In vitro and Numerical Simulation of Blood Removal from Cerebrospinal Fluid: Comparison of Lumbar Drain to Neurapheresis Therapy

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Fluids and Barriers of the CNS BMC

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Abstract

Background: Blood removal from cerebrospinal fluid (CSF) in post-subarachnoid hemorrhage patients may reduce the risk of related secondary brain injury. We formulated a computational fluid dynamics (CFD) model to investigate the impact of a dual-lumen catheter-based CSF filtration system, called Neurapheresis TM therapy, on blood removal from CSF compared to lumbar drain.

Methods: A subject-specific multiphase CFD model of CSF system-wide solute transport was constructed based on MRI measurements. The Neurapheresis catheter geometry was added to the model within the spinal subarachnoid space. Neurapheresis flow aspiration and return rate was 2.0 and 1.8 (mL/min), versus 0.2 (mL/min) drainage for lumbar drain. Blood was modeled as a bulk fluid phase within CSF with a 10% initial tracer concentration and identical viscosity and density as CSF. Subject-specific oscillatory CSF flow was applied at the model inlet. The dura and spinal cord geometry were considered to be stationary. Spatial-temporal tracer concentration was quantified based on time-average steady-streaming velocities throughout the domain under Neurapheresis therapy and lumbar drain. To help verify CFD results, an optically clear in vitro CSF model was constructed with fluorescein used as a blood surrogate. Quantitative comparison of numerical and in vitro results was performed by linear regression of spatial-temporal tracer concentration over 24-hours.

Results: After 24-hours, tracer concentration was reduced to 4.9% under Neurapheresis therapy compared to 6.5% under lumbar drain. Tracer clearance was most rapid between the catheter aspiration and return ports. Neurapheresis therapy was found to have a greater impact on steady-streaming compared to lumbar drain. Steady-streaming in the cranial SAS was ~50X smaller than in the spinal subarachnoid space for both cases. CFD results were strongly correlated with the in vitro spatial-temporal tracer concentration under Neurapheresis therapy (R^2 =0.89 with +2.13% and -1.93% tracer concentration confidence interval).

Conclusion: A subject-specific CFD model of CSF system-wide solute transport was used to investigate the impact of Neurapheresis therapy on tracer removal from CSF compared to lumbar drain over a 24-hour period. Neurapheresis therapy was found to substantially increase tracer clearance compared to

lumbar drain. The multiphase CFD results were verified by in vitro fluorescein tracer experiments.

Full-text

Due to technical limitations, full-text HTML conversion of this manuscript could not be completed.

However, the manuscript can be downloaded and accessed as a PDF.

Figures

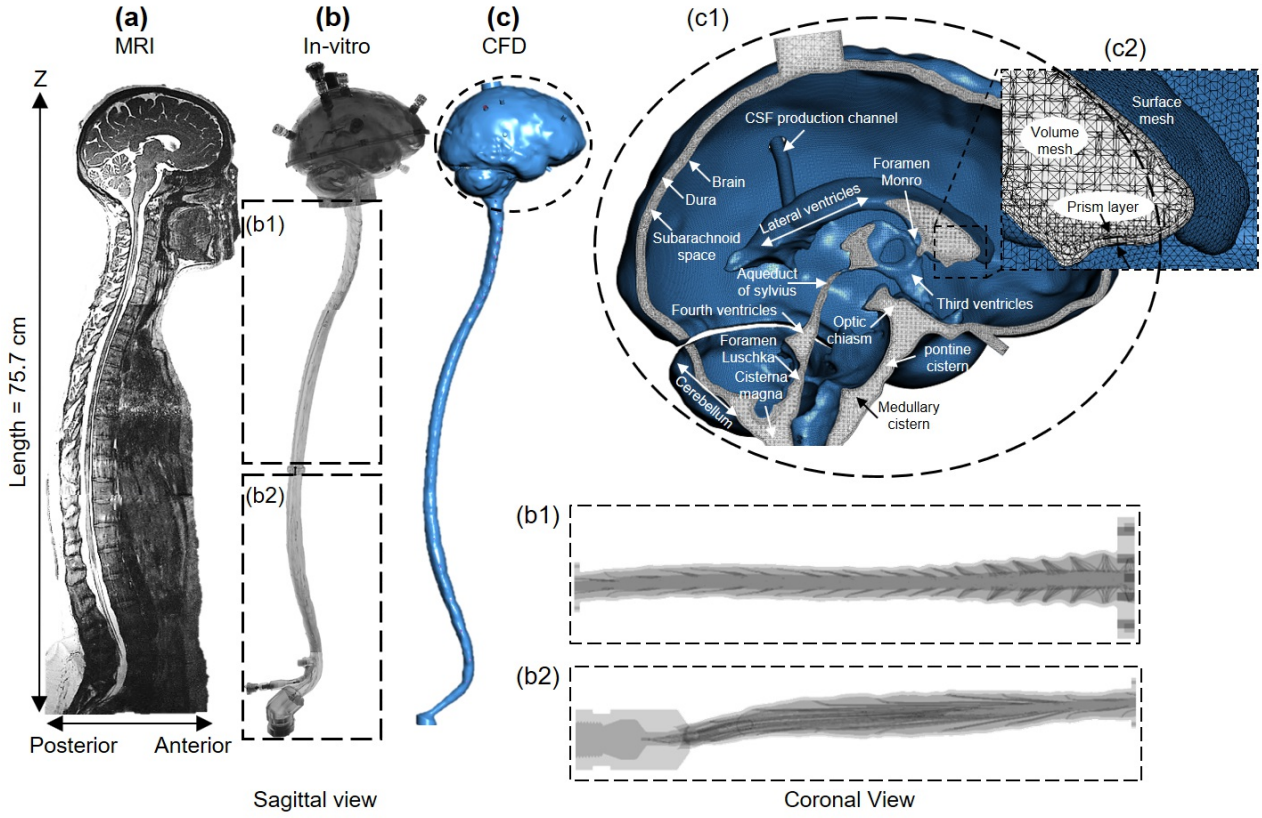

Figure 1

Figure legends available in the PDF

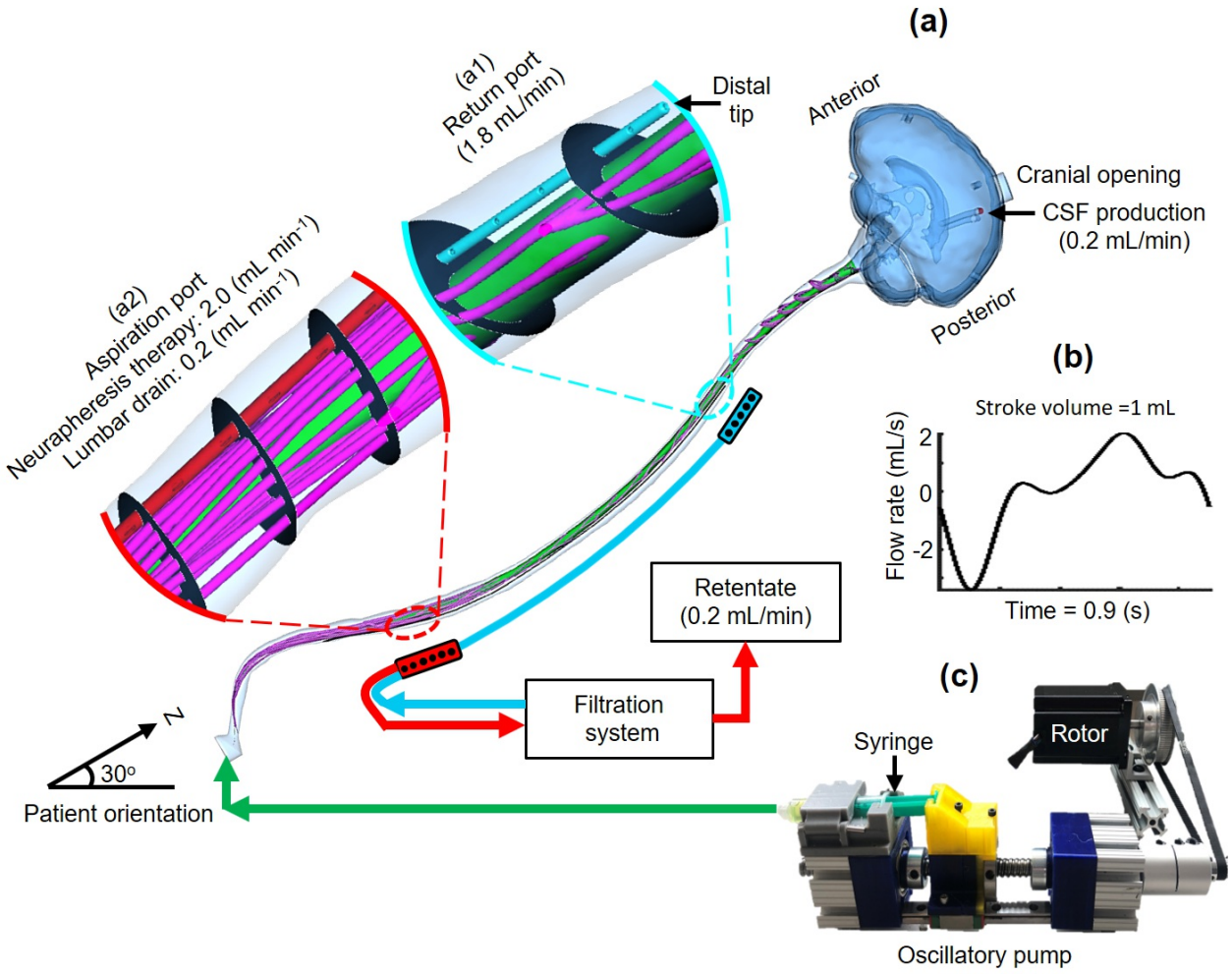
(a)
(a1)
Return port
(1.8 mL/min)
Distal
tip
Anterior
Cranial opening
CSF production
(0.2 mL/min)
Posterior
(a2)
Aspiration port
Neurapheresis therapy: 2.0 (mL min-1)
Lumbar drain: 0.2 (mL min-1)
(b)
Stroke volume =1 mL
Flow rate (mL/s)
2
0
-2
Time = 0.9 (s)
Retentate
(0.2 mL/min)
Filtration
system
(c)
Syringe
Rotor
N
30°
Patient orientation
Oscillatory pump

Figure 2

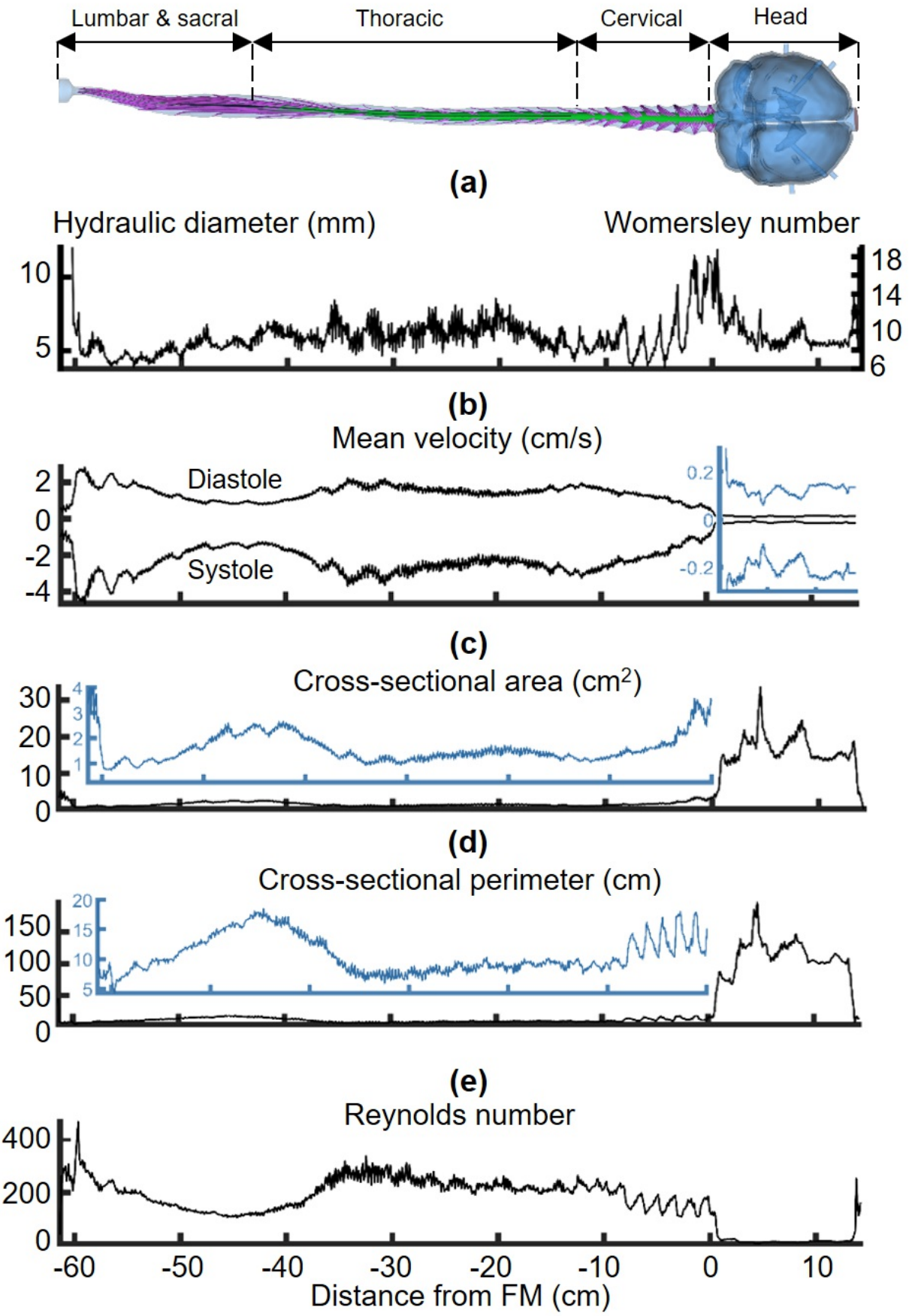
Lumbar & sacral
Thoracic
Cervical
Head
(a)
Hydraulic diameter (mm)
Womersley number
10
5
18
14
10
6
(b)
Mean velocity (cm/s)
Diastole
Systole
2
0
-2
-4
0.2
0
-0.2
(c)
Cross-sectional area (cm²)
30
20
10
0
4
3
2
1
(d)
Cross-sectional perimeter (cm)
150
100
50
0
20
15
10
5
(e)
Reynolds number
400
200
0
-60
-50
-40
-30
-20
-10
0
10
Distance from FM (cm)

Figure 3

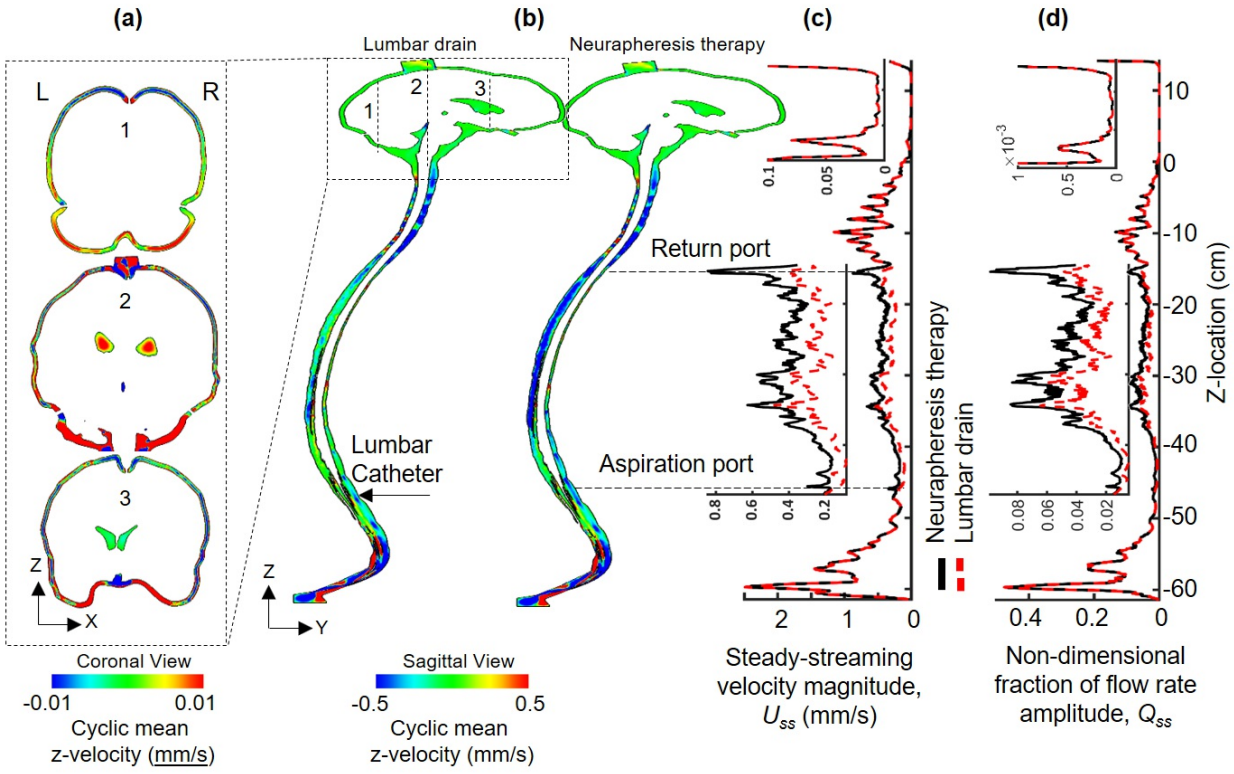

Figure 4

Uss , and (d) non-dimensional fraction of flow rate amplitude, Qss .

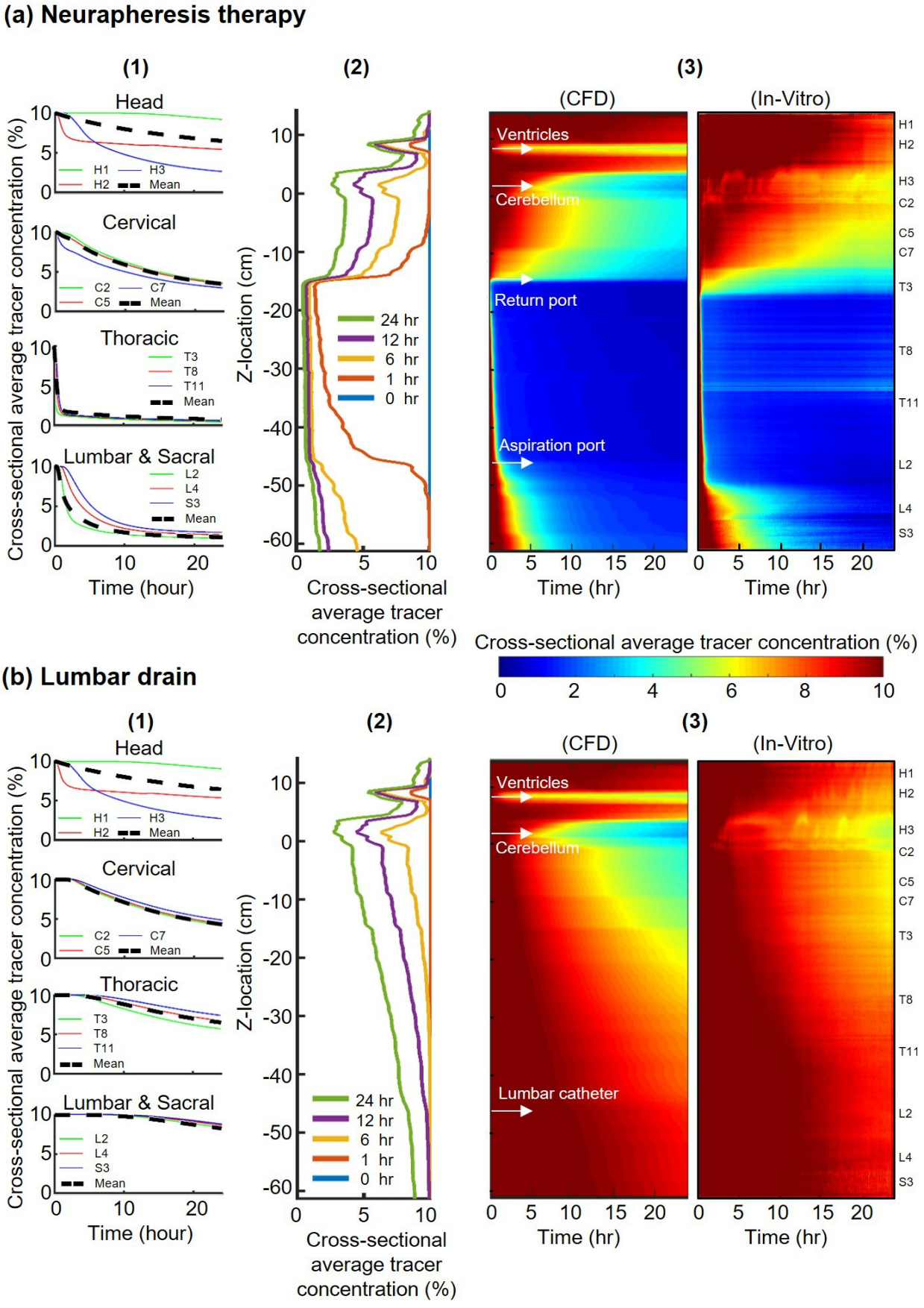
(a) Neurapheresis therapy
(1)
(2)
(3)
Head
H1
H2
H3
Mean
Cervical
C2
C5
C7
Mean
Thoracic
T3
T8
T11
Mean
Lumbar & Sacral
L2
L4
S3
Mean
Cross-sectional average tracer concentration (%)
Time (hour)
Z-location (cm)
24 hr
12 hr
6 hr
1 hr
0 hr
Cross-sectional average tracer concentration (%)
(CFD)
(In-Vitro)
Ventricles
Cerebellum
Return port
Aspiration port
Time (hr)
H1
H2
H3
C2
C5
C7
T3
T8
T11
L2
L4
S3
Cross-sectional average tracer concentration (%)
(b) Lumbar drain
Lumbar catheter

Figure 5

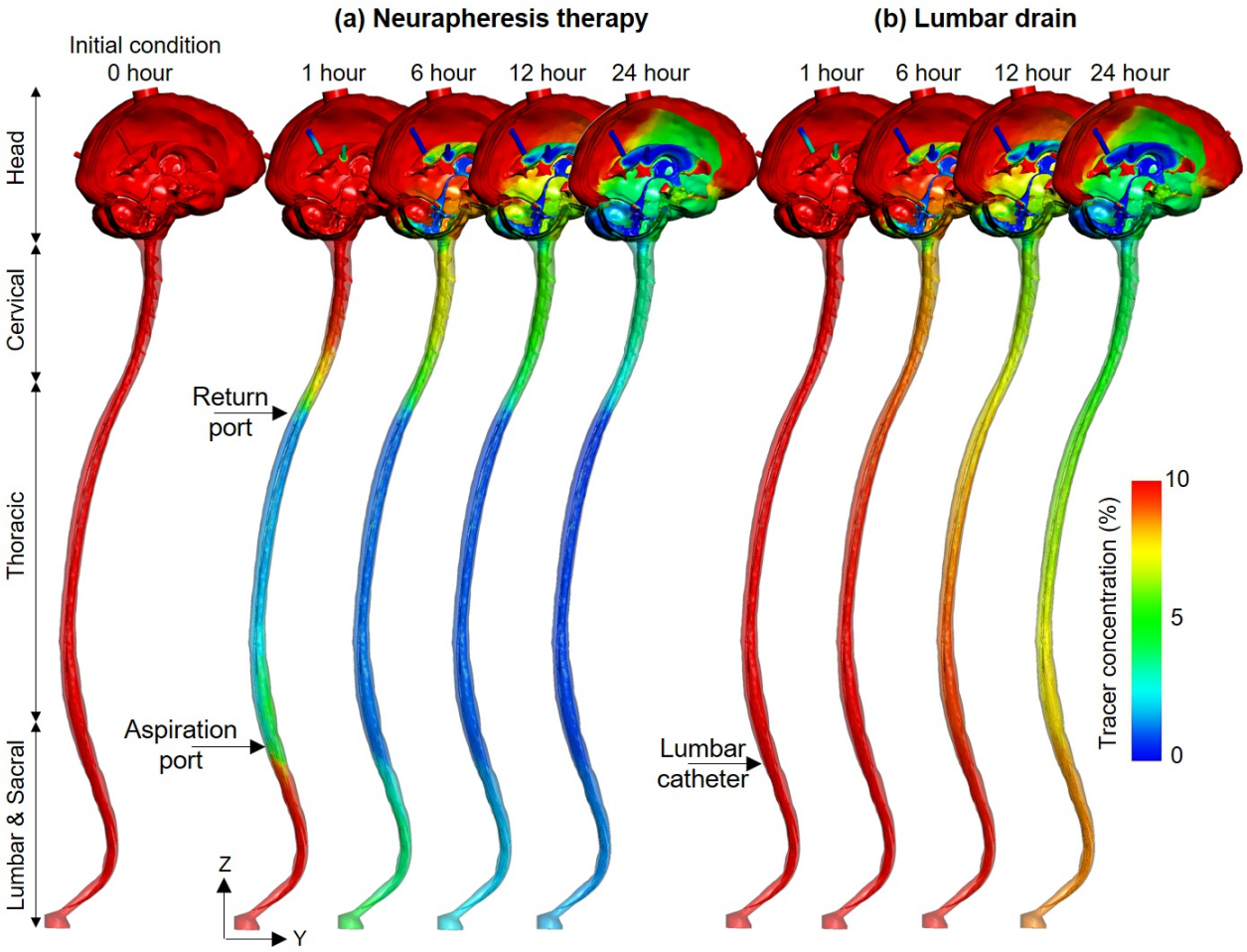
(a) Neurapheresis therapy
(b) Lumbar drain
Initial condition
0 hour
1 hour
6 hour
12 hour
24 hour
1 hour
6 hour
12 hour
24 hour
Head
Cervical
Thoracic
Lumbar & Sacral
Return port
Aspiration port
Lumbar catheter
Z
Y
Tracer concentration (%)
10
5
0

Figure 6

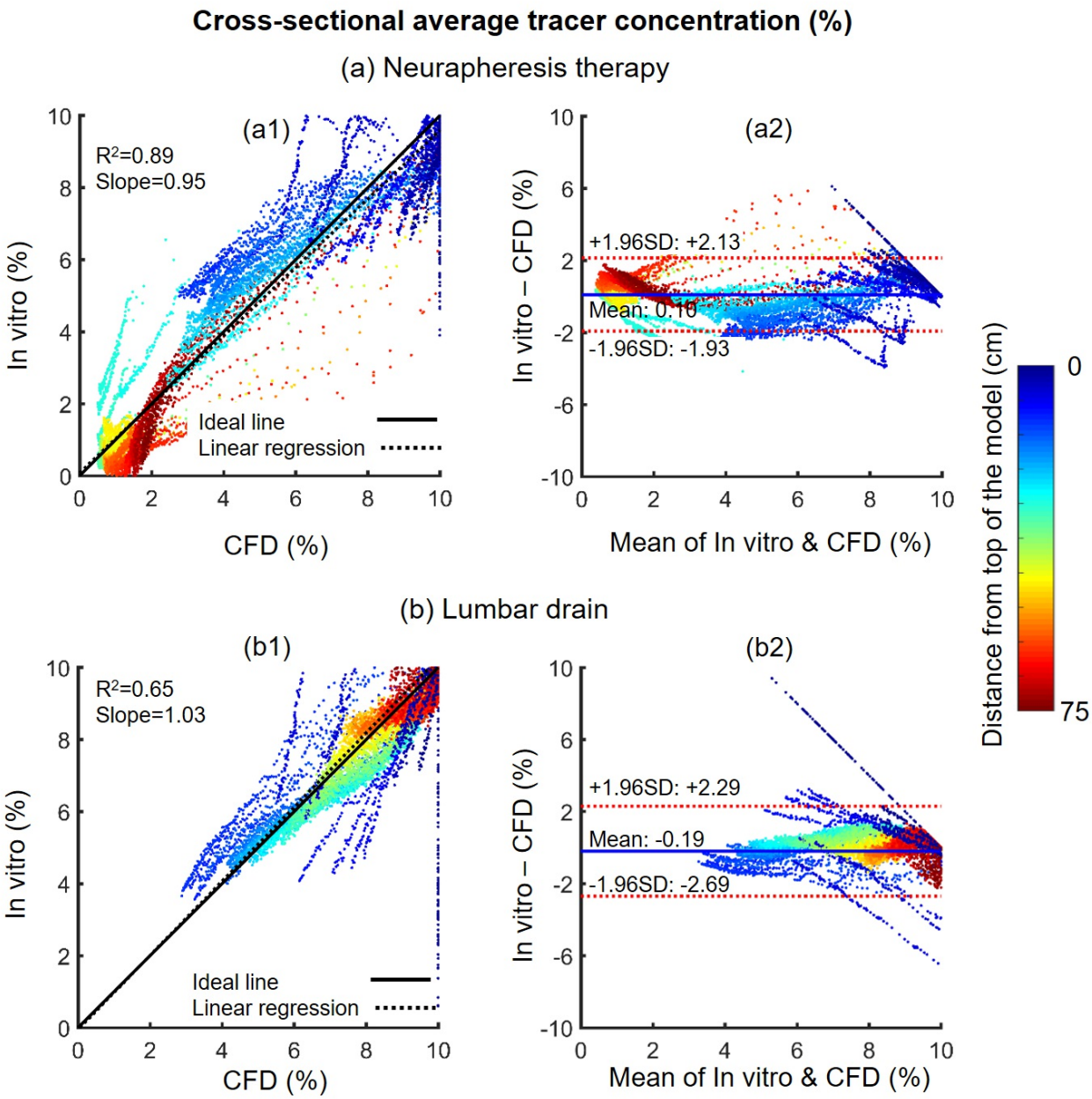
Cross-sectional average tracer concentration (%)
(a) Neurapheresis therapy
(a1)
R²=0.89
Slope=0.95
Ideal line
Linear regression
In vitro (%)
CFD (%)
(a2)
+1.96SD: +2.13
Mean: 0.10
-1.96SD: -1.93
In vitro – CFD (%)
Mean of In vitro & CFD (%)
(b) Lumbar drain
(b1)
R²=0.65
Slope=1.03
Ideal line
Linear regression
In vitro (%)
CFD (%)
(b2)
+1.96SD: +2.29
Mean: -0.19
-1.96SD: -2.69
In vitro – CFD (%)
Mean of In vitro & CFD (%)
Distance from top of the model (cm)
0
75

Figure 7