

Diffusion-weighted magnetic resonance imaging in partially nephrectomized kidneys

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Materials and Methods

Overview of available Data

Table 1: Data overview

Patient	Datasets	KidneyR	KidneyL	Klemmzeit
Aral	3	h	s	10
Berger	3	h	s	10
Suskic	3	s	h	0
Labis	3	h	s	18
Katynski	3	h	s	20
Liedtke	3	h	s	29
Nuetzel	3	h	s	19
Ayvaz	2	h	s	17
Stoer	2	h	s	14
Schellerer	2	s	h	4
Heider	2	h	s	12
Wagner	2	s	h	18
Hoenig	2	s	h	15
Schmidt	2		s	23
Reinert	2	h	s	28

h = healthy, s = sick

Quantification Method

Fractional Anisotropy

The pattern used for the diffusion gradient directions (passing through the vertices of a regular 14-sided polygon) allowed for a simplified calculation of the diffusion tensor as described by Basser et al.(1998). Prior to calculation the diffusion tensor elements, the DWI images were rigidly registered along the b-value dimension using a Fourier cross-correlation method to limit the effect of bulk-motion. Subsequently, images with matching diffusion gradients (number of averages = 2) were averaged and afterwards images were registered once more before calculating the tensor elements and the fractional anisotropy (FA):

$$FA = \sqrt{\frac{1}{2} \frac{\sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_3 - \lambda_1)^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}}, \text{ with the tensor eigenvalues } \lambda_1, \lambda_2, \lambda_3.$$

The median value inside multi-slice (min. 3 slices) regions of interest encompassing the kidney cortex was then used as representative value for the fractional anisotropy.

ADC, IVIM and Kurtosis

Trace-weighted images for each b-value were calculated using the registered DWI images and afterwards registered once more before using a monoexponential model $S(b) = S_0 \cdot e^{-b \cdot ADC}$ fit to calculate ADC s and a segmented biexponential fitting approach[2] to calculate voxelwise IVIM parameters $S(b) = S_0 \cdot (f \cdot e^{-b \cdot (D_{slow} + D_{fast})} + (1 - f) \cdot e^{-b \cdot D_{slow}})$; with tissue diffusion D_{slow} , perfusion induced pseudodiffusion D_{fast} and the perfusion fraction f , representing the proportion of the initial signal intensity S_0 attributed to blood). The kurtosis parameter K was estimated by fitting the Signal intensities to the kurtosis model: $S(b) = S_0 \cdot e^{(-b \cdot D_k + K/6 \cdot (b \cdot D_k)^2)}$. Analogous to the fractional anisotropy, median value inside multi-slice (min. 3 slices) regions of interest encompassing the kidney cortex was then used as representative value for each parameter, respectively.

Statistical Analyses

To compare parameters between baseline and follow-up measurement the paired Wilcoxon signed-rank test was used, to compare non-nephrectomized and partially nephrectomized kidneys the non-paired Mann-Whitney U test was used. P-values of less than 0.05 were considered statistically significant.

Linear correlations were calculated between ADC , f , FA and $K_{kurtosis}$.

Results

Parameter Values

ADC

Median ADC values in the non-nephrectomized kidneys showed an initial increase from $2.47 \frac{mm^2}{10^3s}$ to $2.66 \frac{mm^2}{10^3s}$ ($p = 0.0031$) and a subsequent decrease to $2.57 \frac{mm^2}{10^3s}$ ($p = 0.016$).

Table 2: ADC values in non-nephrectomized kidneys

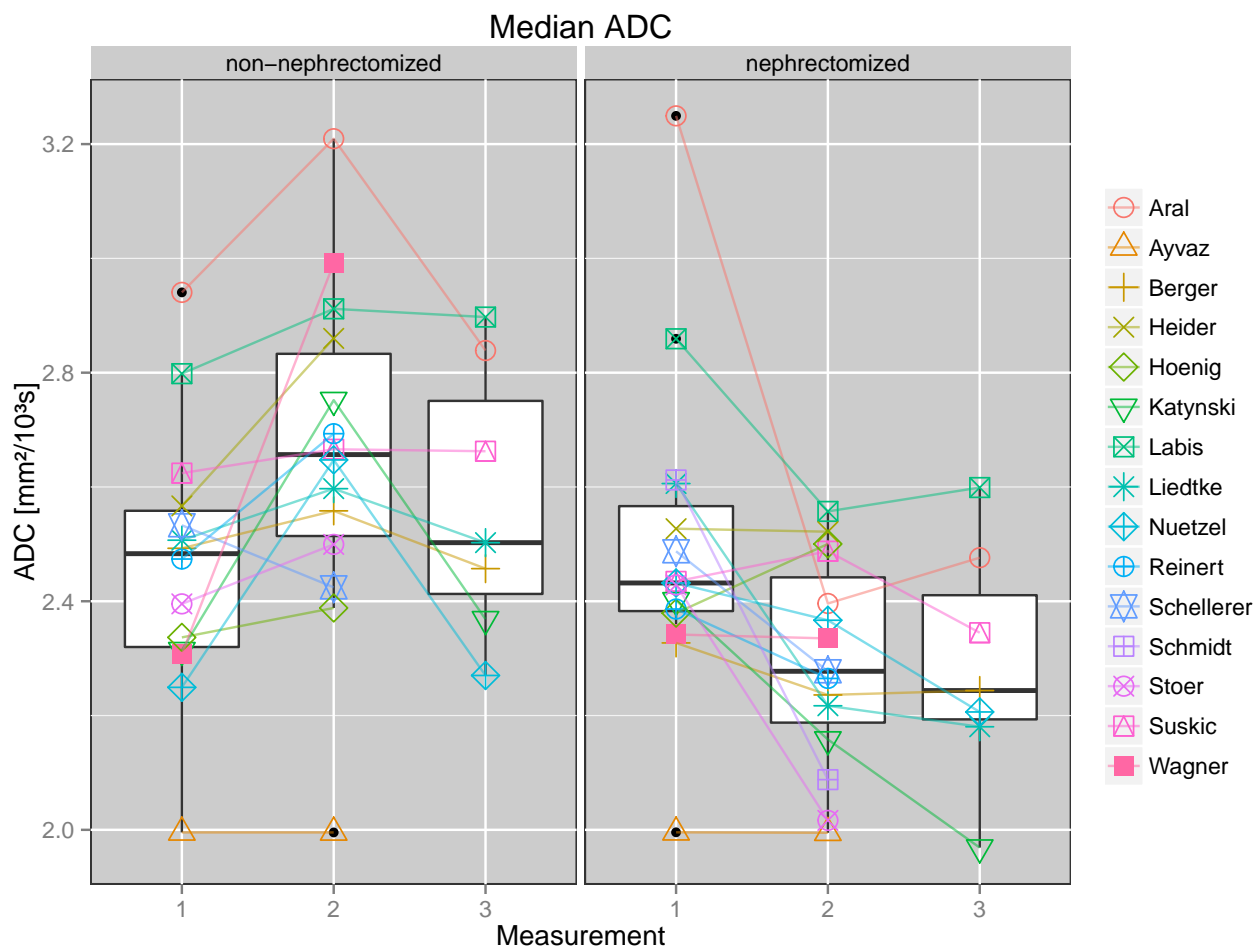
Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	2.941	0.269	3.209	-0.371	2.839
Berger	2.493	0.066	2.558	-0.101	2.457
Suskic	2.624	0.042	2.666	-0.003	2.663
Labis	2.798	0.113	2.912	-0.014	2.897
Katynski	2.314	0.438	2.752	-0.383	2.369
Liedtke	2.507	0.090	2.597	-0.094	2.503
Nuetzel	2.249	0.398	2.647	-0.377	2.270
Ayvaz	1.995	-0.0001	1.995		
Stoer	2.395	0.104	2.499		
Schellerer	2.533	-0.109	2.424		
Heider	2.567	0.293	2.860		
Wagner	2.308	0.684	2.991		
Hoenig	2.337	0.052	2.388		
Reinert	2.474	0.219	2.693		

Median ADC values in the nephrectomized kidneys showed an initial decrease from $2.5 \frac{mm^2}{10^3s}$ to $2.29 \frac{mm^2}{10^3s}$ ($p = 0.0034$) and subsequently remained constant ($2.29 \frac{mm^2}{10^3s}$; $p = 0.38$).

Table 3: ADC values in nephrectomized kidneys

Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	3.249	-0.853	2.396	0.080	2.476
Berger	2.327	-0.091	2.236	0.008	2.244
Suskic	2.435	0.053	2.488	-0.143	2.345
Labis	2.859	-0.302	2.557	0.042	2.599
Katynski	2.402	-0.244	2.158	-0.189	1.969
Liedtke	2.606	-0.389	2.217	-0.037	2.180
Nuetzel	2.432	-0.065	2.367	-0.160	2.206
Ayvaz	1.996	-0.001	1.995		
Stoer	2.429	-0.412	2.017		
Schellerer	2.487	-0.210	2.277		
Heider	2.527	-0.005	2.522		
Wagner	2.342	-0.007	2.335		
Hoenig	2.379	0.121	2.500		
Schmidt	2.612	-0.524	2.088		
Reinert	2.386	-0.121	2.265		

While the comparison of ADC values between nephrectomized and non-nephrectomized kidneys revealed no significant difference for the baseline measurement ($p = 0.88$), second and third measurements showed significantly higher median ADC in non-nephrectomized kidneys ($p = 2.8 \times 10^{-4}$ and $p = 2.8 \times 10^{-4}$).

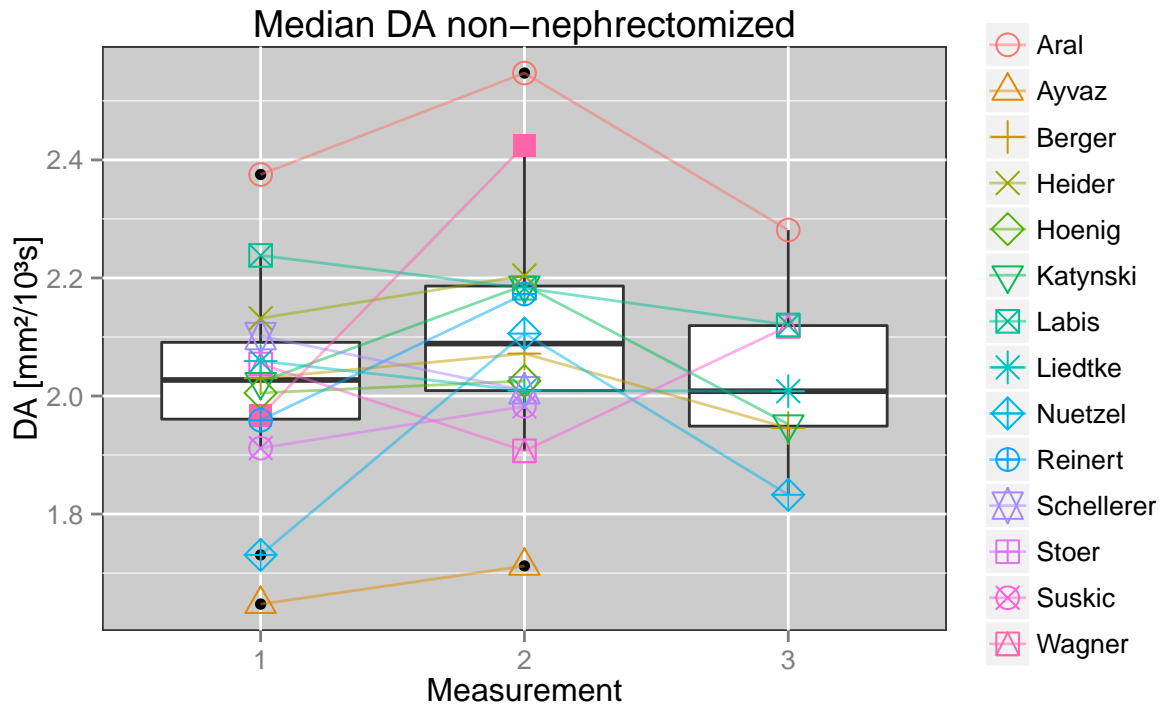


DA

Mean DA values in the non-nephrectomized kidneys showed an initial increase from $2.02 \frac{\text{mm}^2}{10^3 \text{s}}$ to $2.11 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=0.078$) and a subsequent decrease to $2.04 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=0.11$).

Table 4: DA values in non-nephrectomized kidneys

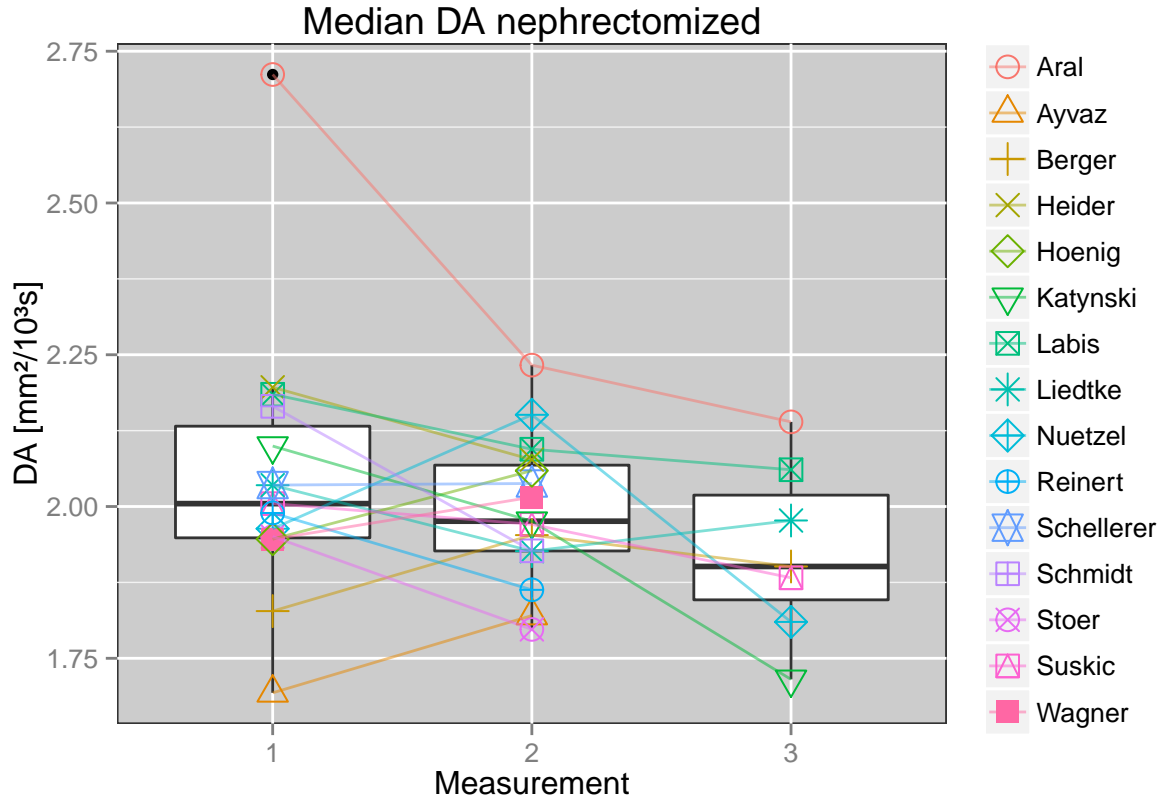
Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	2.375	0.172	2.547	-0.266	2.281
Berger	2.030	0.042	2.072	-0.126	1.946
Suskic	2.054	-0.147	1.907	0.211	2.118
Labis	2.238	-0.056	2.183	-0.062	2.120
Katynski	2.024	0.163	2.188	-0.235	1.952
Liedtke	2.059	-0.050	2.009	-0.001	2.008
Nuetzel	1.731	0.375	2.106	-0.273	1.833
Ayvaz	1.647	0.065	1.712		
Stoer	1.912	0.071	1.983		
Schellerer	2.101	-0.092	2.010		
Heider	2.132	0.072	2.204		
Wagner	1.967	0.458	2.425		
Hoenig	2.005	0.020	2.025		
Reinert	1.959	0.214	2.173		



Mean DA values in the nephrectomized kidneys showed an initial decrease from $2.05 \frac{mm^2}{10^3s}$ to $1.99 \frac{mm^2}{10^3s}$ ($p=0.36$) and a further subsequent decrease to $1.93 \frac{mm^2}{10^3s}$ ($p=0.047$).

Table 5: DA values in nephrectomized kidneys

Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	2.712	-0.479	2.233	-0.093	2.139
Berger	1.828	0.125	1.953	-0.052	1.901
Suskic	2.005	-0.034	1.971	-0.088	1.883
Labis	2.185	-0.090	2.094	-0.034	2.061
Katynski	2.100	-0.124	1.976	-0.261	1.715
Liedtke	2.035	-0.109	1.927	0.050	1.977
Nuetzel	1.963	0.188	2.151	-0.341	1.810
Ayvaz	1.693	0.127	1.820		
Stoer	1.950	-0.153	1.798		
Schellerer	2.035	0.003	2.038		
Heider	2.196	-0.119	2.077		
Wagner	1.946	0.069	2.015		
Hoenig	1.946	0.113	2.059		
Schmidt	2.165	-0.238	1.927		
Reinert	1.989	-0.127	1.863		

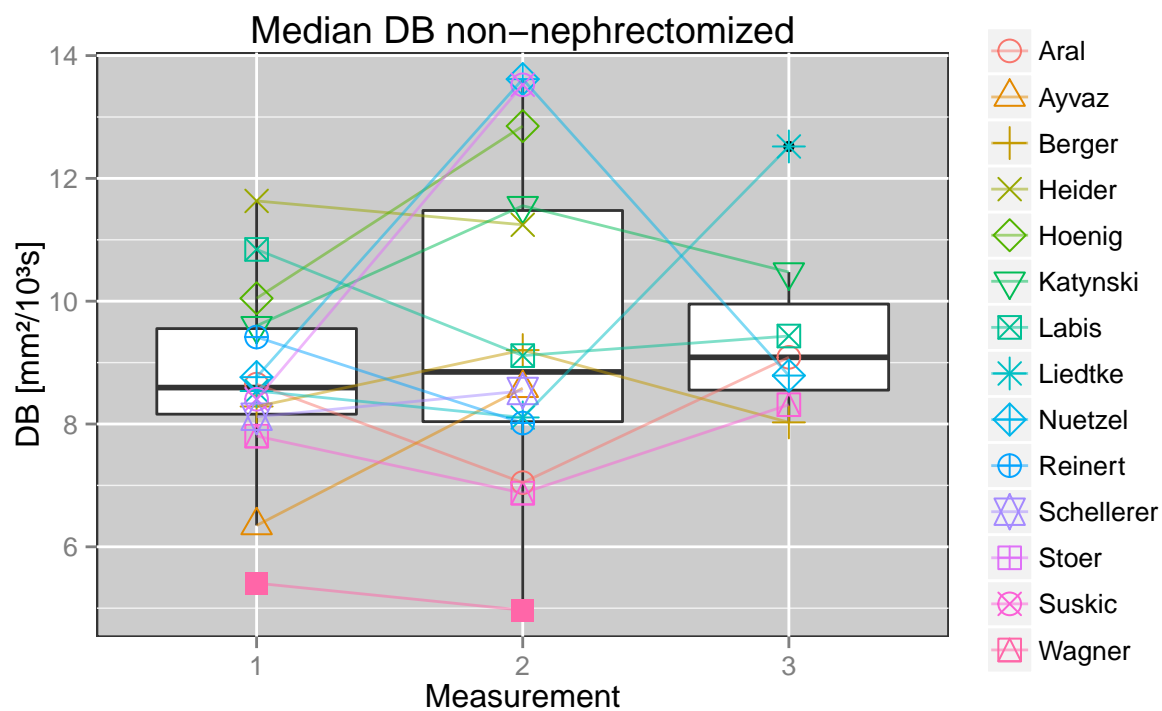


DB

Mean DB values in the non-nephrectomized kidneys showed an initial increase from $8.7 \frac{\text{mm}^2}{10^3 \text{s}}$ to $9.52 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=0.39$) and subsequently remained constant ($9.52 \frac{\text{mm}^2}{10^3 \text{s}}$; $p=0.81$).

Table 6: DB values in non-nephrectomized kidneys

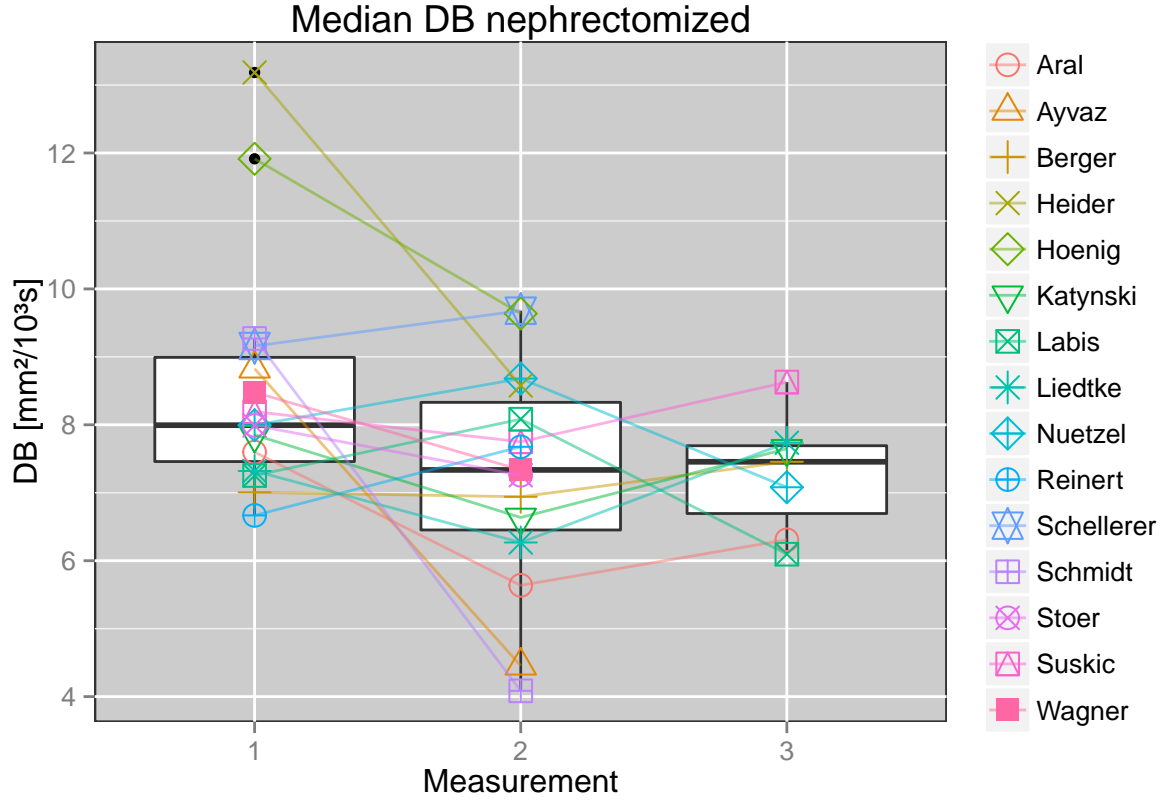
Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	8.649	-1.604	7.045	2.041	9.086
Berger	8.285	0.918	9.203	-1.177	8.027
Suskic	7.803	-0.929	6.875	1.440	8.315
Labis	10.843	-1.730	9.114	0.319	9.433
Katynski	9.600	1.955	11.555	-1.081	10.474
Liedtke	8.537	-0.430	8.107	4.413	12.520
Nuetzel	8.763	4.854	13.616	-4.828	8.789
Ayvaz	6.348	2.235	8.583		
Stoer	8.403	5.121	13.524		
Schellerer	8.118	0.420	8.538		
Heider	11.633	-0.388	11.245		
Wagner	5.408	-0.440	4.968		
Hoenig	10.047	2.804	12.852		
Reinert	9.416	-1.400	8.016		



Mean DB values in the nephrectomized kidneys showed an initial decrease from $8.58 \frac{mm^2}{10^3s}$ to $7.25 \frac{mm^2}{10^3s}$ ($p=0.022$) and subsequently remained constant ($7.28 \frac{mm^2}{10^3s}$; $p=0.94$).

Table 7: DB values in nephrectomized kidneys

Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	7.598	-1.961	5.638	0.670	6.308
Berger	7.006	-0.065	6.941	0.515	7.456
Suskic	8.194	-0.444	7.750	0.879	8.629
Labis	7.254	0.828	8.082	-1.986	6.096
Katynski	7.852	-1.216	6.636	1.011	7.647
Liedtke	7.320	-1.052	6.268	1.468	7.736
Nuetzel	7.994	0.686	8.681	-1.600	7.081
Ayvaz	8.825	-4.371	4.454		
Stoer	7.991	-0.733	7.258		
Schellerer	9.160	0.519	9.679		
Heider	13.185	-4.606	8.579		
Wagner	8.479	-1.143	7.336		
Hoenig	11.914	-2.277	9.637		
Schmidt	9.271	-5.186	4.085		
Reinert	6.667	1.009	7.676		

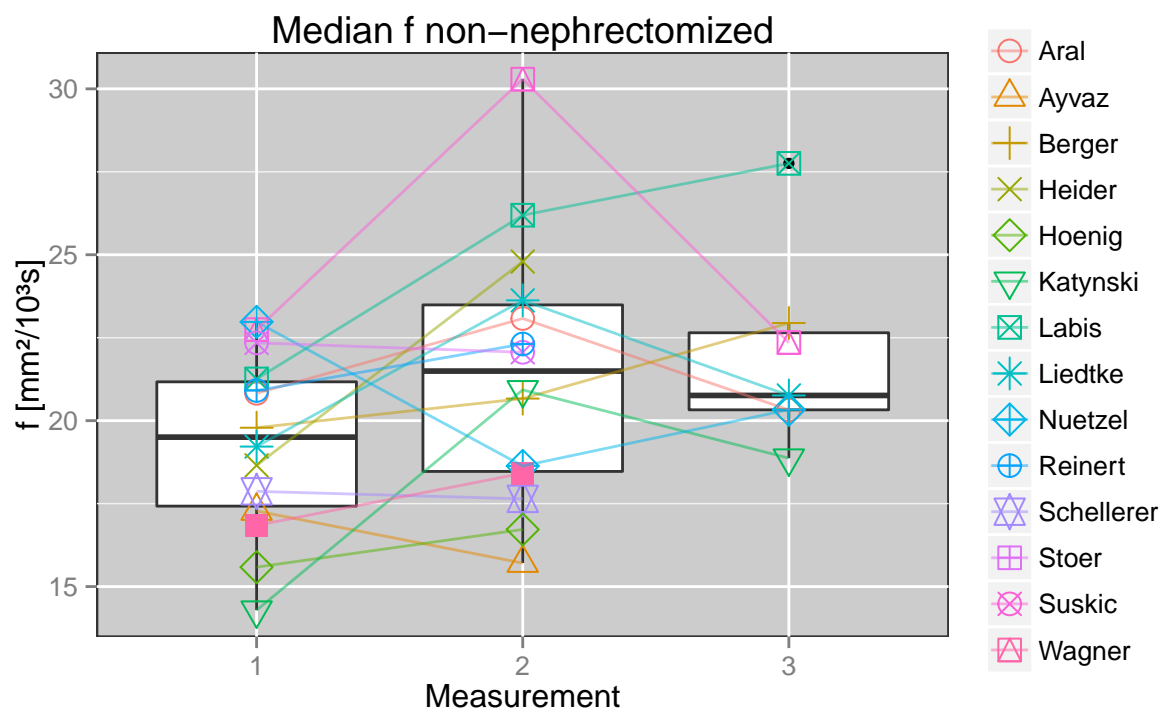


f

Mean f values in the non-nephrectomized kidneys showed an initial increase from $19.3 \frac{mm^2}{10^3s}$ to $21.5 \frac{mm^2}{10^3s}$ ($p=0.03$) and a subsequent increase to $21.9 \frac{mm^2}{10^3s}$ ($p=0.3$).

Table 8: f values in non-nephrectomized kidneys

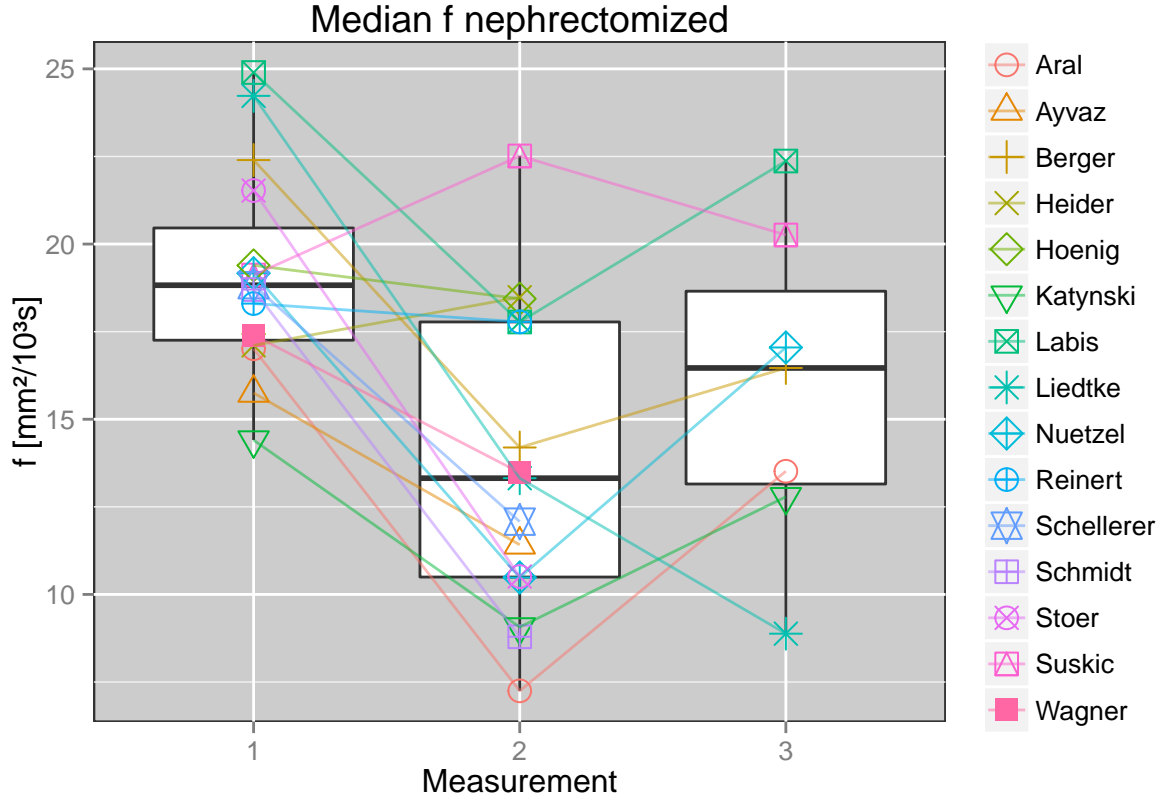
Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	20.824	2.254	23.079	-2.756	20.322
Berger	19.787	0.878	20.666	2.277	22.943
Suskic	22.743	7.549	30.292	-7.937	22.355
Labis	21.258	4.934	26.191	1.562	27.753
Katynski	14.288	6.640	20.928	-2.059	18.869
Liedtke	19.219	4.406	23.625	-2.866	20.759
Nuetzel	22.976	-4.342	18.635	1.696	20.330
Ayvaz	17.276	-1.568	15.708		
Stoer	22.345	-0.284	22.060		
Schellerer	17.870	-0.227	17.643		
Heider	18.653	6.141	24.795		
Wagner	16.845	1.571	18.415		
Hoenig	15.586	1.135	16.721		
Reinert	20.909	1.401	22.310		



Mean f values in the nephrectomized kidneys showed an initial decrease from $19.2 \frac{mm^2}{10^3 s}$ to $13.7 \frac{mm^2}{10^3 s}$ ($p=0.0012$) and a subsequent increase to $15.9 \frac{mm^2}{10^3 s}$ ($p=0.16$).

Table 9: f values in nephrectomized kidneys

Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	17.012	-9.763	7.249	6.267	13.516
Berger	22.397	-8.203	14.194	2.269	16.463
Suskic	19.117	3.398	22.515	-2.255	20.260
Labis	24.896	-7.121	17.776	4.595	22.370
Katynski	14.404	-5.336	9.069	3.718	12.787
Liedtke	24.229	-10.912	13.317	-4.437	8.880
Nuetzel	19.167	-8.684	10.482	6.566	17.049
Ayvaz	15.751	-4.334	11.417		
Stoer	21.527	-11.016	10.511		
Schellerer	18.825	-6.748	12.077		
Heider	17.108	1.374	18.482		
Wagner	17.403	-3.925	13.478		
Hoenig	19.391	-0.951	18.440		
Schmidt	18.701	-9.910	8.792		
Reinert	18.301	-0.523	17.778		

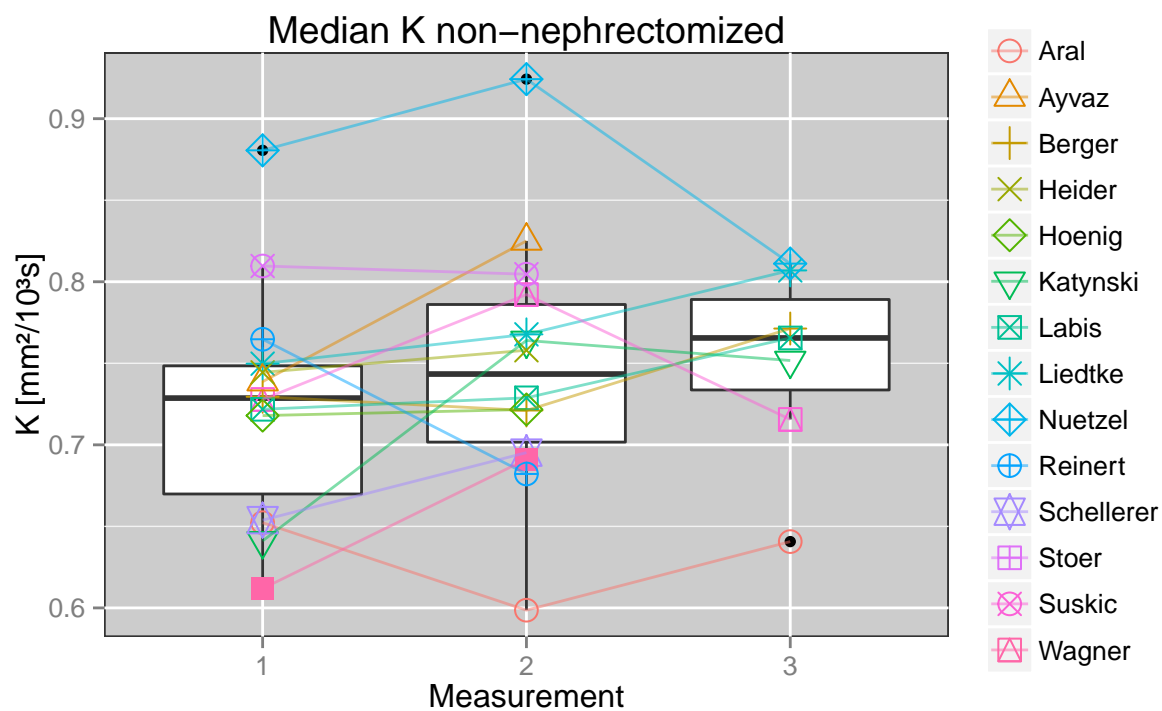


K

Mean K values in the non-nephrectomized kidneys showed an initial increase from $0.725 \frac{\text{mm}^2}{10^3 \text{s}}$ to $0.748 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=0.12$) and a subsequent increase to $0.752 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=1$).

Table 10: K values in non-nephrectomized kidneys

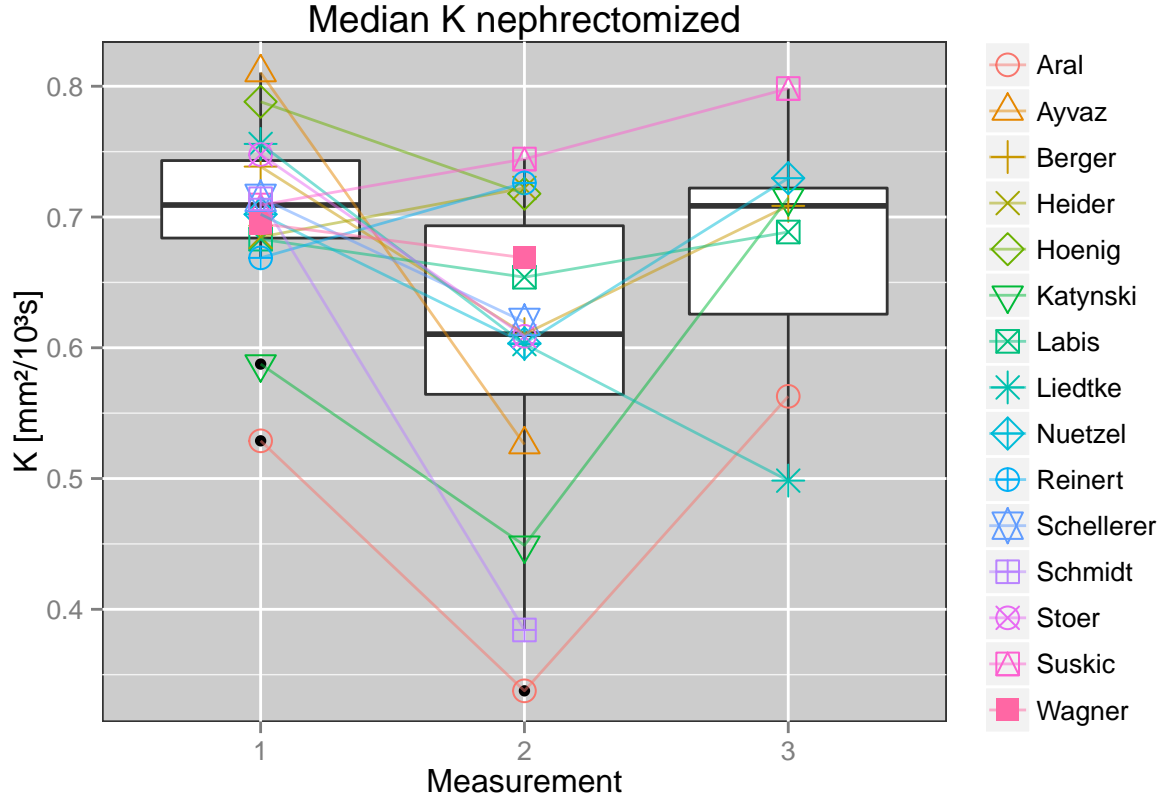
Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	0.652	-0.054	0.599	0.042	0.641
Berger	0.729	-0.008	0.721	0.050	0.771
Suskic	0.728	0.064	0.792	-0.077	0.716
Labis	0.722	0.007	0.729	0.037	0.766
Katynski	0.641	0.123	0.764	-0.012	0.752
Liedtke	0.750	0.018	0.768	0.039	0.807
Nuetzel	0.881	0.044	0.924	-0.113	0.811
Ayvaz	0.739	0.086	0.825		
Stoer	0.810	-0.005	0.805		
Schellerer	0.654	0.041	0.695		
Heider	0.744	0.014	0.758		
Wagner	0.612	0.079	0.691		
Hoenig	0.718	0.004	0.722		
Reinert	0.765	-0.083	0.682		



Mean K values in the nephrectomized kidneys showed an initial decrease from $0.702 \frac{mm^2}{10^3 s}$ to $0.598 \frac{mm^2}{10^3 s}$ ($p=0.0043$) and a subsequent increase to $0.672 \frac{mm^2}{10^3 s}$ ($p=0.11$).

Table 11: K values in nephrectomized kidneys

Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	0.529	-0.191	0.338	0.225	0.563
Berger	0.739	-0.128	0.610	0.098	0.709
Suskic	0.709	0.035	0.744	0.054	0.798
Labis	0.683	-0.029	0.654	0.035	0.689
Katynski	0.588	-0.139	0.449	0.266	0.715
Liedtke	0.756	-0.153	0.603	-0.104	0.498
Nuetzel	0.702	-0.099	0.603	0.126	0.730
Ayvaz	0.811	-0.285	0.526		
Stoer	0.748	-0.139	0.609		
Schellerer	0.715	-0.095	0.620		
Heider	0.685	0.037	0.722		
Wagner	0.695	-0.026	0.669		
Hoenig	0.788	-0.070	0.718		
Schmidt	0.714	-0.330	0.384		
Reinert	0.669	0.057	0.726		

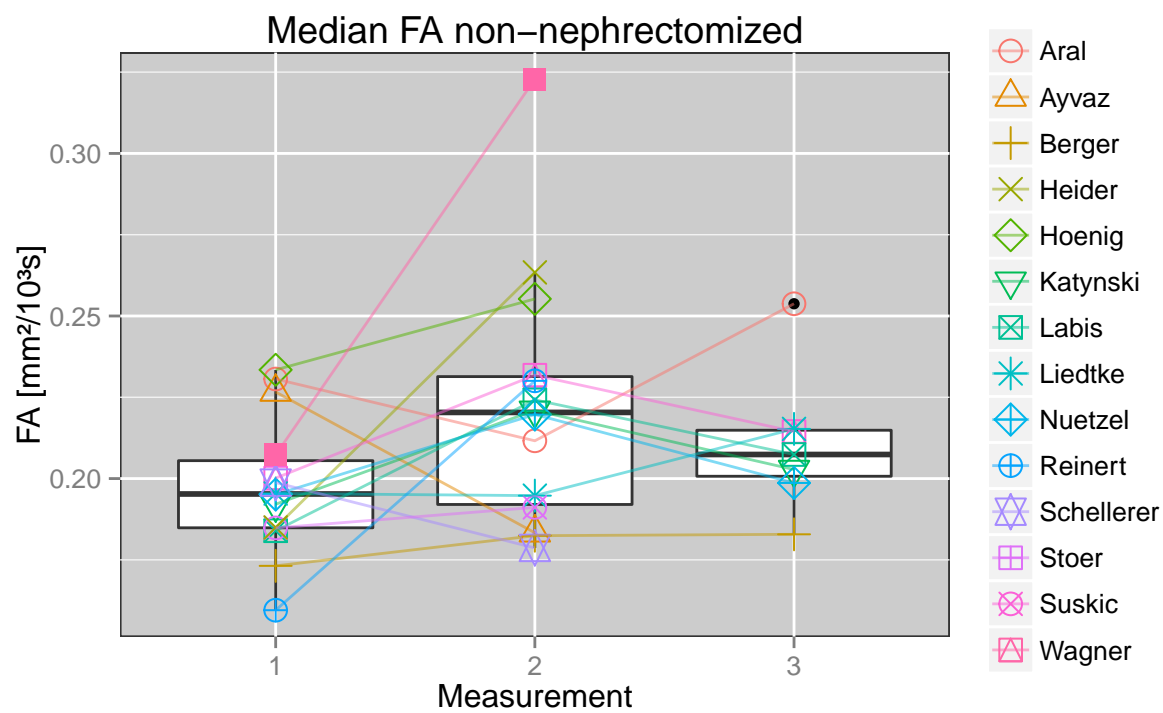


FA

Mean FA values in the non-nephrectomized kidneys showed an initial increase from $0.198 \frac{\text{mm}^2}{10^3 \text{s}}$ to $0.222 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=0.049$) and a subsequent decrease to $0.211 \frac{\text{mm}^2}{10^3 \text{s}}$ ($p=0.94$).

Table 12: FA values in non-nephrectomized kidneys

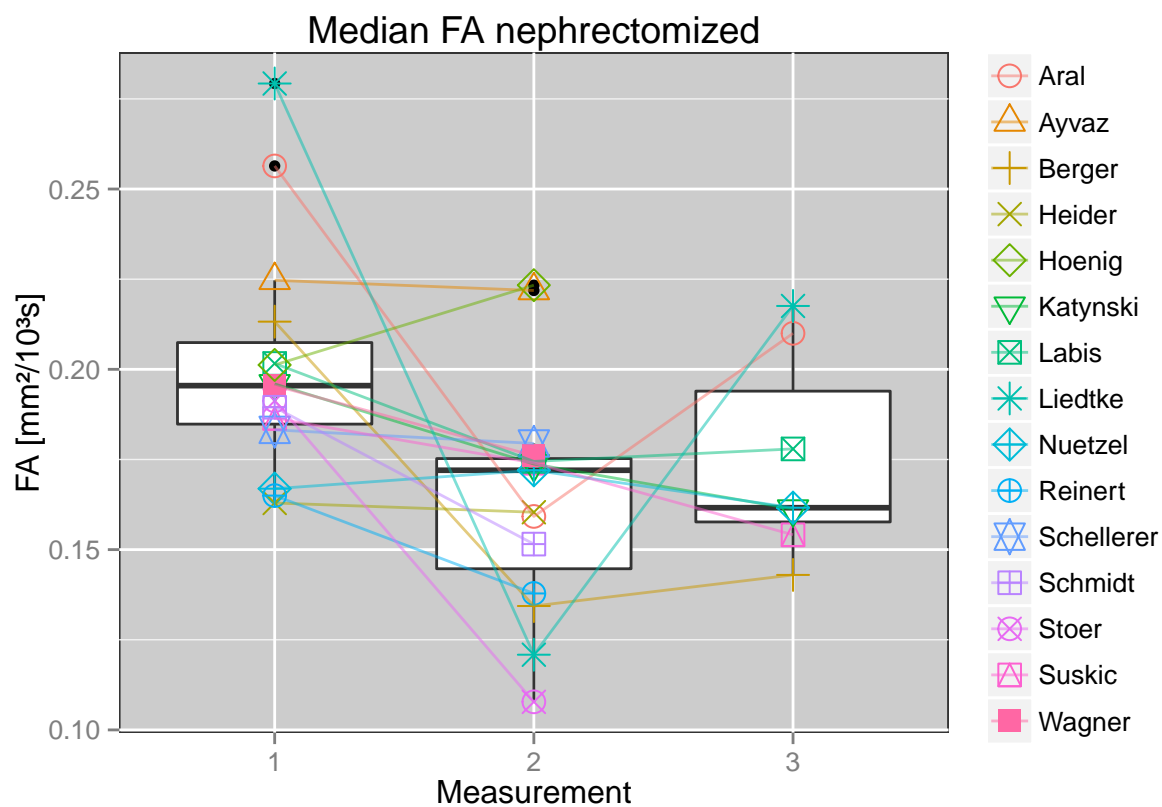
Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	0.231	-0.019	0.212	0.042	0.254
Berger	0.173	0.009	0.182	0.0004	0.183
Suskic	0.200	0.032	0.232	-0.017	0.214
Labis	0.184	0.040	0.224	-0.017	0.207
Katynski	0.192	0.029	0.221	-0.018	0.203
Liedtke	0.195	-0.001	0.195	0.021	0.215
Nuetzel	0.195	0.025	0.220	-0.021	0.199
Ayvaz	0.227	-0.043	0.183		
Stöer	0.185	0.006	0.191		
Schellerer	0.199	-0.020	0.179		
Heider	0.185	0.078	0.263		
Wagner	0.207	0.116	0.323		
Hoenig	0.233	0.022	0.255		
Reinert	0.160	0.071	0.230		



Mean FA values in the nephrectomized kidneys showed an initial decrease from $0.201 \frac{mm^2}{10^3s}$ to $0.164 \frac{mm^2}{10^3s}$ ($p=0.0034$) and a subsequent increase to $0.175 \frac{mm^2}{10^3s}$ ($p=0.81$).

Table 13: FA values in nephrectomized kidneys

Patient	Pre.OP	Delta.1	Post.1	Delta.2	Post.2
Aral	0.256	-0.097	0.159	0.051	0.210
Berger	0.213	-0.079	0.134	0.009	0.143
Suskic	0.186	-0.012	0.174	-0.020	0.154
Labis	0.202	-0.027	0.174	0.003	0.178
Katynski	0.196	-0.022	0.174	-0.013	0.161
Liedtke	0.279	-0.158	0.121	0.097	0.218
Nuetzel	0.167	0.005	0.172	-0.010	0.162
Ayvaz	0.225	-0.003	0.222		
Stoer	0.191	-0.083	0.108		
Schellerer	0.183	-0.004	0.179		
Heider	0.163	-0.003	0.160		
Wagner	0.195	-0.019	0.176		
Hoenig	0.201	0.022	0.223		
Schmidt	0.189	-0.038	0.152		
Reinert	0.165	-0.027	0.138		



Correlations

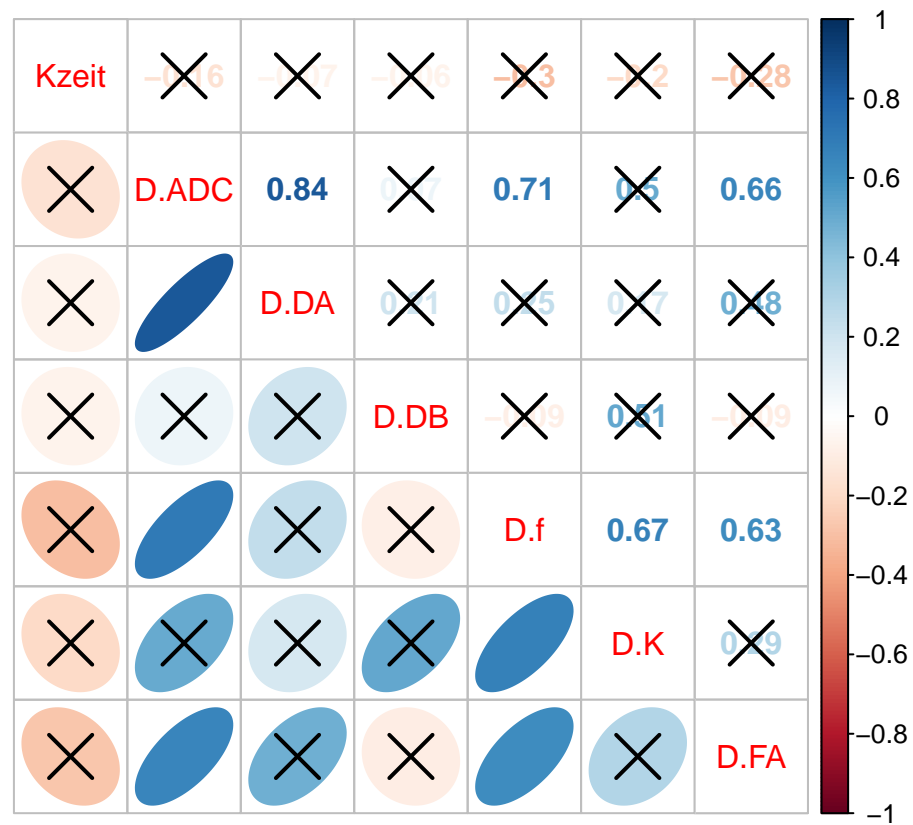


Figure 1: Correlation Matrix. X-ed out combinations did not show significant correlations.