Assessing the agreement between 3D meshes using `MeshAgreement` for R

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Contents

1 Introduction

`MeshAgreement` is an add-on package for the free statistical environment R[1] (R Development Core Team, 2022). It provides functionality to read 3D mesh files, to calculate distance-based as well as volume-overlap-based agreement measures for 3D structures, and to plot the meshes.

The application motivating development of `MeshAgreement` is to compare delineated structures for radiotherapy treatment planning. In order to export 3D mesh files in PLY format from Varian Eclipse, you can use an ESAPI script included in the package. The path to the script can be found like this - re-run in current R session to find the correct path on a given system:

```
esapi_location <- system.file("extdata", package="MeshAgreement")
list.files(esapi_location, full.names=TRUE)
```

```
## [1] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/0
## [2] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/0
## [3] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/0
```

[1] A free short introduction to R can be found at https://www.statmethods.net/.

```
## [4] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/C
## [5] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/C
## [6] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/C
## [7] "C:/Users/Daniel/AppData/Local/Temp/RtmpYttB51/Rinst13b0bb926a9/MeshAgreement/extdata/e
```

Computational geometry is carried out mainly using the `CGAL` library (CGAL Project, 2022) via package `RcppCGAL` (Dunipace & the CGAL Project, 2022) used in package `cgalMeshes` (Laurent, 2022b). Distance maps are calculated using the `VCG` library (Visual Computing Lab of the Italian National Research Council Institute ISTI, 2022) via package `Rvcg` (Schlager, 2017).

To install `MeshAgreement`, you need a current version of R and be online. Preferably, a free development environment like RStudio (Posit Software, PBC, 2022) should be used.

2 Interfaces

`MeshAgreement` provides two interfaces geared towards users with different levels of familiarity with R: The regular command line functions and a built-in web application.

2.1 R command line interface

Users familiar with R can use the `MeshAgreement` package functions from the R command line. This facilitates statistical post-processing of results with the full capabilities of R. After installing `MeshAgreement`, you should be able to run (function `get_mesh_agree()` is explained in section 4):

```
## load MeshAgreement package - required for all following tasks
library(MeshAgreement, verbose=FALSE)

## get agreement measures for all pairs from list of meshes
## data_heart_obsL: list of sample meshes included in MeshAgreement
heartL <- mesh3dL_to_cgalMeshL(data_heart_obsL)

## omit JSC/DSC to reduce run-time
agreeW <- get_mesh_agree(heartL, do_ui=FALSE, silent=TRUE)
agreeW


##        mesh_1      mesh_2     group  vol_1  vol_2 vol_u vol_i  DCOM
## 1 Obs01_HEART Obs02_HEART strct_001 652173 659869    NA    NA 2.612
## 2 Obs01_HEART Obs03_HEART strct_001 652173 580063    NA    NA 4.778
## 3 Obs02_HEART Obs03_HEART strct_001 659869 580063    NA    NA 2.698
## 4  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462    NA    NA 1.294
## 5  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455    NA    NA 1.874
## 6  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455    NA    NA 3.017
##   HD_max HD_avg    ASD   RMSD JSC DSC
## 1 14.055 13.928 1.4366 2.2942  NA  NA
## 2 14.126 14.112 2.3048 3.7402  NA  NA
## 3 14.135 13.656 2.2127 3.2330  NA  NA
## 4  4.164  3.697 0.7241 0.9642  NA  NA
```

```
## 5  4.305  4.200 1.0613 1.3626  NA  NA
## 6  5.454  5.067 1.5629 1.9340  NA  NA
```

2.2 Web-based graphical user interface

For users who are unfamiliar with R, `MeshAgreement` includes a `Shiny`-based web application (Chang et al., 2022) running locally that eliminates the need to use R syntax.[2] Note that packages `shiny` (Chang et al., 2022), `bs4Dash` (Granjon, 2022), `DT` (Xie, Cheng, & Tan, 2022), `sortable` (de Vries, Schloerke, & Russell, 2022), and `rgl` (Murdoch & Adler, 2022) need to be installed to run the GUI. The different analysis steps are displayed in figures 1, 2, 3, 4, 5, and 6.

```
## install required packages
# install.packages(c("shiny", "bs4Dash", "DT", "sortable", "rgl"))

## load MeshAgreement package
# library(MeshAgreement, verbose=FALSE)

## start Shiny app
# run_gui()
```

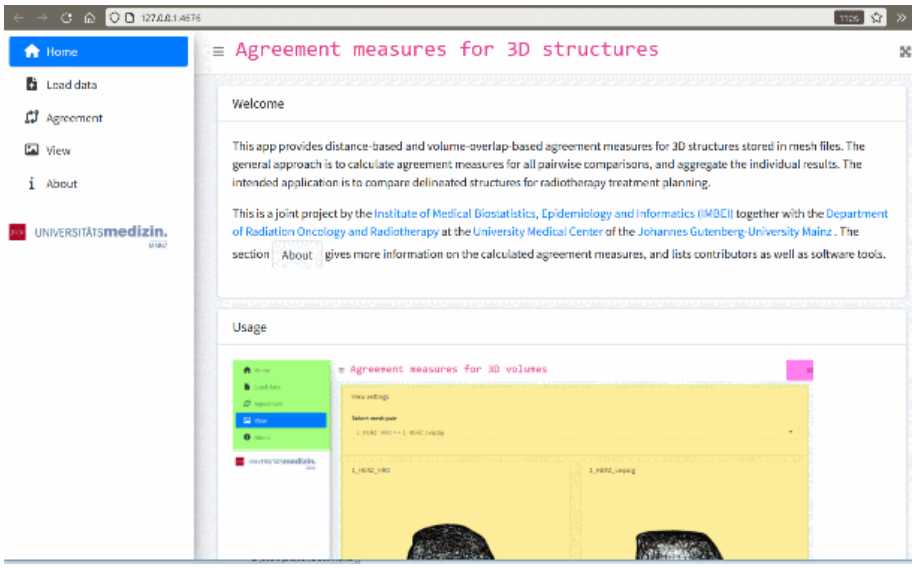

Figure 1: Welcome page in the `MeshAgreement` web application

3 Read mesh files

Supported file formats are STL, PLY, OBJ, and OFF. If the same structures are contoured by three different observers, and the resulting mesh files are stored in three corresponding directories, reading in the observer/mesh list can look like this:

[2] A live demo is available at: http://shiny.imbei.uni-mainz.de:3838/MeshAgreement/

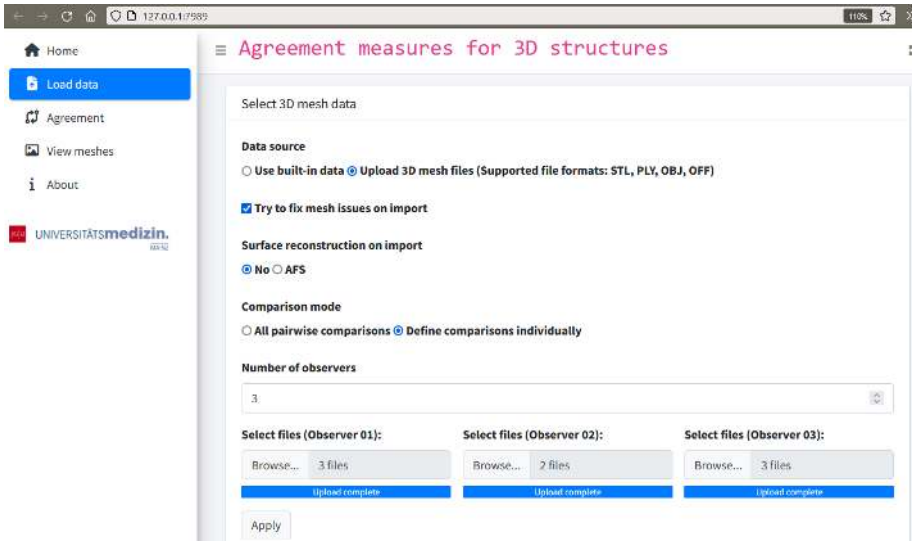

Figure 2: Importing files with options in the `MeshAgreement` web application

```
# ff1 <- list.files("c:/meshes/obs1", pattern="PLY$", full.names=TRUE)
# ff2 <- list.files("c:/meshes/obs2", pattern="PLY$", full.names=TRUE)
# ff3 <- list.files("c:/meshes/obs3", pattern="PLY$", full.names=TRUE)
# obsL <- read_mesh(list(Obs01=ff1, Obs02=ff2, Obs03=ff3),
#                   reconstruct="AFS")
```

If a single structure is contoured by different observers, and all files are stored in the same directory, reading in requires two steps: First, the mesh files are imported into a mesh list, and second, the mesh list is transformed by assigning each mesh to a different observer.

```
# ff    <- list.files("c:/meshes/", pattern="PLY$", full.names=TRUE)
# meshL <- read_mesh_obs(ff)

## assign each mesh to a different observer to enable all
## pairwise comparisons
# obsL <- meshL_to_observerL(meshL)
```

Information on the imported meshes can be printed.

```
## data_heart_obsL: list of sample meshes included in MeshAgreement
heartL <- mesh3dL_to_cgalMeshL(data_heart_obsL)
get_mesh_info(heartL)
```

```
##   observer        name n_verts n_faces volume   ctr_x  ctr_y ctr_z
## 1    Obs01 Obs01_HEART     284     564 652173 18.7108 -45.00 -1379
## 2    Obs01  Obs01_AOKL      71     138  11641 -2.1625 -47.56 -1350
## 3    Obs02 Obs02_HEART     277     550 659869 17.6865 -44.01 -1377
## 4    Obs02  Obs02_AOKL      83     162  11462 -3.3144 -48.15 -1350
## 5    Obs03 Obs03_HEART     279     554 580063 18.5021 -44.38 -1375
## 6    Obs03  Obs03_AOKL     103     202  10455 -0.8261 -46.89 -1349
```

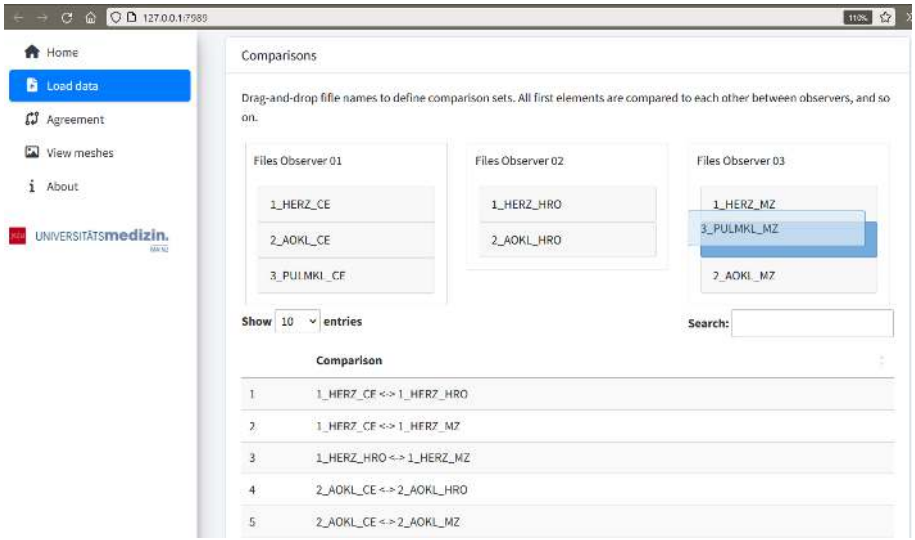

Figure 3: Defining comparisons for agreement measures by drag-and-drop of file lists in the `MeshAgreement` web application

4 Mesh agreement measures

You can calculate distance-based as well as volume-overlap-based agreement measures for all pairwise comparisons between meshes. The following measures are included (Sherer et al., 2021; Heimann & et al., 2009; Fotina, Lütgendorf-Caucig, Stock, Pötter, & Georg, 2012; Babalola et al., 2009; Hanna, Hounsell, & O'Sullivan, 2010; Jaccard, 1912; Dice, 1945):

- Distance-based measures
  - DCOM: Euclidean distance between the respective center of mass of both meshes
  - HDmax: Hausdorff distance - worst case, maximum of both directed Hausdorff distances
  - HDavg: Hausdorff distance - average, arithmetic mean of both directed Hausdorff distances
  - ASD: Average symmetric surface distance
  - RMSD: Root mean squared symmetric surface distance
- Volume-overlap-based measures
  - JSC: Jaccard similarity coefficient
  - DSC: Dice similarity coefficient
  - Note that using package `Boov` (Laurent, 2022a) may have better performance for some meshes than the default `cgalMeshes`. Using `Boov` requires installing package `Boov` as well as setting option `boov=TRUE` when calling agreement functions.

The functions that calculate agreement measures all have two versions.

- The main version of each function operates on an observer/mesh list as generated by `read_mesh()`. These functions are `get_mesh_metro()` as an interface to the `Rvcg::vcgMetro()` distance map function, `get_mesh_ui()` to calculate the structures' union/intersection with corresponding volumes, and `get_mesh_agree()`, which does both of these tasks and summarizes results in a data frame.

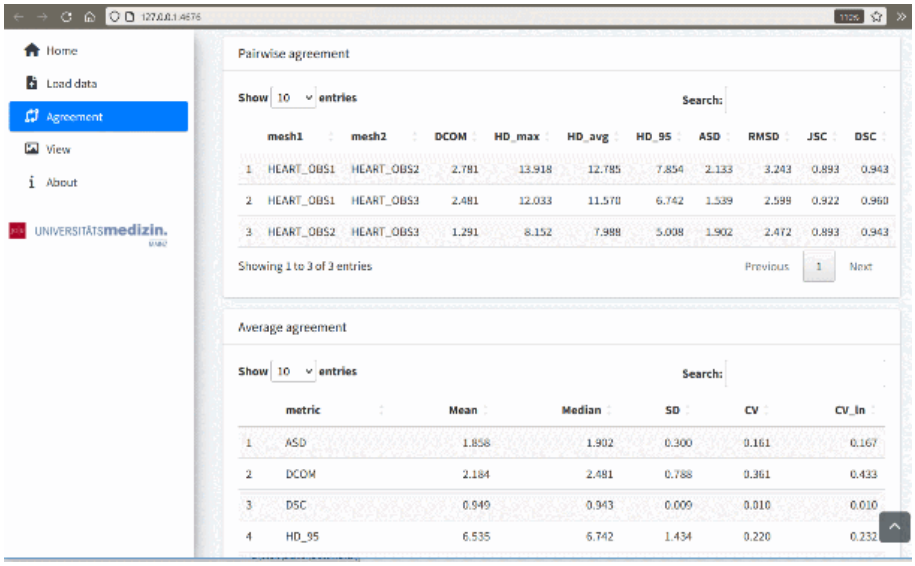

Figure 4: Display distance-based and volume-overlap-based agreement measures for pairwise comparisons as well as as aggregated agreement over all pairs in the `MeshAgreement` web application

- A second version of each function operates on a single pair of meshes as generated by `get_mesh_pairs()`. These functions are `get_mesh_metro_pair()`, `get_mesh_ui_pair()`, and `get_mesh_agree_pair()`.

```
## already called above
# heartL <- mesh3dL_to_cgalMeshL(data_heart_obsL)
# agreeW <- get_mesh_agree(heartL, silent=TRUE)
agreeW
```

```
##        mesh_1      mesh_2     group  vol_1  vol_2 vol_u vol_i  DCOM
## 1 Obs01_HEART Obs02_HEART strct_001 652173 659869    NA    NA 2.612
## 2 Obs01_HEART Obs03_HEART strct_001 652173 580063    NA    NA 4.778
## 3 Obs02_HEART Obs03_HEART strct_001 659869 580063    NA    NA 2.698
## 4  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462    NA    NA 1.294
## 5  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455    NA    NA 1.874
## 6  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455    NA    NA 3.017
##   HD_max HD_avg    ASD   RMSD JSC DSC
## 1 14.055 13.928 1.4366 2.2942  NA  NA
## 2 14.126 14.112 2.3048 3.7402  NA  NA
## 3 14.135 13.656 2.2127 3.2330  NA  NA
## 4  4.164  3.697 0.7241 0.9642  NA  NA
## 5  4.305  4.200 1.0613 1.3626  NA  NA
## 6  5.454  5.067 1.5629 1.9340  NA  NA
```

A utility function transforms the data frame returned by `get_mesh_agree()` to long format which may be more convenient to post-process.

```
agreeL <- get_mesh_agree_long(agreeW)
agreeL
```

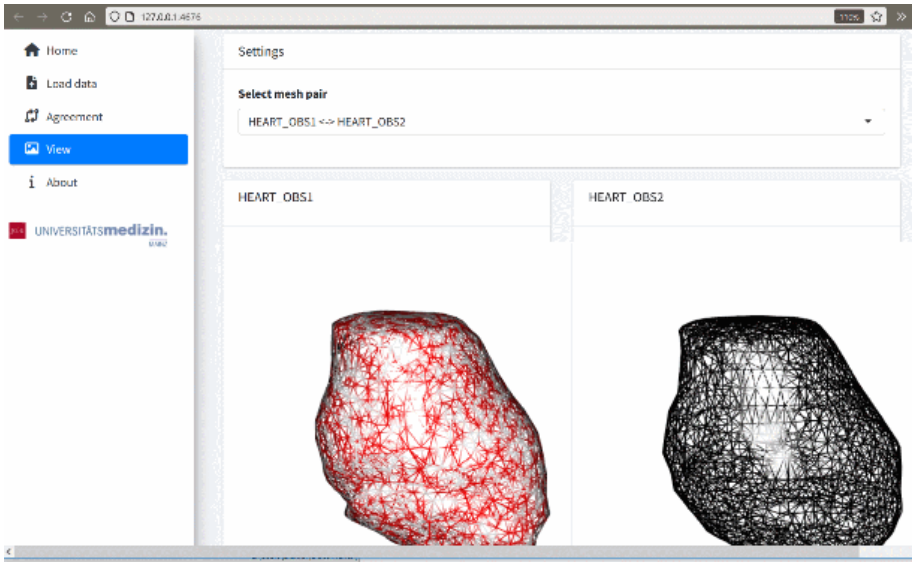

Figure 5: View pairs of imported meshes together with a color-coded distance map in the `MeshAgreement` web application

```
##         mesh_1      mesh_2     group  vol_1  vol_2 metric observed
## 1  Obs01_HEART Obs02_HEART strct_001 652173 659869   DCOM   2.6123
## 2  Obs01_HEART Obs03_HEART strct_001 652173 580063   DCOM   4.7784
## 3  Obs02_HEART Obs03_HEART strct_001 659869 580063   DCOM   2.6983
## 4   Obs01_AOKL  Obs02_AOKL strct_002  11641  11462   DCOM   1.2938
## 5   Obs01_AOKL  Obs03_AOKL strct_002  11641  10455   DCOM   1.8738
## 6   Obs02_AOKL  Obs03_AOKL strct_002  11462  10455   DCOM   3.0174
## 7  Obs01_HEART Obs02_HEART strct_001 652173 659869 HD_max  14.0552
## 8  Obs01_HEART Obs03_HEART strct_001 652173 580063 HD_max  14.1261
## 9  Obs02_HEART Obs03_HEART strct_001 659869 580063 HD_max  14.1345
## 10  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462 HD_max   4.1635
## 11  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455 HD_max   4.3051
## 12  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455 HD_max   5.4539
## 13 Obs01_HEART Obs02_HEART strct_001 652173 659869 HD_avg  13.9283
## 14 Obs01_HEART Obs03_HEART strct_001 652173 580063 HD_avg  14.1124
## 15 Obs02_HEART Obs03_HEART strct_001 659869 580063 HD_avg  13.6563
## 16  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462 HD_avg   3.6970
## 17  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455 HD_avg   4.1998
## 18  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455 HD_avg   5.0675
## 19 Obs01_HEART Obs02_HEART strct_001 652173 659869    ASD   1.4366
## 20 Obs01_HEART Obs03_HEART strct_001 652173 580063    ASD   2.3048
## 21 Obs02_HEART Obs03_HEART strct_001 659869 580063    ASD   2.2127
## 22  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462    ASD   0.7241
## 23  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455    ASD   1.0613
## 24  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455    ASD   1.5629
## 25 Obs01_HEART Obs02_HEART strct_001 652173 659869   RMSD   2.2942
## 26 Obs01_HEART Obs03_HEART strct_001 652173 580063   RMSD   3.7402
## 27 Obs02_HEART Obs03_HEART strct_001 659869 580063   RMSD   3.2330
## 28  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462   RMSD   0.9642
```

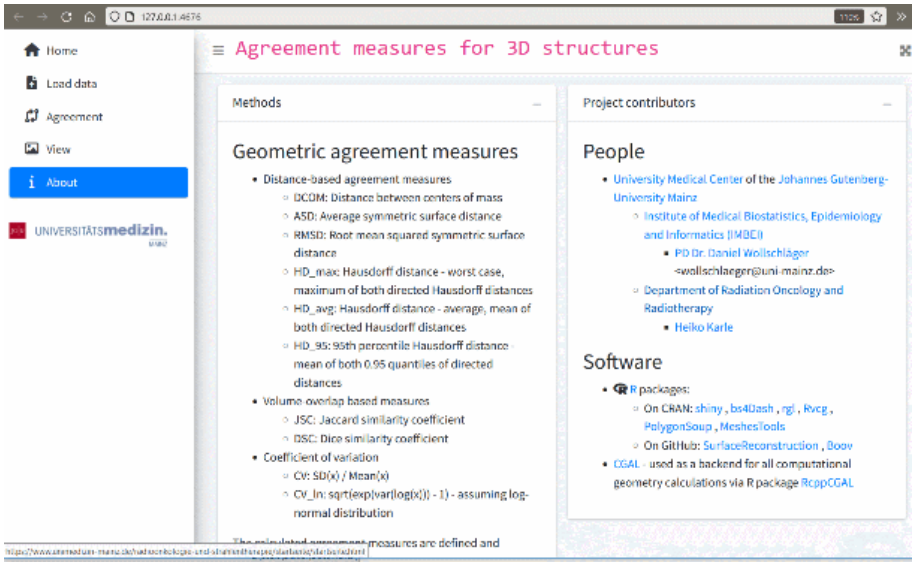

Figure 6: Background information on the `MeshAgreement` web application

```
## 29  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455   RMSD   1.3626
## 30  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455   RMSD   1.9340
## 31 Obs01_HEART Obs02_HEART strct_001 652173 659869  vol_u       NA
## 32 Obs01_HEART Obs03_HEART strct_001 652173 580063  vol_u       NA
## 33 Obs02_HEART Obs03_HEART strct_001 659869 580063  vol_u       NA
## 34  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462  vol_u       NA
## 35  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455  vol_u       NA
## 36  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455  vol_u       NA
## 37 Obs01_HEART Obs02_HEART strct_001 652173 659869  vol_i       NA
## 38 Obs01_HEART Obs03_HEART strct_001 652173 580063  vol_i       NA
## 39 Obs02_HEART Obs03_HEART strct_001 659869 580063  vol_i       NA
## 40  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462  vol_i       NA
## 41  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455  vol_i       NA
## 42  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455  vol_i       NA
## 43 Obs01_HEART Obs02_HEART strct_001 652173 659869    JSC       NA
## 44 Obs01_HEART Obs03_HEART strct_001 652173 580063    JSC       NA
## 45 Obs02_HEART Obs03_HEART strct_001 659869 580063    JSC       NA
## 46  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462    JSC       NA
## 47  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455    JSC       NA
## 48  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455    JSC       NA
## 49 Obs01_HEART Obs02_HEART strct_001 652173 659869    DSC       NA
## 50 Obs01_HEART Obs03_HEART strct_001 652173 580063    DSC       NA
## 51 Obs02_HEART Obs03_HEART strct_001 659869 580063    DSC       NA
## 52  Obs01_AOKL  Obs02_AOKL strct_002  11641  11462    DSC       NA
## 53  Obs01_AOKL  Obs03_AOKL strct_002  11641  10455    DSC       NA
## 54  Obs02_AOKL  Obs03_AOKL strct_002  11462  10455    DSC       NA
```

Agreement measures for all pairwise comparisons for a structure between observers may be aggregated to assess overall agreement.

```
agree_aggrW <- get_mesh_agree_aggr(agreeW)
agree_aggrW
```

```
##        group metric   Mean Median      SD       CV    CV_ln
## 1  strct_001    ASD  1.985  2.213 0.47691 0.240296 0.266515
## 2  strct_001   DCOM  3.363  2.698 1.22652 0.364709 0.349718
## 3  strct_001 HD_avg 13.899 13.928 0.22941 0.016506 0.016534
## 4  strct_001 HD_max 14.105 14.126 0.04353 0.003086 0.003089
## 5  strct_001   RMSD  3.089  3.233 0.73365 0.237497 0.254928
## 6  strct_002    ASD  1.116  1.061 0.42209 0.378192 0.399385
## 7  strct_002   DCOM  2.062  1.874 0.87700 0.425380 0.444355
## 8  strct_002 HD_avg  4.321  4.200 0.69329 0.160430 0.159621
## 9  strct_002 HD_max  4.641  4.305 0.70765 0.152484 0.147962
## 10 strct_002   RMSD  1.420  1.363 0.48745 0.343209 0.358828
```

A utility function transforms the returned data frame to long format which may be more convenient to post-process.

```
agree_aggrL <- get_mesh_agree_aggr_long(agree_aggrW)
agree_aggrL
```

```
##        group metric statistic  observed
## 1  strct_001    ASD      Mean  1.984673
## 2  strct_001   DCOM      Mean  3.363023
## 3  strct_001 HD_avg      Mean 13.898998
## 4  strct_001 HD_max      Mean 14.105270
## 5  strct_001   RMSD      Mean  3.089118
## 6  strct_002    ASD      Mean  1.116085
## 7  strct_002   DCOM      Mean  2.061682
## 8  strct_002 HD_avg      Mean  4.321430
## 9  strct_002 HD_max      Mean  4.640835
## 10 strct_002   RMSD      Mean  1.420278
## 11 strct_001    ASD    Median  2.212678
## 12 strct_001   DCOM    Median  2.698318
## 13 strct_001 HD_avg    Median 13.928299
## 14 strct_001 HD_max    Median 14.126059
## 15 strct_001   RMSD    Median  3.232959
## 16 strct_002    ASD    Median  1.061255
## 17 strct_002   DCOM    Median  1.873818
## 18 strct_002 HD_avg    Median  4.199766
## 19 strct_002 HD_max    Median  4.305101
## 20 strct_002   RMSD    Median  1.362647
## 21 strct_001    ASD        SD  0.476910
## 22 strct_001   DCOM        SD  1.226524
## 23 strct_001 HD_avg        SD  0.229412
## 24 strct_001 HD_max        SD  0.043532
## 25 strct_001   RMSD        SD  0.733655
## 26 strct_002    ASD        SD  0.422095
```

```
## 27 strct_002   DCOM        SD  0.876998
## 28 strct_002 HD_avg        SD  0.693289
## 29 strct_002 HD_max        SD  0.707651
## 30 strct_002   RMSD        SD  0.487452
## 31 strct_001    ASD        CV  0.240296
## 32 strct_001   DCOM        CV  0.364709
## 33 strct_001 HD_avg        CV  0.016506
## 34 strct_001 HD_max        CV  0.003086
## 35 strct_001   RMSD        CV  0.237497
## 36 strct_002    ASD        CV  0.378192
## 37 strct_002   DCOM        CV  0.425380
## 38 strct_002 HD_avg        CV  0.160430
## 39 strct_002 HD_max        CV  0.152484
## 40 strct_002   RMSD        CV  0.343209
## 41 strct_001    ASD     CV_ln  0.266515
## 42 strct_001   DCOM     CV_ln  0.349718
## 43 strct_001 HD_avg     CV_ln  0.016534
## 44 strct_001 HD_max     CV_ln  0.003089
## 45 strct_001   RMSD     CV_ln  0.254928
## 46 strct_002    ASD     CV_ln  0.399385
## 47 strct_002   DCOM     CV_ln  0.444355
## 48 strct_002 HD_avg     CV_ln  0.159621
## 49 strct_002 HD_max     CV_ln  0.147962
## 50 strct_002   RMSD     CV_ln  0.358828
```


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The authors thank Stéphane Laurent, Eric Dunipace and Stefan Schlager for creating the necessary R packages for handling 3D meshes with methods from the CGAL and VCG libraries.

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