sequenza usage example

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1 Abstract

Deep sequence of tumor DNA along with corresponding normal DNA can provide a valuable perspective on the mutations and aberrations that characterize the tumor. However, analysis of this data can be impeded by tumor cellularity and heterogeneity and by unwieldy data. Here we describe *Sequenza*, which comprises a fast python-based pre-processor and an R-based analysis package. *Sequenza* enables the efficient estimation of tumor cellularity and ploidy, and generation of copy number, loss-of-heterozygosity, and mutation frequency profiles.

This document details a typical analysis of matched tumor-normal exome sequence data using *sequenza*.

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2 Getting started

2.1 Minimum requirements

- Software: R, Python
- Operating system: Linux, OSX
- Memory: Minimum 4GB of RAM. Recommended >8GB.
- Disk space: 1.5 GB for sample
- R version: 2.15.1
- Python version: 2.7; rpy2 is required to run sequenza R functions from the python command line programs.

2.2 Installation

In order to install sequenza, you can download the package from the nearest CRAN mirror doing:

```
> install.packages("sequenza")
```

2.3 Workflow overview

A typical workflow developed with Sequenza on pre-aligned sequencing files (BAM format) is structured as follows:

1. Convert pileup to *ABfreq* format
2. GC normalization
3. Allele-specific segmentation using the depth ratio and the B allele frequencies (BAFs)
4. Infer cellularity and ploidy by model fitting
5. Call CNV and variant alleles

2.4 Preparing inputs for Sequenza

In order to obtain precise mutational and aberration patterns in a tumor sample, Sequenza requires a matched normal sample from the same patient. In summary, the following files are needed to get started with Sequenza.

1. A bam file or a derived pileup file from the tumor specimen.
2. A bam file or a derived pileup file from the normal specimen.
3. A FASTA reference genomic sequence file (to extract GC-content information, and to transform bam to pileup if needed.)

We recommend using pre-processed and quality filtered BAM files to obtain pileup calls for both samples.

Pileup files can be generated using `samtools`[2]. The genome sequence file can be obtained from (url).

```
samtools mpileup -f hg19.fasta -Q 20 normal.bam | gzip > normal.pileup.gz
samtools mpileup -f hg19.fasta -Q 20 tumor.bam | gzip > tumor.pileup.gz
```

Alternatively, it is possible to use the output of VarScan2[1] (http://varscan.sourceforge.net), which would require a similar approach and the generation of pileups as well.

2.5 Obtaining the required ABfreq file.

2.5.1 Processing the data with *sequenza-utils.py*.

For convenience and efficiency we have implemented pre-processing algorithms in a standalone (not called from R) Python program. This program is provided with the R package; its exact location can be found like this:

```
> system.file("exec", "sequenza-utils.py", package="sequenza")
```

You may wish to copy this program to a location on your path.

To obtain the GC content information (required to obtain an *ABfreq* file), it is possible to use a function from *sequenza-utils*, and extract the average GC content using a fixed genomic windows, or download the gc5Base from golden path (`http://hgdownload-test.cse.ucsc.edu/goldenPath/hg19/gc5Base/`). The following example calculates GC content for 50 nucleotides windows:

```
sequenza-utils.py GC-windows -w 50 hg19.fa | gzip > hg19.gc50Base.txt.gz
```

When the GC content file is available, it is possible to process the two pileup files to obtain an *ABfreq* file containing genotype information, alleles and mutation frequency, and more other features.

```
sequenza-utils.py pileup2abfreq -gc hg19.gc50Base.txt.gz \
                                -r normal.pileup.gz \
                                -s tumor.pileup.gz | gzip > out.abfreq.gz
```

If you don't yet have the pileup, or you are not interested in storing the pileup for further use, you can use two *FIFO* files, to pipe the samtools output directly to *sequenza-utils*:

```
mkfifo normal.fifo tumor.fifo
samtools mpileup -f hg19.fasta -Q 20 normal.bam > normal.fifo &
samtools mpileup -f hg19.fasta -Q 20 tumor.bam > tumor.fifo &
sequenza-utils.py pileup2abfreq -gc hg19.gc50Base.txt.gz \
                                -r normal.fifo \
                                -s tumor.fifo | gzip > out.abfreq.gz
rm normal.fifo tumor.fifo
```

To compress further the results, it is possible to use a binning function provided in *sequenza-utils*. This would decrease the memory requirement to load all the available positions in memory. as well it would speedup the processing of the sample:

```
sequenza-utils.py abfreq-binning -w 50 \
                                 out.abfreq.gz | gzip > out_small.abfreq.gz
```

Where the parameter *-w* indicate a window size in nucleotides, to be used for the binning. The heterozygous and the position carrying variant calls would remain untouched.

2.5.2 Converting VarScan2 output to ABfreq.

Since many projects might already have been processed with VarScan2, it can be convenient to be able to import such results. For this purpose a simple function is provided within the package, to convert the output of the *somatic* and *copynumber* programs of the VarScan2 suite into the *ABfreq* format.

```
> cnv <- read.table("varscan.copynumber", header = TRUE, sep = "\t")
> snp <- read.table("varscan.snp", header = TRUE, sep = "\t")
> abf.data <- VarScan2abfreq(varscan.somatic = snp, varscan.copynumber = cnv)
> write.table(abf.data, "my.sample.abfreq", col.names = TRUE, row.names = FALSE, sep = "\t")
```

For whole genome sequencing the information in the *varscan.snp* could be enough to estimate the ploidy and cellularity, and define the copy number and mutations, hence the *varscan.copynumber* argument is optional, but it is strongly suggested to use it in case of exome sequencing.

3 Exploring the *ABfreq* file and GC-correction details

After the aligned sequence data have been pre-processed, the *sequenza* R package handles all the normalization and analysis steps. So the following part of this vignette will take place in R.

```
> library("sequenza")
```

3.1 Read the file

In the package we provide an example file, to find the complete path of the example data file:

```
> data.file <-  system.file("data", "abf.data.abfreq.txt.gz", package = "sequenza")
> data.file
```

The ABfreq file can be read all at once, but processing one chromosome at a time is less demanding on computational resources, especially while processing NGS data and might be preferable in case of limited computational resources.

Read only the data corresponding to chromosome 1:

```
> abf.data <- read.abfreq(data.file, chr.name = "1")
```

Alternatively, read all data at once:

```
> abf.data <- read.abfreq(data.file)
```

```
> str(abf.data, vec.len = 2)
```

```
'data.frame':        45003 obs. of  13 variables:
 $ chromosome  : chr  "1" "1" ...
 $ n.base      : int  133037 330227 883223 884960 896946 ...
 $ base.ref    : chr  "T" "G" ...
 $ depth.normal: int  170 9 126 29 151 ...
 $ depth.sample: int  130 13 96 23 131 ...
 $ depth.ratio : num  0.765 1.444 ...
 $ Af          : num  0.573 0.615 0.533 0.524 0.557 ...
 $ Bf          : num  0.427 0.385 0.467 0.476 0.443 ...
 $ ref.zygosity: chr  "het" "het" ...
 $ GC.percent  : num  38 56 50 68 66 ...
 $ good.s.reads: num  124 13 92 21 115 ...
 $ AB.germline : chr  "CT" "CT" ...
 $ AB.sample   : chr  "." "." ...
```

The files can be read even faster; after mapping the chromosomes location in the file, it is possible to select the coordinate (in terms of from line x to line y) of the file to read. See the man page of *read.abfreq* for an example.

3.2 Quality control and normalization

Each aligned base, in the next generation sequencing, is associated with a quality score. The *sequenza-utils* software is capable of filtering the base with a quality score lower then a specified value (default, 20). The number of reads that have passed the filter is returned in the column *good.s.reads*, while the *depth.sample* column contains the raw depth indicated in the pileup.

3.3 GC-normalization

The GC content bias affects most of the samples; however, some samples are more biased than others. We attempt to remove this bias by normalizing with the mean depth ratio value of a corresponding GC content value.

It is possible to gather GC-content information from the entire file and in the meantime map the chromosome position in the file (to fast access chromosome by chromosome later, see ?read.abfreq):

```
> gc.stats <- gc.sample.stats(data.file)
```

```
> str(gc.stats)
```

```
List of 6
 $ raw         : num [1:43, 1:3] 0.625 0.504 0.534 0.406 0.502 ...
  ..- attr(*, "dimnames")=List of 2
  .. ..$ : chr [1:43] "8" "10" "12" "14" ...
  .. ..$ : chr [1:3] "25%" "50%" "75%"
 $ adj         : num [1:43, 1:3] 0.866 0.662 0.775 0.601 0.64 ...
  ..- attr(*, "dimnames")=List of 2
  .. ..$ : chr [1:43] "8" "10" "12" "14" ...
  .. ..$ : chr [1:3] "25%" "50%" "75%"
 $ gc.values   : num [1:43] 8 10 12 14 16 18 20 22 24 26 ...
 $ raw.mean    : Named num [1:43] 0.843 0.829 0.7 0.684 0.821 ...
  ..- attr(*, "names")= chr [1:43] "8" "10" "12" "14" ...
 $ raw.median  : Named num [1:43] 0.722 0.762 0.69 0.675 0.785 ...
  ..- attr(*, "names")= chr [1:43] "8" "10" "12" "14" ...
 $ file.metrics:'data.frame':        23 obs. of  4 variables:
  ..$ chr    : Factor w/ 23 levels "1","10","11",..: 1 12 16 17 18 19 20 21 22 2 ...
  ..$ n.lines: int [1:23] 4542 2728 2396 1822 1775 2370 2178 1425 2087 2430 ...
  ..$ start  : num [1:23] 1 4543 7271 9667 11489 ...
  ..$ end    : num [1:23] 4542 7270 9666 11488 13263 ...
```

Or alternatively, it is possible to collect the GC-contents information from an object already loaded in the environment.

```
> gc.stats <- gc.norm(x = abf.data$depth.ratio,
+                     gc = abf.data$GC.percent)
```

In either case the the normalization to the depth.ratio is performed in the following way:

```
> gc.vect  <- setNames(gc.stats$raw.mean, gc.stats$gc.values)
> abf.data$adjusted.ratio <- abf.data$depth.ratio /
+                            gc.vect[as.character(abf.data$GC.percent)]
```

```
> par(mfrow = c(1,2), cex = 1, las = 1, bty = 'l')
> matplot(gc.stats$gc.values, gc.stats$raw,
+         type = 'b', col = 1, pch = c(1, 19, 1), lty = c(2, 1, 2),
+         xlab = 'GC content (%)', ylab = 'Uncorrected depth ratio')
> legend('topright', legend = colnames(gc.stats$raw), pch = c(1, 19, 1))
> hist2(abf.data$depth.ratio, abf.data$adjusted.ratio,
+       breaks = prettyLog, key = vkey, panel.first = abline(0, 1, lty = 2),
+       xlab = 'Uncorrected depth ratio', ylab = 'GC-adjusted depth ratio')
```

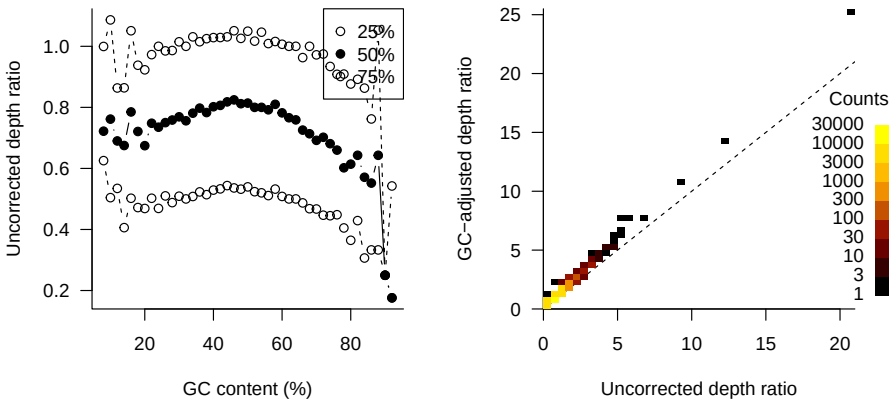

Figure 1: Visualization of depth.ratio bias in relation of GC content (left), and resulting normalization effect (right).

4 Analyzing sequencing data with *sequenza*

The R package *sequenza* offers an ensemble of functions and models that can be used to design customized workflows and analyses. Here we provide generic and most commonly used analysis steps.

- Extract the relevant information from the raw *ABfreq* file.
- Fit the *sequenza* model to infer cellularity and ploidy (ploidy).
- Apply the estimated parameter to detect CNV variant alleles

4.1 Extract the information from the *ABfreq* file.

The function *sequenza.extract* is designed to efficiently access the raw ABfreq data and take care of normalization steps. The arguments enable customization of a set of actions listed below:

- binning depth ratio and B allele frequency in a desired window size (allowing a desired number of overlapping windows);
- performing a fast, allele specific segmentation using the *copynumber* package[3];
- filter mutations by frequency and noise.

```
> test <- sequenza.extract(data.file)
> names(test)
```

After the raw data is processed, the size of the data is considerably reduced. For instance the R object resulting from *sequenza.extract* can be stored as a file of a few megabytes, even for whole genome sequencing data.

The result of this first step consists of a list of lists. All the sub-lists have a different information subdivided by chromosome. Every list share the same chromosome order.

4.1.1 Plot chromosome view with mutations, BAF, depth ratio and segments

Each chromosome can be visualized using the function *chromosome.view* as in Figure 2. The same function can be used to visualize the data after the estimation of *cellularity* and *ploidy* parameters as in Figure 5.

```
> chromosome.view(mut.tab = test$mutations[[1]], baf.windows = test$BAF[[1]],
+                 ratio.windows = test$ratio[[1]], min.N.ratio = 1,
+                 segments = test$segments[[1]], main = test$chromosomes[1])
```

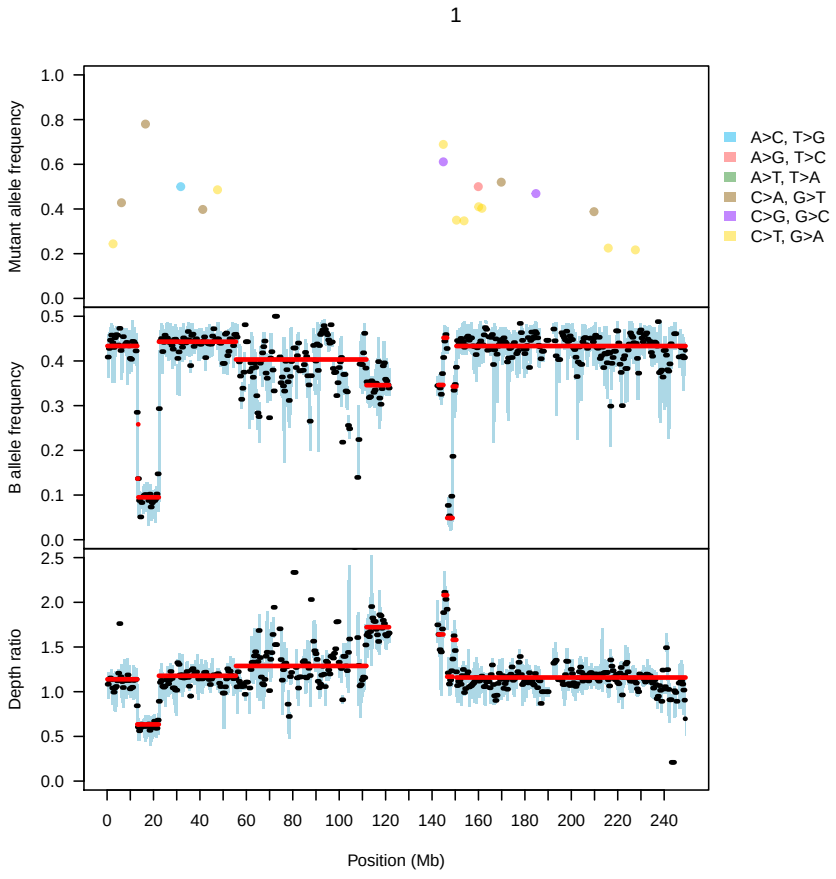

Figure 2: Plots of mutant allele frequency (top), B-allele frequency (middle) and depth ratio (bottom) for chromosome position.

4.2 Inference of cellularity and ploidy

After the raw data is conveniently processed, we can apply the Bayesian inference implemented in the package. The function *sequenza.fit* performs the inference using the calculated B allele frequency and depth ratio of the obtained segments. The method can be explored in more detail by reading the manual pages for the function *baf.model.fit*.

```
> CP.example <- sequenza.fit(test)
```

The result is a list in the format *list(x, y, z)*, which is directly usable by standard graphical functions, such as *image*. However we provide functions to explore and better display the results, and to extract the point estimate and confidence intervals.

4.3 Results of model fitting

The last part of the workflow is to apply the estimated parameters. There is an all-in-one function that plots and saves the results, giving control on file names and output directory:

```
> sequenza.results(sequenza.extract = test, sequenza.fit = CP.example,
+                  sample.id = "Test", out.dir="TEST", )
```

Although this standard way of presenting the result would be appropriate for most situations, it is possible to create an alternative wrapper by using functions in the following sub-sections.

4.3.1 Confidence intervals, confidence region and point estimate

The object resulting from *sequenza.fit* has two vectors, x and y, indicating respectively the tested values of ploidy and cellularity, and a matrix z with x columns and y rows, containing the estimated log-likelihood. Confidence intervals for these two parameters can be calculated using the function *get.ci*.

```
> cint <- get.ci(CP.example)
```

It is also possible to plot the likelihood over the combinations of the two parameters, highlighting the point estimate and the confidence region.

```
> cp.plot(CP.example)
> cp.plot.contours(CP.example, add = TRUE, likThresh = c(0.999))
```

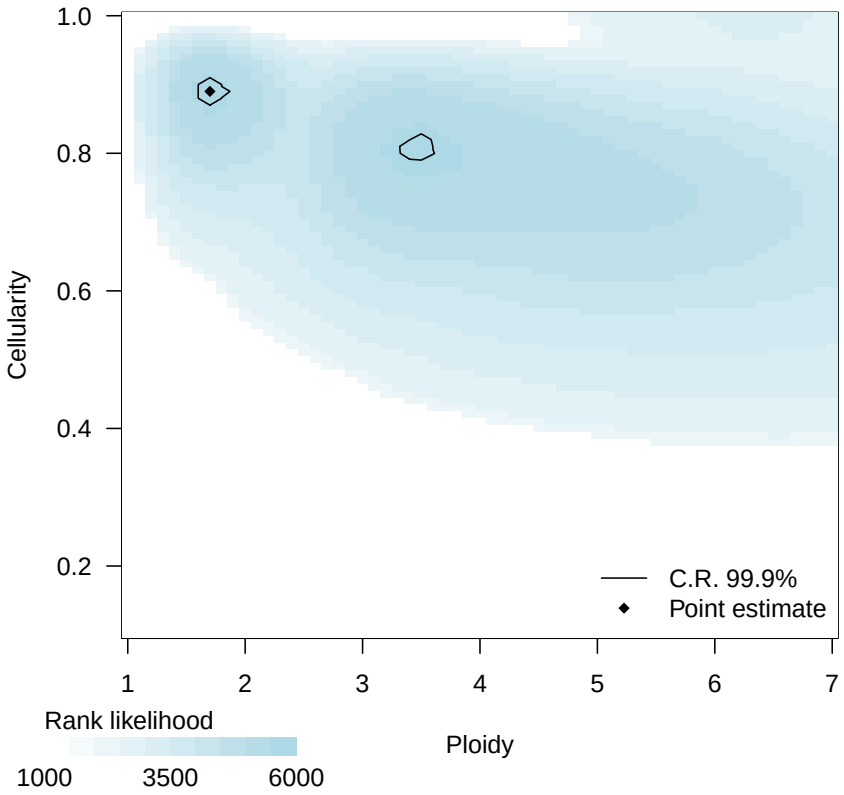

Figure 3: Result from the Bayesian inference over the defined range of cellularity and ploidy. Color intensity indicates the log-likelihood of corresponding cellularity/ploidy values.

By exploring the results for *cellularity* and *ploidy* separately, it is possible to draw the likelihood distribution for each parameter. The information is returned by the *get.ci* function.

```
> par(mfrow = c(2,2))
> cp.plot(CP.example)
> cp.plot.contours(CP.example, add = TRUE)
> plot(cint$values.y, ylab = "Cellularity",
+      xlab = "likelihood", type = "n")
> select <- cint$confint.y[1] <= cint$values.y[,2] &
+           cint$values.y[,2] <= cint$confint.y[2]
> polygon(y = c(cint$confint.y[1], cint$values.y[select, 2], cint$confint.y[2]),
+         x = c(0, cint$values.y[select, 1], 0), col='red', border=NA)
> lines(cint$values.y)
> abline(h = cint$max.y, lty = 2, lwd = 0.5)
> plot(cint$values.x, xlab = "Ploidy",
+      ylab = "likelihood", type = "n")
> select <- cint$confint.x[1] <= cint$values.x[,1] &
+           cint$values.x[,1] <= cint$confint.x[2]
> polygon(x = c(cint$confint.x[1], cint$values.x[select, 1], cint$confint.x[2]),
+         y = c(0, cint$values.x[select, 2], 0), col='red', border=NA)
> lines(cint$values.x)
> abline(v = cint$max.x, lty = 2, lwd = 0.5)
>
```

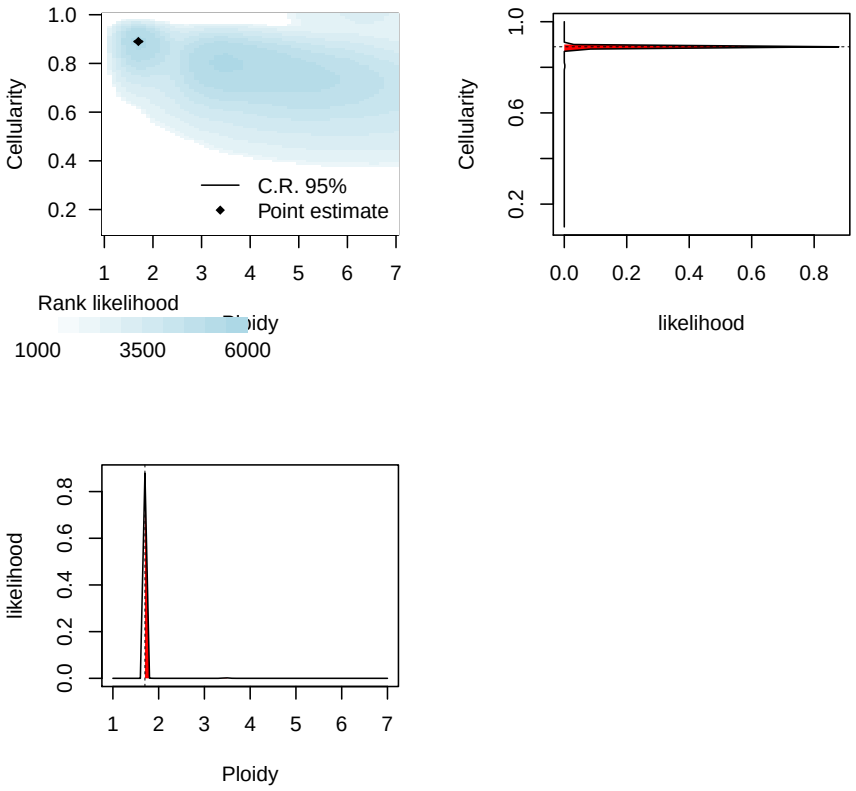

Figure 4: Plot of the log-likelihood with respective cellularity and ploidy probability distribution and confidence intervals.

4.4 Call CNVs and mutations using the estimated parameters

The point estimate value corresponds to the point of maximum likelihood, detected after the confidence interval computation:

```
> cellularity <- cint$max.y
> cellularity
```

```
[1] 0.89
```

```
> ploidy <- cint$max.x
> ploidy
```

```
[1] 1.7
```

In addition we need to calculate the average normalized depth ratio, used to set a value for the baseline copy number.

```
> avg.depth.ratio <- mean(test$gc$adj[, 2])
> avg.depth.ratio
```

```
[1] 1
```

4.4.1 Detect variant alleles (mutations)

To detect variant alleles, we use a mutation frequency model that is implemented as the *mufreq.bayes* function:

```
> mut.tab     <- na.exclude(do.call(rbind, test$mutations))
> mut.alleles <- mufreq.bayes(mufreq = mut.tab$F,
+                             depth.ratio = mut.tab$adjusted.ratio,
+                             cellularity = cellularity, ploidy = ploidy,
+                             avg.depth.ratio = avg.depth.ratio)
> head(mut.alleles)
```

```
   CNn CNt Mt         L
4    2   2  1 -25.30391
41   2   2  1 -12.49285
2    2   1  1 -12.33863
42   2   2  1 -13.30915
43   2   2  1 -12.99802
44   2   2  1 -13.01904
```

```
> head(cbind(mut.tab[,c("chromosome","n.base","F","adjusted.ratio", "mutation")],
+            mut.alleles))
```

```
       chromosome   n.base     F adjusted.ratio mutation
1.95            1  2585089 0.244      1.1393516      C>T
1.162           1  6197233 0.428      1.1393516      G>T
1.673           1 16535060 0.780      0.6341823      G>T
1.1253          1 31740870 0.500      1.1779920      T>G
1.1446          1 41234537 0.398      1.1779920      C>A
1.1576          1 47583731 0.486      1.1779920      C>T
       CNn CNt Mt         L
1.95     2   2  1 -25.30391
1.162    2   2  1 -12.49285
1.673    2   1  1 -12.33863
1.1253   2   2  1 -13.30915
1.1446   2   2  1 -12.99802
1.1576   2   2  1 -13.01904
```

The result consists of four values for every imputed mutation: *CNn* is the provided copy number of the normal sample at the given position (default = 2); *CNt* is the estimated copy number of the tumor at the given position; *Mt* is the estimated numbers of alleles carrying the mutation; *L* is the log-likelihood of the model fit.

4.4.2 Detect copy number variations

To detect copy number variations we use a B allele frequency model, implemented in the function *baf.bayes*, with the estimated parameters of *cellularity* and *ploidy*:

```
> seg.tab     <- na.exclude(do.call(rbind, test$segments))
> cn.alleles <- baf.bayes(Bf = seg.tab$Bf, depth.ratio = seg.tab$depth.ratio,
+                         cellularity = cellularity, ploidy = ploidy,
+                         avg.depth.ratio = avg.depth.ratio)
> head(cn.alleles)
```

```
     CNt A B         L
[1,]   2 1 1 -11.68157
[2,]   1 1 0 -12.28254
[3,]   1 1 0 -26.57928
[4,]   1 1 0 -10.86406
[5,]   2 1 1 -11.61929
[6,]   2 1 1 -12.33114
```

```
> seg.tab <- cbind(seg.tab, cn.alleles)
> head(seg.tab)
```

```
    chromosome start.pos   end.pos         Bf N.BAF
1.1          1    133037  12988756 0.43349084   405
1.2          1  13000305  13380725 0.13668009    50
1.3          1  13380510  13448938 0.25821883     9
1.4          1  13450081  22304519 0.09495172   461
1.5          1  22317088  55523989 0.44303403   624
1.6          1  55524484 111741107 0.40325013   471
    depth.ratio N.ratio CNt A B         L
1.1   1.1393516     430   2 1 1 -11.68157
1.2   0.6345426      57   1 1 0 -12.28254
1.3   0.6341432      10   1 1 0 -26.57928
1.4   0.6341823     541   1 1 0 -10.86406
1.5   1.1779920     646   2 1 1 -11.61929
1.6   1.2879646     538   2 1 1 -12.33114
```

The result consists of four values for every imputed segment: *CNt* is the estimated copy number of the tumor of the given segment; *A* is the estimated number of A alleles; *B* is the estimated number of B alleles; *L* is the log-likelihood of the model fit.

4.5 Visualize detected copy number changes and variant alleles

To visualize the data after detection of CNV and variant alleles, it is possible to use the *chromosome.view*. In order to draw the relative model points (and to evaluate how the estimated model fits the real data) more information is needed compared to Figure 2:

- Each segment must have the columns relative to the copy number variation calling.
- *Cellularity* and *ploidy* estimates.
- Average normalized depth ratio.

```
> chromosome.view(mut.tab = test$mutations[[3]], baf.windows = test$BAF[[3]],
+                 ratio.windows = test$ratio[[3]],  min.N.ratio = 1,
+                 segments = seg.tab[seg.tab$chromosome == test$chromosomes[3],],
+                 main = test$chromosomes[3],
+                 cellularity = cellularity, ploidy = ploidy,
+                 avg.depth.ratio = avg.depth.ratio)
```

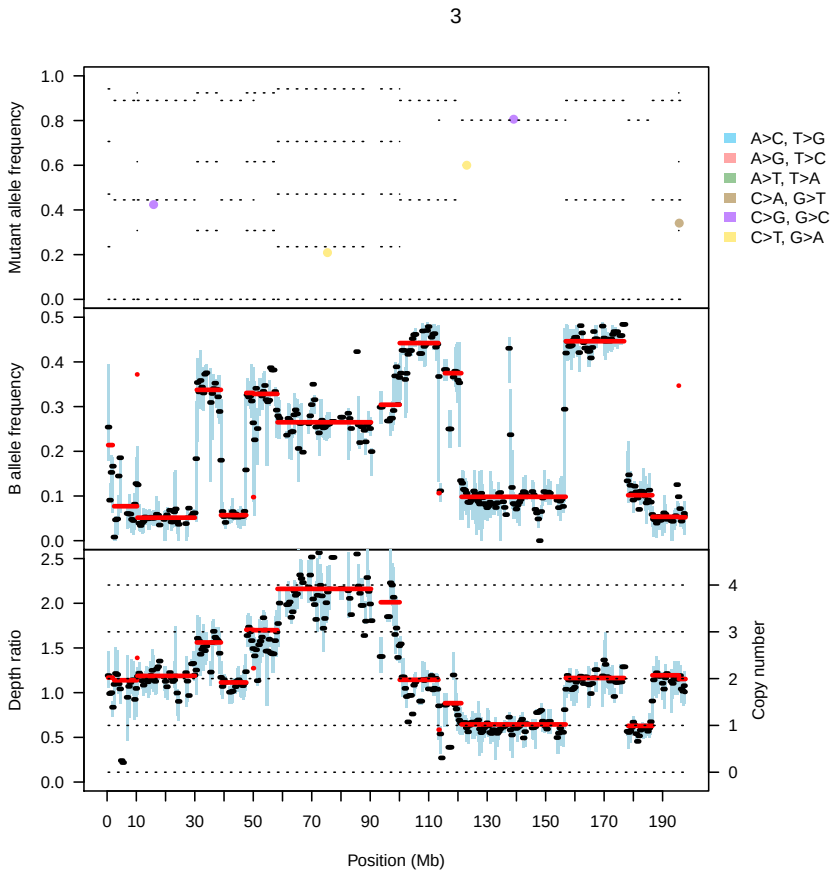

Figure 5: Plots of mutant allele frequency (top), B-allele frequency (middle) and depth ratio (bottom) for chromosome position. Horizontal dotted lines indicate expectation values for various copy number/allele states.

4.5.1 Genome-wide view of the allele and copy number state

```
> genome.view(seg.cn = seg.tab, info.type = "CNt")
> legend("bottomright", bty="n", c("Tumor copy number"),col = c("red"),
+        inset = c(0, -0.4), pch=15, xpd = TRUE)
```

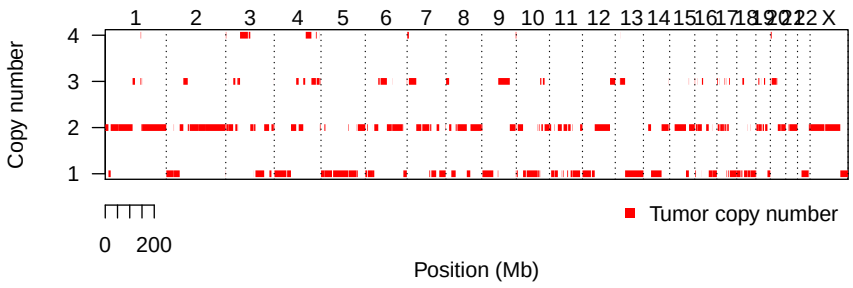

Figure 6: Genome-wide copy number profile obtained from exome sequencing.

```
> genome.view(seg.cn = seg.tab, info.type = "AB")
> legend("bottomright", bty = "n", c("A-allele","B-allele"), col= c("red", "blue"),
+        inset = c(0, -0.45), pch = 15, xpd = TRUE)
```

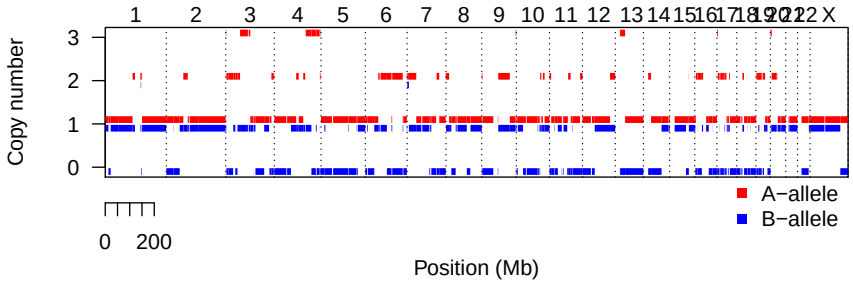

Figure 7: Genome-wide A and B alleles profile obtained from exome sequencing.

References

[1] Daniel C Koboldt, Qunyuan Zhang, David E Larson, Dong Shen, Michael D McLellan, Ling Lin, Christopher A Miller, Elaine R Mardis, Li Ding, and Richard K Wilson. VarScan 2: somatic mutation and copy number alteration discovery in cancer by exome sequencing. *Genome Research*, 22(3):568–76, March 2012.

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