

Analyzing Hi-C data with the *HiTC* BioC package

Nicolas Servant

October 29, 2019

1 Introduction

The Hi-C technic was first introduced by [Lieberman-Aiden et al. \[2009\]](#) to simultaneously detect all chromosomal interactions in a single experiment. The Hi-C aims at measuring the population-averaged frequency at which two genomic loci physically interact in three-dimensional space. Briefly, after a first crosslink and digestion with a restriction enzyme, all genomic fragments are labeled with a biotinylated nucleotide before ligation. These junctions can then be purified efficiently by streptavidin-coated magnetic beads, and finally sequenced using an Illumina paired-end protocol. After sequencing, raw reads have to be processed to generate the inter/intrachromosomal contact maps. The main steps of this processing are described in [Imakaev et al. \[2012\]](#). The raw paired-end reads are first independently aligned on a reference genome. The two mates from the same DNA fragment therefore define the two interacting loci on the genome. Imakaev et al. also proposed an iterative mapping procedure to rescue the reads spanning the ligation junction (and thus containing the two interactors in a single read).

After the reads alignment, the Hi-C molecule generated from the DNA digestion and the ligation products are reconstructed using the position and direction of the sequenced mates. Self-circle ligations, single side reads and dangling ends are discarded, and the valid ligation products aligned to different restriction fragments and face toward the restriction site are used to reconstruct the contact maps. The interaction frequencies are therefore estimated by counting how many times two genomic bins (at a given resolution) were found as interactors. The data resolution usually depends on the sequencing depth. In their first paper, [Lieberman-Aiden et al. \[2009\]](#) generated data at a resolution of 1Mb (up to 100kb) and reveal the compartmentalization of the genome into regions of open and closed (active and inactive) chromatin as well as the three-dimensional structure of the genome (fractal globule). More recently, [Dixon et al. \[2012\]](#) generated 20 to 40kb contact maps in order to go deeper in the conformation structure and to study topological domains ([Nora et al. \[2012\]](#)). The *HiTC* is designed to import processed data as contact maps. In order to generate these maps from raw sequencing reads a couple of pipeline are available on the web. We have recently developed the *HiC-Pro* software which is an optimized pipeline to process Hi-C data from raw reads to normalized contact maps [Servant et al. \[2015\]](#). The outputs of *HiC-Pro* is fully compatible with the *HiTC* package.

Analyzing Hi-C data with the *HiTC* BioC package

This vignette is based on the analysis of the [Dixon et al. \[2012\]](#) contact maps, at a resolution of 40kb. These data are stored as a *HTClist* object, i.e. a list of inter/intrachromosomal contact maps, one for each pair of chromosomes. The goal of this vignette is to describe how the *HiTC* R package can be used to explore such data.

If you use *HiTC* for analyzing your data, please cite:

- Servant N., Lajoie B.R., Nora E.P., Giorgetti L., Chen C., Heard E., Dekker J., Barillot E. (2012) HiTC : Exploration of High-Throughput 'C' experiments. *Bioinformatics*.

2 Working with Hi-C data

The *HTCexp* (High-Throughput 'C' experiment) class aims at representing a single 'C' experiment, characterized by :

- A contact map (i.e a *Matrix*)
- Two *GRanges* objects that describe each features of the contact map, respectively, the x (i.e. columns) and y (i.e. rows) labels of the matrix. In the context of 5C, these two *GRanges* objects will describe the set of forward and reverse primers, and for the Hi-C the binned genomic intervals at a given resolution.

Whereas a 5C dataset is usually composed of a single intrachromosomal contact map (i.e. *HTCexp* object), a Hi-C dataset is represented by a list of inter/intrachromosomal contact maps, characterized by the physical interactions of each pair of chromosomes. The *HTClist* was designed as a list of *HTCexp* objects, with a couple of dedicated methods.

Working at a resolution of 40kb (or even at a lower resolution) can result in an intensive memory usage. Assuming that every restriction fragment could ligate to any other, there are on the order of 10^{11} possible HindIII restriction fragment pairs in the Human genome. In addition to the fact that the generation of a Hi-C library with enough complexity or sequence depth to cover all possible restriction fragment interactions is difficult, this will result in contact maps with a very high level of sparsity. The *HiTC* package provides an efficient memory storage of the data, based on the *sparseMatrix* class and the *Matrix* R package. In addition, binned intrachromosomal maps are expected to be symmetrical around the diagonal and can thus be stored as symmetrical matrix (*dsCMatrix* *Matrix* class). In the same way, the interchromosomal maps are also stored once as the chr1-chr2 map is expected to be the transposed of the chr2-chr1 map.

Analyzing Hi-C data with the *HiTC* BioC package

```
> require(HiTC)
> require(HiCDataHumanIMR90)
> data(Dixon2012_IMR90)
> show(hic_imr90_40)

HTClist object of length 325
25 intra / 300 inter-chromosomal maps

> class(intdata(hic_imr90_40$chr1chr1))

[1] "dsCMatrix"
attr(,"package")
[1] "Matrix"

> object.size(hic_imr90_40)

1209797816 bytes
```

3 Description of the Hi-C data

The *HiTC* package provides several methods to describe a *HTClist* object.

```
> ## Show data
> show(hic_imr90_40)

HTClist object of length 325
25 intra / 300 inter-chromosomal maps

> ## Is my data complete (i.e. composed of intra + the related inter chromosomal maps)
> isComplete(hic_imr90_40)

[1] TRUE

> ## Note that a complete object is not necessarily pairwise
> ## (is both chr1-chr2 and chr2-chr1 stored ?)
> isPairwise(hic_imr90_40)

[1] FALSE

> ## Which chromosomes ?
> seqlevels(hic_imr90_40)

[1] "chr1" "chr2" "chr3" "chr4" "chr5" "chr6" "chr7" "chr8" "chr9"
[10] "chr10" "chr11" "chr12" "chr13" "chr14" "chr15" "chr16" "chr17" "chr18"
[19] "chr19" "chr20" "chr21" "chr22" "chrX" "chrY" "chrM"

> ## Details about a given map
> detail(hic_imr90_40$chr6chr6)
```

Analyzing Hi-C data with the *HiTC* BioC package

```
HTC object
Focus on genomic region [chr6:1-171115067]
CIS Interaction Map
Matrix of Interaction data: [4278-4278]
Binned data - window size = 40000
4278 genome intervals
Total Reads = 21565450
Number of Interactions = 3657661
Median Frequency = 1
Sparsity = 0.1

> ## Descriptive statistics
> head(summary(hic_imr90_40))
```

	seq1	seq2	nbreads	nbinteraction	averagefreq	medfreq	sparsity
chr1chr1	chr1	chr1	25914788	4524734	5.7274	1	0.8835
chr1chr2	chr1	chr2	504332	497291	1.0142	1	0.9869
chr1chr3	chr1	chr3	440865	434917	1.0137	1	0.9859
chr1chr4	chr1	chr4	456924	450005	1.0154	1	0.9849
chr1chr5	chr1	chr5	399067	393926	1.0131	1	0.986
chr1chr6	chr1	chr6	382580	377654	1.013	1	0.9858

4 Hi-C Visualization

The Hi-C data can be visualized as contact maps, representing the contact frequencies between two chromosomes, or at the level of the genome. By default, objects from the *HTClist* class will be represented as an heatmap, whereas object from the *HTCexp* class (i.e. single map) as a triangle. Depending on what you want to visualize the resolution of the map can also be changed (from high to lower resolution).

```
> ## Go back to a smaller dataset (chr21, 22, X) at lower resolution
> sset <- reduce(hic_imr90_40, chr=c("chr5","chr6","chr7"))
> imr90_500 <- HTClist(mclapply(sset, binningC,
+                             binsize=500000, bin.adjust=FALSE, method="sum", step=1))
> mapC(imr90_500)
```

Analyzing Hi-C data with the *HiTC* BioC package



As we can see on this exemple, only half of the inter-chromosomal maps as stored and thus plotted. To display the full pairwise maps, methods such as `forcePairwise`, or `forceSymmetric` can be used to switch from a pairwise (and more memory consuming) form to a reduced form.

```
> mapC(forcePairwise(imr90_500), maxrange=200)
```



5 Hi-C Normalization

5.1 Back to restriction fragments

In addition to descriptive methods on the *HTClist* object, the *HiTC* package provides functions to extract biological information related to the data processing. These functions are useful for data normalization, in order to extract the expected bias at the level of the restriction fragment.

```
> ## Example on chromosome X
> ## GRanges of restriction fragments after HindIII digestion
> resFrag <- getRestrictionFragmentsPerChromosome(resSite="AAGCTT", overhangs=1,
+                                               chromosomes="chr6",
+                                               genomePack="BSgenome.Hsapiens.UCSC.hg18")
> resFrag
```

```
[[1]]
GRanges object with 51298 ranges and 0 metadata columns:
      seqnames      ranges strand
      <Rle>        <IRanges> <Rle>
 [1]   chr6         1-10366    +
 [2]   chr6       10367-18359    +
 [3]   chr6       18360-19010    +
 [4]   chr6       19011-24020    +
 [5]   chr6       24021-25008    +
 ...    ...             ...    ...
[51294] chr6 170887666-170888246    +
[51295] chr6 170888247-170891362    +
[51296] chr6 170891363-170893508    +
[51297] chr6 170893509-170896737    +
[51298] chr6 170896738-170899992    +
-----
seqinfo: 1 sequence from an unspecified genome; no seqlengths
```

5.2 Local genomic feature (LGF) normalization

As any sequencing application, the Hi-C library preparation contains bias, which can be broadly classified as ligation bias and sequence content bias. These effects were first described by [Yaffe and Tanay \[2011\]](#) and require appropriate normalization methods.

[Hu et al. \[2012\]](#) recently proposed a linear model strategy to normalize the data. Their method (named HiCNorm) requires that the bias was inferred from the restriction fragments and then used at the Hi-C resolution. The `getAnnotatedRestrictionSites` function aims at annotating the restriction fragments according to their mappability

Analyzing Hi-C data with the *HiTC* BioC package

(optional), GC content and effective length features. The local genomic features can be then assign to each genomic region, and normalized using the [Hu et al. \[2012\]](#) method.

In the following example, we will focus on chromosome 6 only. The same code can be easily applied on a *HTClist* object using the `mclapply` function. In the same way, we will not use here the mappability information for space issue. In practice, the mappability track can be downloaded from the ENCODE project data, and is important to normalize the Hi-C data.

```
> ## Annotation of genomic features for LGF normalization
> ## Example on chromosome 6
>
> ## Load mappability track
> require(rtracklayer)
> ##map_hg18 <- import("wgEncodeCrgMapabilityAlign100mer_chr6.bw", format="BigWig")
> map_hg18 <- NULL
> cutSites <- getAnnotatedRestrictionSites(resSite="AAGCTT", overhangs=1,
+                                         chromosomes="chr6",
+                                         genomePack="BSgenome.Hsapiens.UCSC.hg18",
+                                         wingc=200, mappability=map_hg18, winmap=500)
> head(cutSites)
```

GRangesList object of length 1:

\$chr6

GRanges object with 51297 ranges and 6 metadata columns:

	seqnames	ranges	strand	len_U	len_D	GC_U
	<Rle>	<IRanges>	<Rle>	<numeric>	<integer>	<matrix>
[1]	chr6	10367-10370	*	10370	7996	0.37
[2]	chr6	18360-18363	*	7996	654	0.385
[3]	chr6	19011-19014	*	654	5013	0.3
[4]	chr6	24021-24024	*	5013	991	0.395
[5]	chr6	25009-25012	*	991	4638	0.345
...
[51293]	chr6	170887666-170887669	*	269	584	0.555
[51294]	chr6	170888247-170888250	*	584	3119	0.555
[51295]	chr6	170891363-170891366	*	3119	2149	0.35
[51296]	chr6	170893509-170893512	*	2149	3232	0.405
[51297]	chr6	170896738-170896741	*	3232	3254	0.555
	GC_D	map_U	map_D			
	<matrix>	<numeric>	<numeric>			
[1]	0.37	<NA>	<NA>			
[2]	0.35	<NA>	<NA>			
[3]	0.26	<NA>	<NA>			
[4]	0.34	<NA>	<NA>			
[5]	0.335	<NA>	<NA>			
...			

Analyzing Hi-C data with the *HiTC* BioC package

```

[51293]    0.465    <NA>    <NA>
[51294]    0.415    <NA>    <NA>
[51295]     0.29    <NA>    <NA>
[51296]     0.33    <NA>    <NA>
[51297]    0.475    <NA>    <NA>
-----
seqinfo: 1 sequence from an unspecified genome; no seqlengths

> ## Annotation of Hi-C object
> imr90_500_chr6annot <- setGenomicFeatures(imr90_500$chr6chr6, cutSites)
> y_intervals(imr90_500_chr6annot)

GRanges object with 343 ranges and 3 metadata columns:
      seqnames      ranges strand |      len
      <Rle>      <IRanges> <Rle> | <numeric>
chr6:1-5e+05      chr6      1-500000    * |    127453
chr6:500001-1e+06 chr6      500001-1000000    * |    124817
chr6:1000001-1500000 chr6      1000001-1500000    * |    103076
chr6:1500001-2e+06 chr6      1500001-2000000    * |    127725
chr6:2000001-2500000 chr6      2000001-2500000    * |    122886
...
chr6:169000001-169500000 chr6 169000001-169500000    * |    110009
chr6:169500001-1.7e+08 chr6 169500001-170000000    * |    110434
chr6:170000001-170500000 chr6 170000001-170500000    * |     68293
chr6:170500001-1.71e+08 chr6 170500001-171000000    * |    114877
chr6:171000001-171115066 chr6 171000001-171115066    * |         0
      GC      map
      <numeric> <numeric>
chr6:1-5e+05    0.419    NaN
chr6:500001-1e+06 0.419    NaN
chr6:1000001-1500000 0.433    NaN
chr6:1500001-2e+06   0.4    NaN
chr6:2000001-2500000 0.394    NaN
...
chr6:169000001-169500000 0.424    NaN
chr6:169500001-1.7e+08 0.411    NaN
chr6:170000001-170500000 0.473    NaN
chr6:170500001-1.71e+08 0.418    NaN
chr6:171000001-171115066  NaN    NaN
-----
seqinfo: 1 sequence from an unspecified genome; no seqlengths

> ## LGF normalization
> imr90_500_LGF <- normLGF(imr90_500_chr6annot)

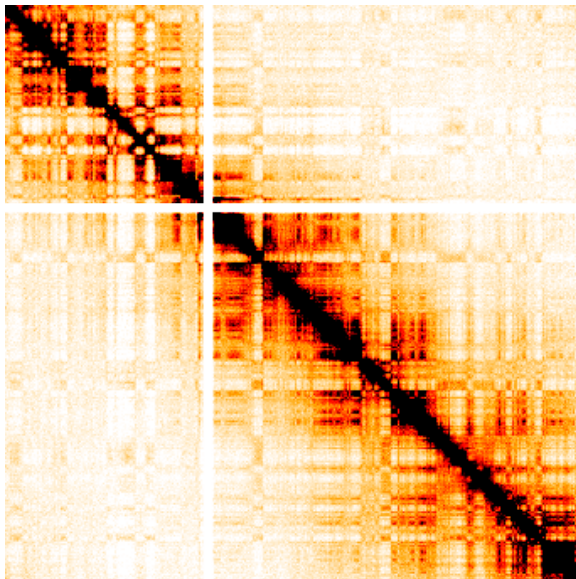
```


5.3 Iterative correction and eigenvector decomposition (ICE) normalization

The ICE normalization is one of the most popular method to correct data from Hi-C bias. This method is based on the assumption of equal visibility of each genomic locus. The matrix of contact probabilities, M , for all given pairs of regions (i,j) is thus normalized such as $\sum_{i,i \neq j, j \pm 1} M_{ij} = 1$ for each region j . Note that running

the ICE normalization method can be memory consuming because it uses the full genome matrix, and then store the bias vectors. If we advice to use apply the ICE normalization on a full Hi-C dataset (using inter and intrachromosomal maps), the *HiTC* package also allows to run it on a single intrachromosomal map.

```
> imr90_500_ICE <- normICE(imr90_500, max_iter=10)
> mapC(HTClist(imr90_500_ICE$chr6chr6), trim.range=.95,
+       col.pos=c("white", "orange", "red", "black"))
```



6 Detection of Topological Domains

Recent studies on a high resolution human and mouse Hi-C dataset have discovered that the genome organization can be further divided into megabase-long and evolutionarily conserved topological domains (TADs), with high frequencies of intra-domain chromatin interactions but infrequent inter-domain chromatin interactions (Nora et al. [2012], Dixon et al. [2012]). More recently, Phillips-Cremins et al. [2013] have demonstrated that the cell-type-specific chromatin organization seems to occur at the sub-megabase scale involving different ligation proteins and epigenomic mech-

Analyzing Hi-C data with the *HiTC* BioC package

anisms.

The following code shows how to focus on TADs, such as the ones describes in IMR90 around the Hox genes.

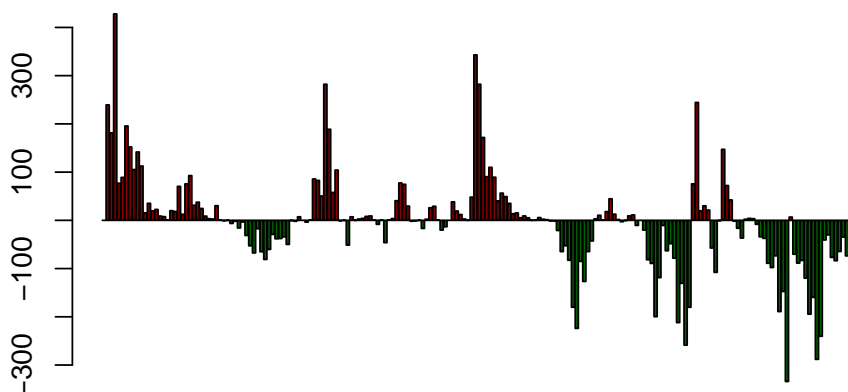
```
> hox <- extractRegion(hic_imr90_40$chr6chr6, chr="chr6", from=50e6, to=58e6)
> plot(hox, maxrange=50, col.pos=c("white", "orange", "red", "black"))
```



Different algorithms have been proposed to detect TADs. The directionality index was proposed by [Dixon et al. \[2012\]](#) as an input to their HMM model.

```
> di<-directionalityIndex(hox)
> barplot(di, col=ifelse(di>0,"darkred","darkgreen"))
```

Analyzing Hi-C data with the *HiTC* BioC package



Package versions

This vignette was generated using the following package versions:

- R version 3.6.1 (2019-07-05), x86_64-apple-darwin15.6.0
- Running under: OS X El Capitan 10.11.6
- Matrix products: default
- BLAS:
/Library/Frameworks/R.framework/Versions/3.6/Resources/lib/libRblas.0.dylib
- LAPACK:
/Library/Frameworks/R.framework/Versions/3.6/Resources/lib/libRlapack.dylib
- Base packages: base, datasets, grDevices, graphics, methods, parallel, stats, stats4, utils
- Other packages: BSgenome 1.54.0, BSgenome.Hsapiens.UCSC.hg18 1.3.1000, BiocGenerics 0.32.0, Biostrings 2.54.0, GenomeInfoDb 1.22.0, GenomicRanges 1.38.0, HiCDataHumanIMR90 1.5.0, HiTC 1.30.0, IRanges 2.20.0, S4Vectors 0.24.0, XVector 0.26.0, rtracklayer 1.46.0
- Loaded via a namespace (and not attached): Biobase 2.46.0, BiocManager 1.30.9, BiocParallel 1.20.0, BiocStyle 2.14.0, DelayedArray 0.12.0, GenomeInfoDbData 1.2.2, GenomicAlignments 1.22.0, Matrix 1.2-17, RColorBrewer 1.1-2, RCurl 1.95-4.12, Rcpp 1.0.2, Rsamtools 2.2.0, SummarizedExperiment 1.16.0, XML 3.98-1.20, bitops 1.0-6, compiler 3.6.1, digest 0.6.22, evaluate 0.14, grid 3.6.1, htmltools 0.4.0, knitr 1.25, lattice 0.20-38, matrixStats 0.55.0, rlang 0.4.1, rmarkdown 1.16, tools 3.6.1, xfun 0.10, yaml 2.2.0, zlibbioc 1.32.0

Analyzing Hi-C data with the *HiTC* BioC package

Acknowledgements

Many thanks to Nelle Varoquaux and Pierre Gestraud for useful discussion and help in developing this R package. Thank you to Ming Hu who developed the HiCNorm method, and help us in the integration of its method in the HiTC package. A special thanks to the *HiTC* users for useful discussions and idea to improve it.

References

- J. R. Dixon, S. Selvaraj, F. Yue, A. Kim, Y. Li, Y. Shen, M. Hu, J. S. Liu, and B. Ren. Topological domains in mammalian genomes identified by analysis of chromatin interactions. *Nature*, Apr 2012. doi: 10.1038/nature11082. URL <http://dx.doi.org/10.1038/nature11082>.
- M. Hu, K. Deng, S. Selvaraj, Z. Qin, B. Ren, and J. S. Liu. Hicnorm: removing biases in hi-c data via poisson regression. *Bioinformatics*, 28(23):3131–3133, Dec 2012. doi: 10.1093/bioinformatics/bts570. URL <http://dx.doi.org/10.1093/bioinformatics/bts570>.
- M. Imakaev, G. Fudenberg, R. P. McCord, N. Naumova, A. Goloborodko, B. R. Lajoie, J. Dekker, and L. A. Mirny. Iterative correction of hi-c data reveals hallmarks of chromosome organization. *Nat Methods*, 9(10):999–1003, Oct 2012. doi: 10.1038/nmeth.2148. URL <http://dx.doi.org/10.1038/nmeth.2148>.
- E. Lieberman-Aiden, N. L. van Berkum, L. Williams, M. Imakaev, T. Ragoczy, A. Telling, I. Amit, B. R. Lajoie, P. J. Sabo, M. O. Dorschner, R. Sandstrom, B. Bernstein, M. A. Bender, M. Groudine, A. Gnirke, J. Stamatoyannopoulos, L. A. Mirny, E. S. Lander, and J. Dekker. Comprehensive mapping of long-range interactions reveals folding principles of the human genome. *Science*, 326(5950):289–293, Oct 2009. doi: 10.1126/science.1181369. URL <http://dx.doi.org/10.1126/science.1181369>.
- E. P. Nora, B. R. Lajoie, E. G. Schulz, L. Giorgetti, I. Okamoto, N. Servant, T. Piolot, N. L. van Berkum, J. Meisig, J. Sedat, J. Gribnau, E. Barillot, N. Bluthgen, J. Dekker, and E. Heard. Spatial partitioning of the regulatory landscape of the x-inactivation centre. *Nature*, Apr 2012. doi: 10.1038/nature11049. URL <http://dx.doi.org/10.1038/nature11049>.
- J. E. Phillips-Cremins, M. E. G. Sauria, A. Sanyal, T. I. Gerasimova, B. R. Lajoie, J. S. K. Bell, C.-T. Ong, T. A. Hookway, C. Guo, Y. Sun, M. J. Bland, W. Wagstaff, S. Dalton, T. C. McDevitt, R. Sen, J. Dekker, J. Taylor, and V. G. Corces. Architectural protein subclasses shape 3d organization of genomes during lineage commitment. *Cell*, 153(6):1281–1295, Jun 2013. doi: 10.1016/j.cell.2013.04.053. URL <http://dx.doi.org/10.1016/j.cell.2013.04.053>.
- N. Servant, N. Varoquaux, B. R. Lajoie, E. Viara, C.-J. Chen, J.-P. Vert, E. Heard, J. Dekker, and E. Barillot. Hic-pro: an optimized and flexible pipeline for hi-c data processing. *Genome Biol*, 16:259, 2015. doi: 10.1186/s13059-015-0831-x. URL <http://dx.doi.org/10.1186/s13059-015-0831-x>.
- E. Yaffe and A. Tanay. Probabilistic modeling of hi-c contact maps eliminates systematic biases to characterize global chromosomal architecture. *Nat Genet*, 43(11):1059–1065, Nov 2011. doi: 10.1038/ng.947. URL <http://dx.doi.org/10.1038/ng.947>.