up)
## Chain 3:
                            0.064 seconds (Sampling)
## Chain 3:
                            0.152 seconds (Total)
##
  Chain 3:
##
## SAMPLING FOR MODEL 'modelo' NOW (CHAIN 4).
## Chain 4:
## Chain 4: Gradient evaluation took 0 seconds
## Chain 4: 1000 transitions using 10 leapfrog steps per transition would take 0 seconds.
## Chain 4: Adjust your expectations accordingly!
## Chain 4:
## Chain 4:
## Chain 4: Iteration:
                           1 / 2000 [
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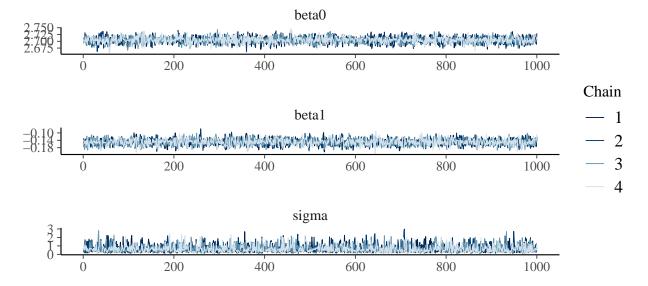
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## Chain 4: Iteration: 1999 / 2000 [ 99%]
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## Chain 4: Iteration: 2000 / 2000 [100%]
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## Chain 4:
## Chain 4:
             Elapsed Time: 0.083 seconds (Warm-up)
## Chain 4:
                            0.072 seconds (Sampling)
## Chain 4:
                            0.155 seconds (Total)
## Chain 4:
## $summary
##
                                                    2.5%
                                                                25%
                                                                           50%
               mean
                          se_mean
                                          sd
## beta0 2.7045725 0.0002025604 0.01175686
                                              2.6812714
                                                         2.6967731
## beta1 -0.1498774 0.0002854266 0.01738852 -0.1832807 -0.1618263 -0.1502502
  sigma 0.6569737 0.0076321750 0.42707839
                                             0.1676122 0.3401691
                                                                     0.5363026
        -1.7514203 0.0270781387 1.13979102 -4.6088348 -2.2997432 -1.4484729
##
##
                75%
                         97.5%
                                   n eff
## beta0 2.7124118
                     2.7274770 3368.788 0.9995626
## beta1 -0.1381890 -0.1157583 3711.391 0.9995771
## sigma 0.8538902 1.7674650 3131.256 1.0005998
         -0.9029628 -0.4559848 1771.792 1.0001817
## lp__
##
## $c_summary
##
   , , chains = chain:1
##
##
            stats
                                                                              75%
##
                                          2.5%
                                                       25%
                                                                  50%
  parameter
                   mean
                                 sd
##
       beta0 2.7043289 0.01182552
                                    2.6801620
                                               2.6965780
                                                           2.7046043
                                                                       2.7121072
       beta1 -0.1504994 0.01693629 -0.1833368 -0.1619215 -0.1506965 -0.1391592
##
```

```
##
      sigma 0.6567892 0.41026165 0.1657910 0.3529705 0.5396843 0.8568346
      lp_ -1.6994866 1.09994893 -4.5874947 -2.2393202 -1.4036101 -0.8805603
##
##
            97.5%
## parameter
      beta0 2.7280201
##
##
      beta1 -0.1192230
      sigma 1.7363385
##
      lp__ -0.4433148
##
##
##
  , , chains = chain:2
##
##
          stats
## parameter mean
                        sd 2.5%
                                             25%
                                                           50%
      beta0 2.7046113 0.01167248 2.6813727 2.6966298 2.7046657 2.7124742
##
      beta1 -0.1501268 0.01688361 -0.1808877 -0.1618484 -0.1505937 -0.1390323
      sigma 0.6722284 0.45424873 0.1692241 0.3446113 0.5371469 0.8765645
##
      lp_ -1.7280866 1.15258786 -4.5843348 -2.2489986 -1.4458961 -0.8713107
##
##
       stats
## parameter 97.5%
      beta0 2.7273986
##
##
      beta1 -0.1161457
##
     sigma 1.9110406
##
      lp__ -0.4607321
##
## , , chains = chain:3
##
          stats
                          sd 2.5%
## parameter mean
                                                 25%
                                                           50%
      beta0 2.7042954 0.01178907 2.6812714 2.6966054 2.7040652 2.7121466
      beta1 -0.1494221 0.01784475 -0.1837326 -0.1622894 -0.1497293 -0.1372279
##
      sigma 0.6531057 0.43310351 0.1647376 0.3271844 0.5314889 0.8515050
##
##
      1p\_\_ -1.8113141 \ 1.15956472 \ -4.8006717 \ -2.3964533 \ -1.5088334 \ -0.9305386
         stats
##
## parameter 97.5%
      beta0 2.7265654
##
##
      beta1 -0.1141382
##
     sigma 1.7999642
##
      lp__ -0.4634172
##
## , , chains = chain:4
##
##
         stats
## parameter mean
                                                           50%
                            sd 2.5%
                                                 25%
      beta0 2.7050542 0.01174173 2.6831146 2.6975224 2.7050345 2.7129069
##
      beta1 -0.1494615 0.01786593 -0.1845714 -0.1610144 -0.1499015 -0.1378454
      sigma 0.6457713 0.40929551 0.1723421 0.3409491 0.5408103 0.8339016
##
##
      lp_ -1.7667938 1.14472117 -4.5883817 -2.3339363 -1.4658365 -0.9282772
##
         stats
## parameter 97.5%
      beta0 2.7276522
##
##
      beta1 -0.1153487
##
      sigma 1.6951329
##
      lp__ -0.4637120
```

Nuestro modelo actualizado con 1 obs es:

$$\begin{cases} \ln(T(t) - T_{\text{amb}}) \sim \mathcal{N}_{(\mu,\sigma)} \\ \mu = \beta_0 + \beta_1 \cdot t \end{cases}$$

$$\begin{cases} \beta_0 \sim \mathcal{N}_{(2.705,0.012)} \\ \beta_1 \sim \mathcal{N}_{(-0.15,0.017)} \\ \sigma \sim \mathcal{N}_{(0.427)}^+ \end{cases}$$



Las cadenas parece que convergen todas

Evaluamos la calidad predictiva del nuevo modelo

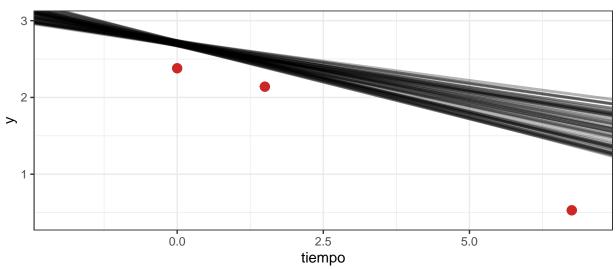


Figura 3: rectas predictivas a posteriori con el modelo 1

Las Figuras 2 y 3 son practicamente iguales porque el modelo no cambia para β_0 y β_1 todas mezcladas. eso es bueno. el sigma no esta tan bueno. RARI recorren bien la distri

es amplio el intervalo de prediccion de horario de muerte. tiene sentido porque el posterior se calculo con una sola observacion. va aprox entre -2.5 y 0 (esto es dos horas con 30 minutos)

Modelo con 2 obs

Ahora, el modelo actualizado es:

$$\begin{cases} \ln(T(t) - T_{\text{amb}}) \sim \mathcal{N}_{(\mu,\sigma)} \\ \mu = \beta_0 + \beta_1 \cdot t \end{cases}$$

$$\begin{cases} \beta_0 \sim \mathcal{N}_{(2.704,0.012)} \\ \beta_1 \sim \mathcal{N}_{(-0.15,0.017)} \\ \sigma \sim \mathcal{N}_{(0.33)}^+ \end{cases}$$

Evaluamos la calidad predictiva del nuevo modelo

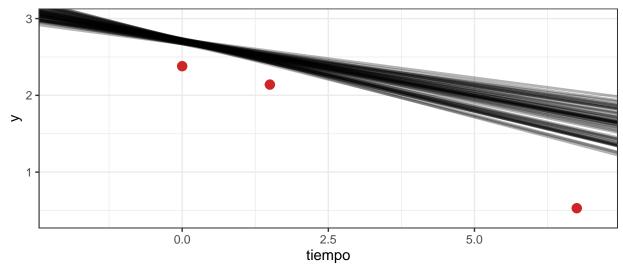


Figura 3: rectas predictivas a posteriori con el modelo 1

este codigo no funciona:

lo que hay que hacer: generar un nuevo modelo stan con los parametros actualizados del que nos dio arriba. copiar y pegar codigo de arriba cambiando el modelo stan y la nueva obs.

media beta0 = 2.5 sd = 0.06

Ahora, el modelo actualizado es:

$$\begin{cases} \ln(T(t) - T_{\text{amb}}) \sim \mathcal{N}_{(\mu,\sigma)} \\ \mu = \beta_0 + \beta_1 \cdot t \end{cases}$$

$$\begin{cases} \beta_0 \sim \mathcal{N}_{(2.705,0.012)} \\ \beta_1 \sim \mathcal{N}_{(-0.15,0.017)} \\ \sigma \sim \mathcal{N}_{(0.33)}^+ \end{cases}$$

Cosas que no entiendo y me da cosa borrar

Punto 5: leer el repo de las diapositivas de clases.(presentaciones -> presentacion_06 -> linea 401 a linea 425)

Se considera a la hora de muerte entre las 4 y las 6 beta0=ln(temp a las 6.45 - 22) temp baja por hora entre 1 y 1.5 si ocurrio a las 4: si vale 1: maximo: 37.2 - 2.45=34.75 minimo 36.1 - 2.45=33.65 si vale 1.5: maximo: 37.2 - 2.451.5=33.525 minimo: 36.1 - 2.45por1.5=32.425 si ocurrio a las 6: si vale 1: maximo: 37.2 - 0.45=36.75 minimo: 36.1 - 0.45=35.65 si vale 1.5: maximo: 37.2 - 0.451.5=36.525 minimo: 36.1 - 0.45*1.5=35.426

cuerpo en la heladera por eso outlier

Teniendo en cuenta la información cronológica presentada al inicio del trabajo, se presenta la tabla 1 (por ponerle un número). Se considera como t=0 al horario en el que se le registra la temperatura por primera vez al cuerpo de Sergio (6:45hs), mientras que los demás tiempos son la diferencia, en minutos, entre esa hora y la hora en la que se tomán las restantes temperaturas (8:15hs y 13:30hs).