GTR 7 Informal Working Group
December 5, 2011
Geneva

Preliminary PMHS Injury Risk Curves & Potential IARVs in Rear Impact

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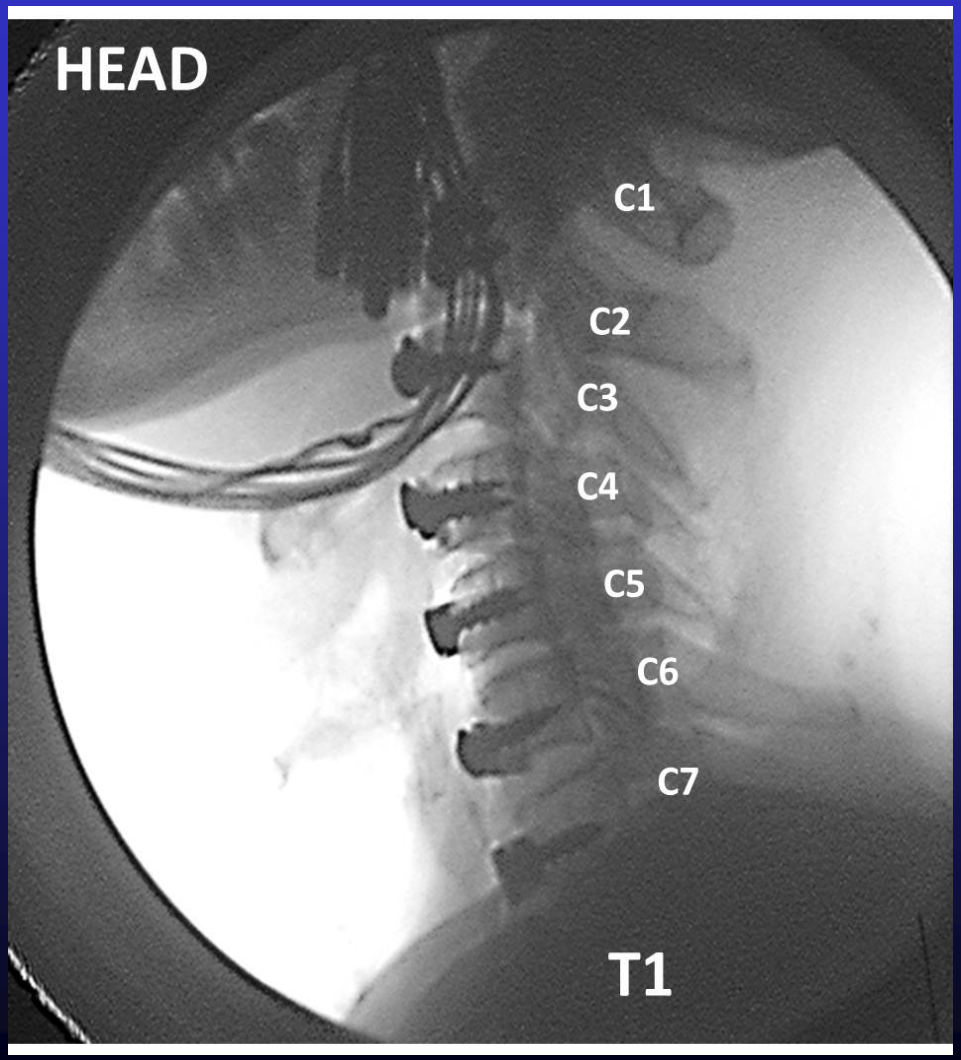
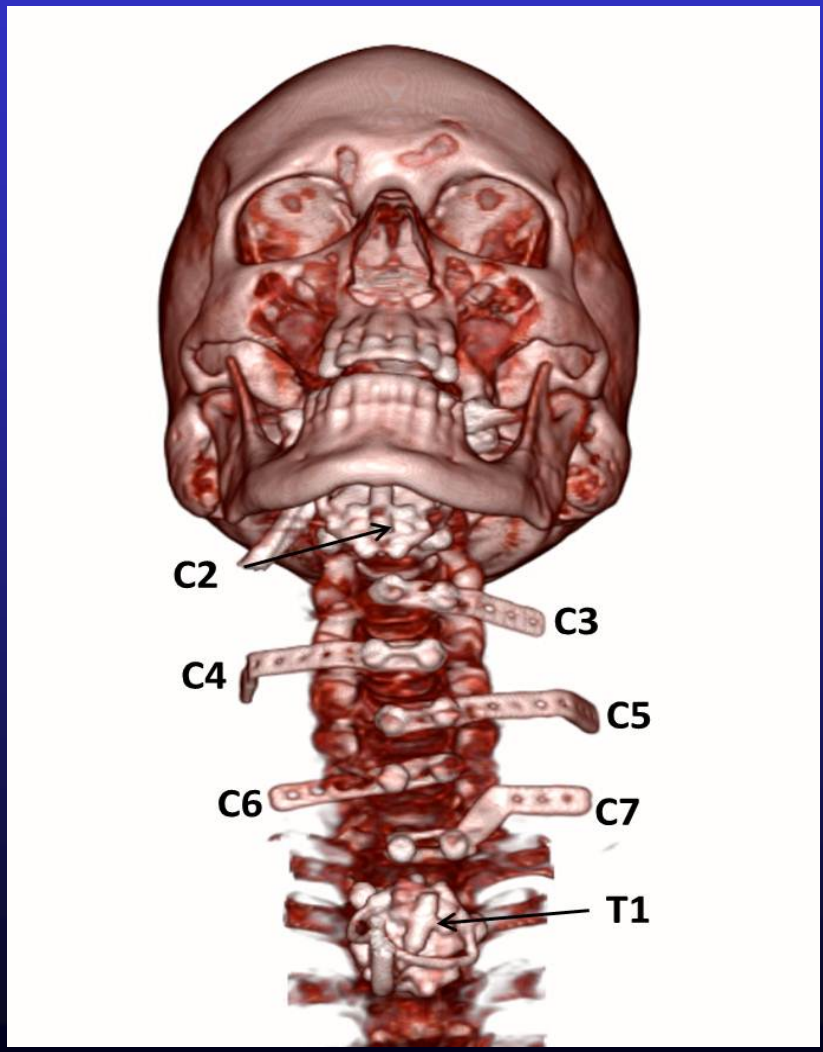
Rear Impact Research Objectives

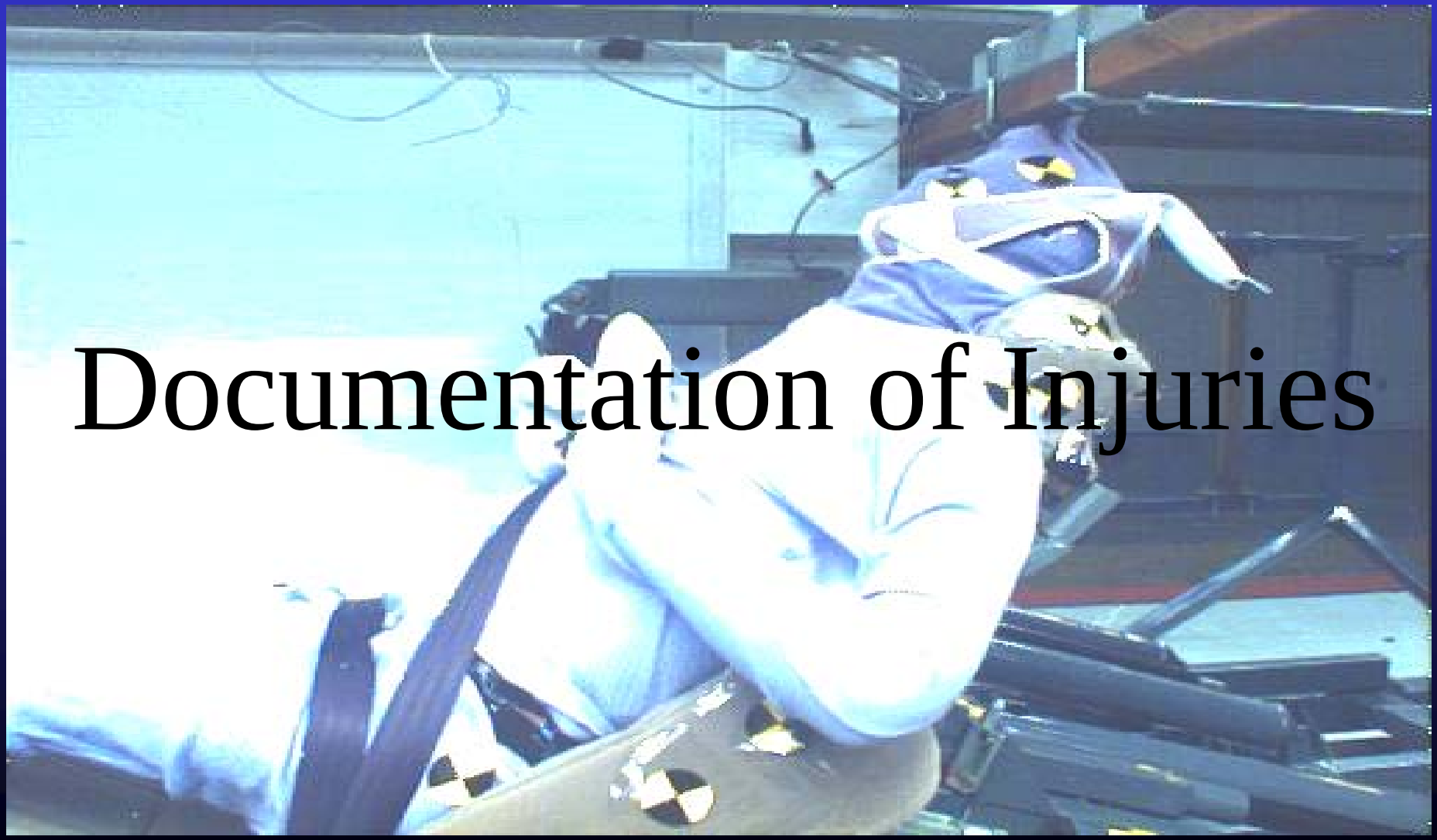
- **Evaluate biofidelity of available RIDs (BioRID, RID3D, HyIII)**
  - Choose biofidelity test condition
  - Develop experimental seat for rear impact sled testing
  - Conduct sled tests
    - PMHS (Post-Mortem Human Subjects)
    - Dummies (BioRID II, RID3D, Hybrid III)
  - Assess biofidelity and repeatability of dummies
- **Investigate the mechanism of injury**
  - Develop and validate 3-D cervical spine kinematic instrumentation
  - Identify injurious kinematics
- **Choose appropriate injury criterion**
  - Assess efficacy of various ICs

Rear Impact Injury Mechanism



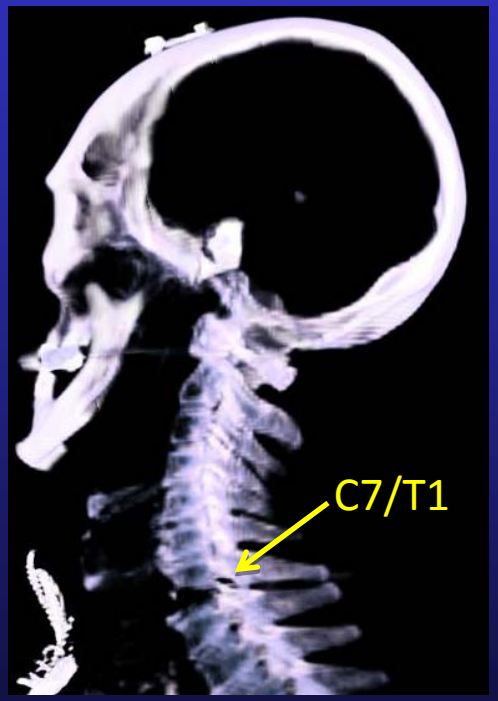


Documentation of Injuries

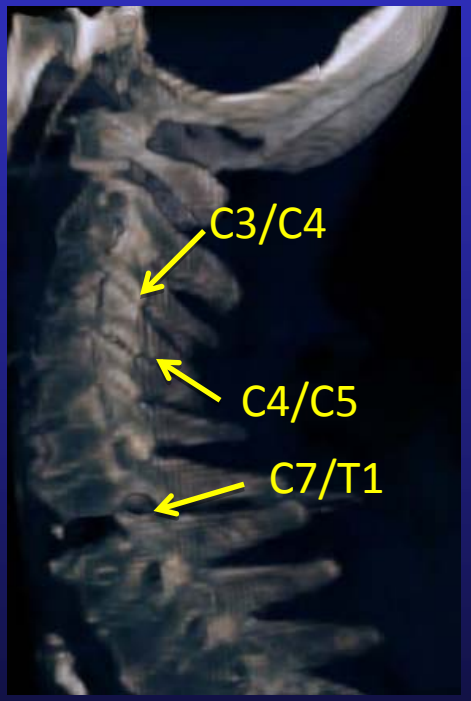


Injury Examples (Post-test CT)

<CT sagittal view>



<Disc rupture w fracture>



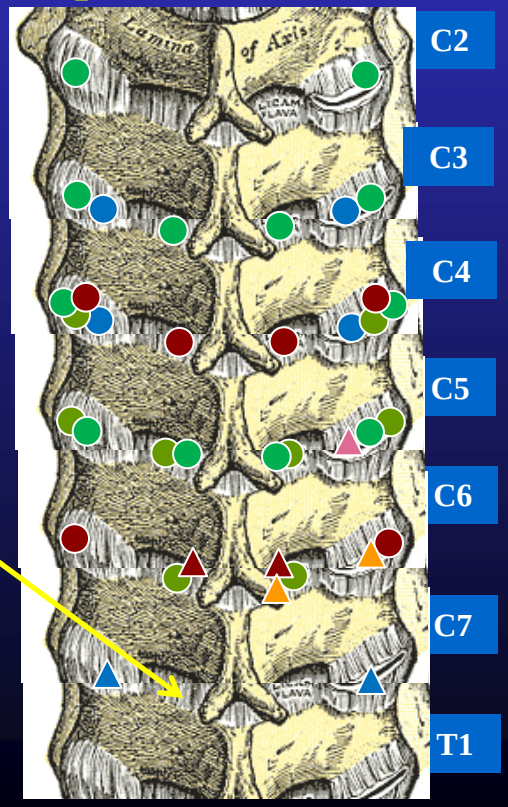
<Facet joint>

Documentation of Injuries

: disc rupture
: subluxation
: laceration (tear)

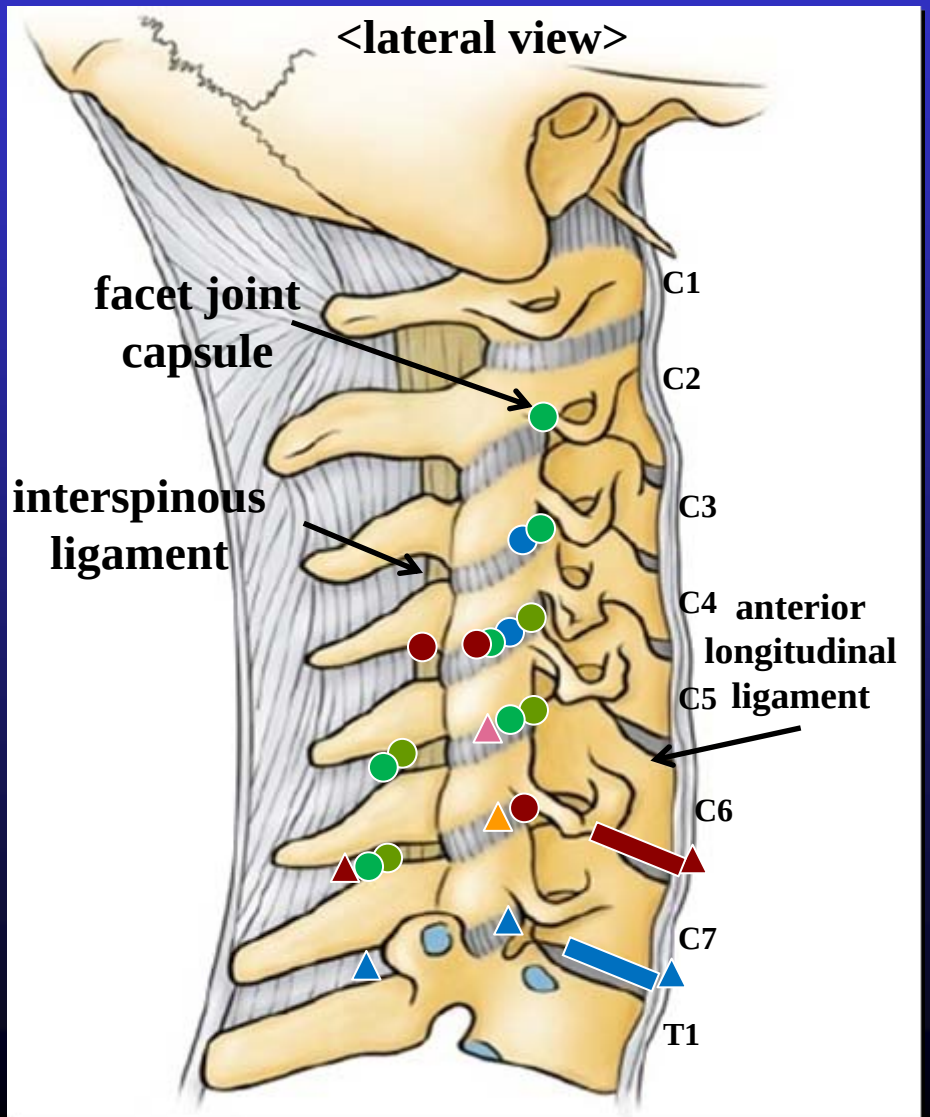
PMHS03
PMHS04
PMHS05
PMHS06
PMHS07
PMHS08

<posterior view>



ligamentum flavum

<lateral view>



Documentation of Injuries

NHTSA
www.nhtsa.gov

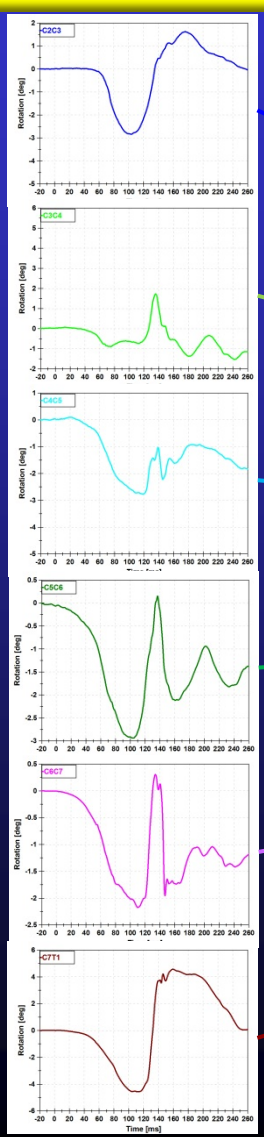
PMHS	#1	#2	#3	#4	#5	#6	#7	#8
C2/C3	No injury	No injury	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	No injury	No injury	No injury
C3/C4	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum (AIS1)	No injury	No injury	No injury
C4/C5	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig(AIS1)	No injury
C5/C6	No injury	No injury	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig(AIS1)	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig(AIS1)	Facet joint capsule tear on right side/ degeneration disc-mild subluxation (AIS1)	No injury	No injury
C6/C7	No injury	No injury	No injury	Subluxation bilateral@ ligamentum flavum (AIS1) & interspinous lig (AIS1)	Subluxation @ Interspinous lig (AIS1)	No injury	Anterior longitudinal lig tear (posterior intact), Severe Subluxation @ FJ on both sides, ligamentum flavum tear, Disc injury w ruptured (AIS3), Interspinous lig tear (AIS1)	Seperation of degenerative disc, ligamentum flavum tear @ right side close to spinous process, facet joint capsule tear on the right side (AIS1)
C7/T1	No injury	No injury	Anterior longitudinal lig. tear (posterior intact), FJ capsule tear on both sides, ligamentum flavum tear on left side, Disc rupture w fracture (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc	No injury	No injury	No injury	No injury

Injury Criteria Analysis

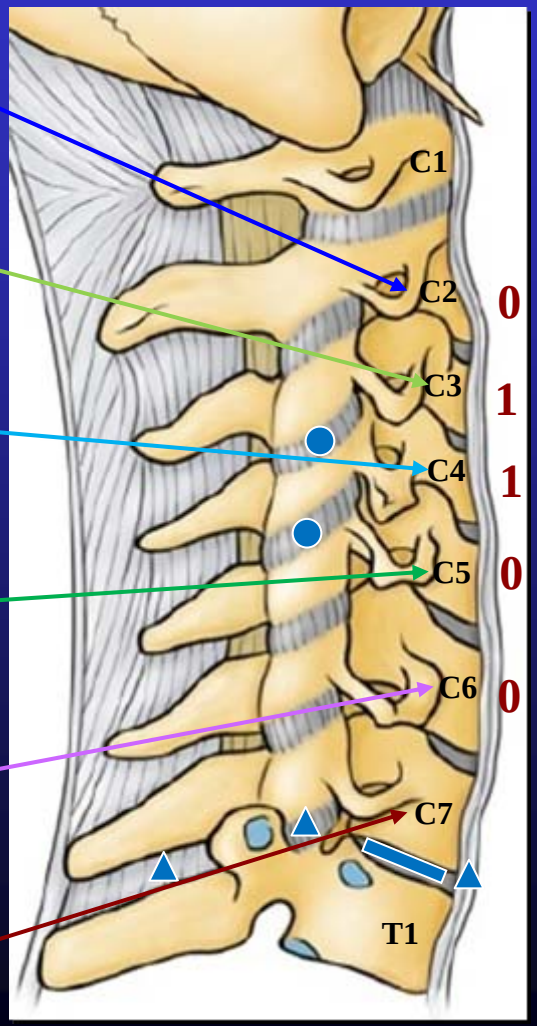
Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

Intervertebral kinematics

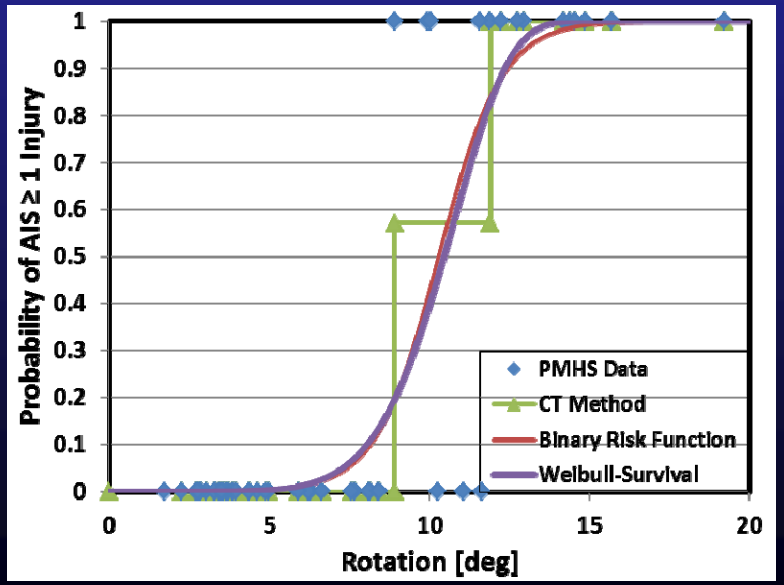


Injuries @ intervertebral levels



- C2/C3 – C6/C7: 5 levels
- 5 data points per test
- Two speeds
- n ~ 10 per subject

Injury Risk Curves



Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Acceleration x	(+)	0.05	0.08	-30.377	0.067	0.49
	(-)	0.17	0.25	-26.744	0.001	0.72
	Max	0.09	0.14	-29.142	0.016	0.59
Acceleration z	(+)	0.17	0.26	-26.584	0.001	0.62
	(-)	0.10	0.15	-28.963	0.013	0.59
	Max	0.12	0.19	-28.179	0.005	0.58
Velocity x	(+)	0.04	0.07	-30.612	0.089	0.34
	(-)	0.20	0.29	-25.785	0.000	0.54
	Max	0.20	0.29	-25.797	0.000	0.54
Velocity z	(+)	0.01	0.01	-31.855	0.527	-0.05
	(-)	0.12	0.18	-28.31	0.006	0.47
	Max	0.04	0.06	-30.908	0.130	0.14
Angular velocity y	**(+)**	**0.30**	**0.43**	**-20.696**	**0.000**	**0.83**
	(-)	0.05	0.08	-33.195	0.074	0.42
	Max	0.17	0.26	-28.837	0.001	0.7
Displacement x	Max	0.11	0.17	-29.93	0.008	0.41
Displacement z	**Max**	**0.29**	**0.41**	**-23.76**	**0.000**	**0.69**
Rotation y	**Max**	**0.72**	**0.83**	**-8.236**	**0.000**	**0.96**

(+) : positive peak, (-): negative peak, Max: maximum peak

Peudo $R^2 > 0.2$, Nagelkerke $R^2 > 0.4$, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction

Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Acceleration x	(+)	0.05	0.08	-30.377	0.067	0.49
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Rotation y	**Max**	**0.72**	**0.83**	**-8.236**	**0.000**	**0.96**
Facet JT Slide	**Max**	**0.38**	**0.52**	**-18.5276**	**0.000**	**0.77**
Facet JT Slide Rate	Max	0.13	0.20	-30.388	0.003	0.49
Facet JT Axial	Max	0.06	0.10	-32.7106	0.041	0.28
Facet JT Axial Rate	Max	0.05	0.09	-32.953	0.055	0.38

(+) : positive peak, (-): negative peak, Max: maximum peak

Peudo $R^2 > 0.2$, Nagelkerke $R^2 > 0.4$, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction

Injury Analysis

Injury Risk Curves – Intervertebral Kinematics

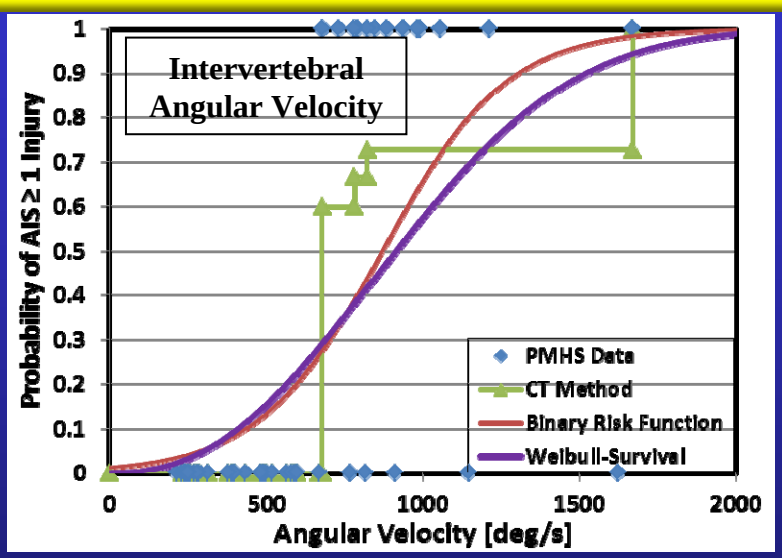
Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
Rotation y	Max	0.72	0.83	-8.236	0.000	0.96
Angular velocity y	(+)	0.30	0.43	-20.696	0.000	0.83
Facet JT Slide	Max	0.38	0.52	-18.5276	0.000	0.77
(+) : positive peak, (-): negative peak, Max: maximum peak						

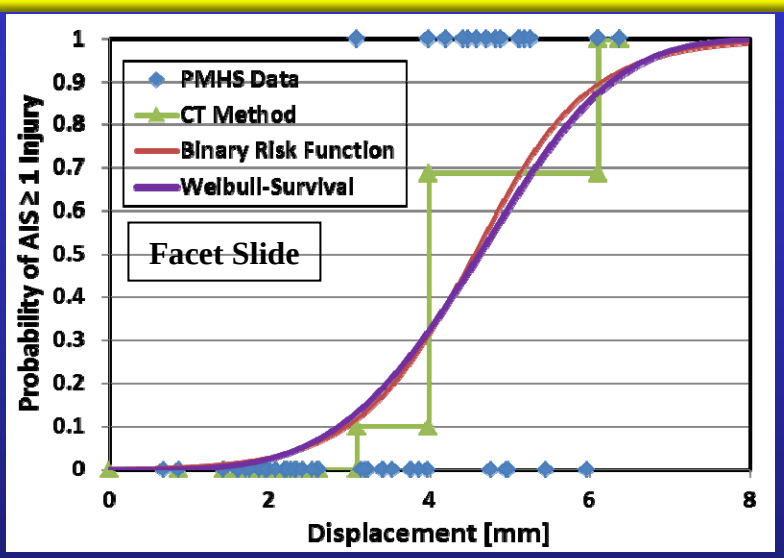
Peudo R^2 > 0.2, Nagelkerke R^2 > 0.4, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

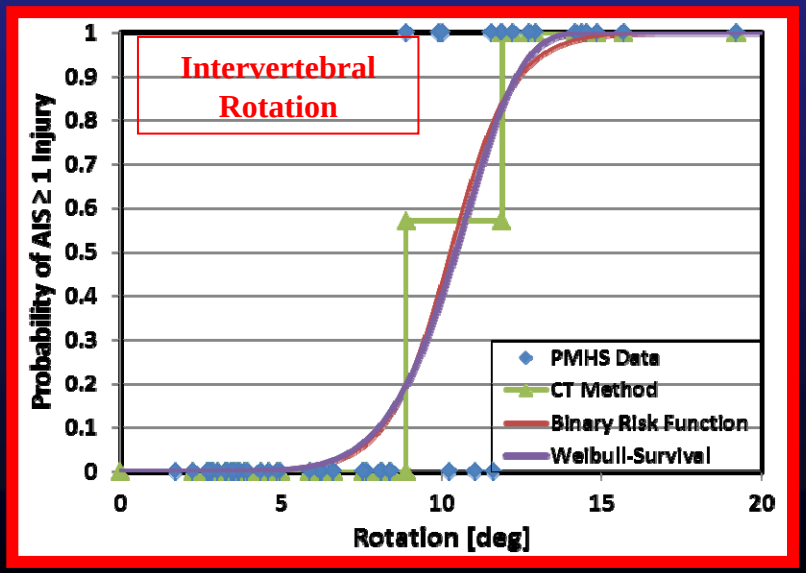
Best correlation and prediction

Injury Analysis

Injury Risk Curves – Intervertebral Kinematics







- Each intervertebral level may have different threshold
  - Normalization using physiological range of motion
  - IV-NIC [Panjabi et al., 1999]

Qualitative Correlation - IV-NIC and Injuries

IV-NIC (Rotation)												
	PMHS03		PMHS04		PMHS05		PMHS06		PMHS07		PMHS08	
	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate
C2/C3	-0.85	-0.79	-1.06**	-0.87	-1.84	-1.52	-0.40	-0.49	-0.90	-0.99	-0.34	-0.45
	+0.26	+0.67	+0.17	+0.26	0.46	0.86	0.23	+0.41	+0.21	+0.30	+0.04	+0.19
C3/C4	-1.18	-1.07	-0.27	-0.41	-1.59	-1.54	-0.09	-0.07	-0.87	-1.00	-0.68	-0.90
	+0.48	+1.05	+1.02**	+0.51	+0.05	+0.18	+0.54	+0.94	+0.15	+0.10	+0.19	+0.28
C4/C5	-1.47	-1.87	-1.17	-1.40	-1.37	-1.16	-0.13	-0.19	-1.48	-1.44	-0.54	-0.79
	+0.01	+0.01	+0.00	+0.00	+0.00	+0.05	+0.39	+0.62	+0.05	+0.09	+0.05	+0.10
C5/C6	-0.56	-0.40	-0.96	-1.00	-1.08	-1.19	-0.09	-0.09	-0.85	-0.91	-0.69	-0.69
	+0.27	+0.30	+0.00	+0.01	+0.01	+0.00	+0.36	+1.00	+0.00	0.00	+0.00	+0.50
C6/C7	-0.33	-0.54	-1.15	-1.33	-0.84	-1.20	-0.16	-0.16	-0.72	-0.73	-0.79	-1.05
	+0.05	+0.68	+0.00	+0.00	+0.44	+0.20	+0.05	+0.47	+0.06	+1.69	+0.00	+0.35
C7/T1	-0.61	-0.73	-0.80	-0.68	-0.69	-0.56	-0.48	-0.32	-0.73	-0.76	-0.89	-1.16
	+0.19	+3.79	+0.00	+1.93	+0.81	+0.90	+0.10	+0.96	+0.84	+1.86	0.05	1.54

Qualitative Correlation - IV-NIC and Injuries

	Injury Documentation					
	PMHS03	PMHS04	PMHS05	PMHS06	PMHS07	PMHS08
C2/C3	No injury	No injury	Subluxation bilateral@ FJ (AIS3)	No injury	No injury	No injury
C3/C4	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum	No injury	No injury	No injury
C4/C5	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig.	No injury
C5/C6	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig.	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig.	Facet joint capsule tear on right side/ degeneration disc-mild subluxation	No injury	No injury
C6/C7	No injury	Subluxation bilateral@ ligamentum flavum & interspinous lig.	Subluxation @ Interspinous lig	No injury	Anterior longitudinal lig. tear (posterior intact), Severe Subluxation @ FJ on both sides, ligamentum flavum tear, Disc injury w ruptured (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc, ligamentum flavum tear @ right side close to spinous process, facet joint capsule tear on the right side
C7/T1	Anterior longitudinal lig. tear (posterior intact), FJ capsule tear on both sides, ligamentum flavum tear on left side, Disc injury w ruptured (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc	No injury	No injury	No injury	No injury

Qualitative Correlation - IV-NIC and Injuries

IV-NIC (Rotation)												
	PMHS03		PMHS04		PMHS05		PMHS06		PMHS07		PMHS08	
	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate	Low	Moderate
C2/C3	-0.85	-0.79	-1.06**	-0.87	-1.84	-1.52	-0.40	-0.49	-0.90	-0.99	-0.34	-0.45
	+0.26	+0.67	+0.17	+0.26	0.46	0.86	0.23	+0.41	+0.21	+0.30	+0.04	+0.19
C3/C4	-1.18	-1.07	-0.27	-0.41	-1.59	-1.54	-0.09	-0.07	-0.87	-1.00	-0.68	-0.90
	+0.48	+1.05	+1.02**	+0.51	+0.05	+0.18	+0.54	+0.94	+0.15	+0.10	+0.19	+0.28
C4/C5	-1.47	-1.87	-1.17	-1.40	-1.37	-1.16	-0.13	-0.19	-1.48	-1.44	-0.54	-0.79
	+0.01	+0.01	+0.00	+0.00	+0.00	+0.05	+0.39	+0.62	+0.05	+0.09	+0.05	+0.10
C5/C6	-0.56	-0.40	-0.96	-1.00	-1.08	-1.19	-0.09	-0.09	-0.85	-0.91	-0.69	-0.69
	+0.27	+0.30	+0.00	+0.01	+0.01	+0.00	+0.36	+1.00	+0.00	0.00	+0.00	+0.50
C6/C7	-0.33	-0.54	-1.15	-1.33	-0.84	-1.20	-0.16	-0.16	-0.72	-0.73	-0.79	-1.05
	+0.05	+0.68	+0.00	+0.00	+0.44	+0.20	+0.05	+0.47	+0.06	+1.69	+0.00	+0.35
C7/T1	-0.61	-0.73	-0.80	-0.68	-0.69	-0.56	-0.48	-0.32	-0.73	-0.76	-0.89	-1.16
	+0.19	+3.79	+0.00	+1.93	+0.81	+0.90	+0.10	+0.96	+0.84	+1.86	0.05	1.54

Qualitative Correlation - IV-NIC and Injuries

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C4/C5	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	Subluxation bilateral@ FJ (AIS3)	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig.	No injury
C5/C6	No injury	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig.	Subluxation bilateral@ FJ (AIS3) and ligametum flavum/interspinous lig.	Facet joint capsule tear on right side/ degeneration disc-mild subluxation	No injury	No injury
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C7/T1	Anterior longitudinal lig. tear (posterior intact), FJ capsule tear on both sides, ligamentum flavum tear on left side, Disc injury w ruptured (AIS3), Interspinous lig. tear (AIS1)	Seperation of degenerative disc	No injury	No injury	No injury	No injury

Injury Analysis

Injury Risk Curves – IV-NIC parameters

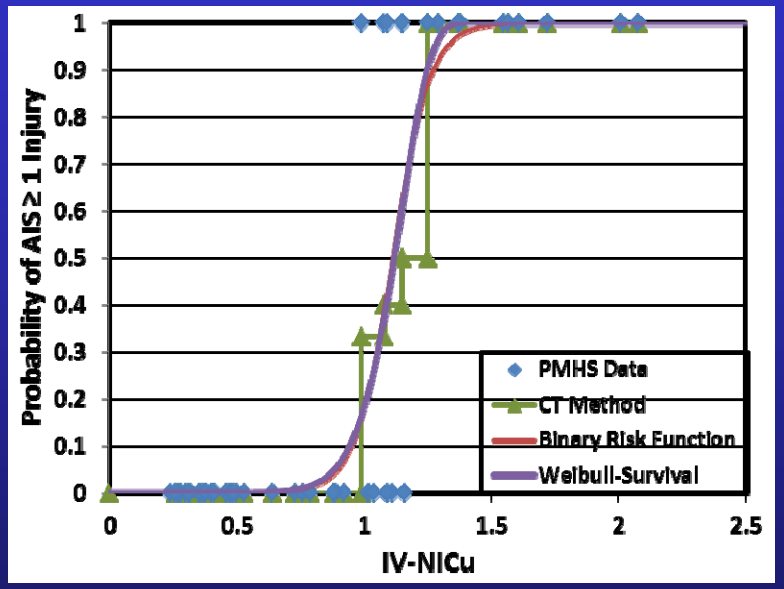
Intervertebral kinematics		Pseudo R^2	Nagelkerke R^2	Log-Likelihood	P-value	Goodman-Kruskal Gamma
IV-NICs (slide)	Max	0.19	0.30	-23.912	0.001	0.58
IV-NICs rate	Max	0.10	0.17	-26.555	0.013	0.44
IV-NICs product	Max	0.16	0.25	-24.824	0.002	0.57
IV-NICa (axial)	Max	0.01	0.02	-29.212	0.350	0.17
IV-NICa rate	Max	0.004	0.007	-29.526	0.621	0.15
IV-NICa product	Max	0.005	0.009	-29.493	0.578	0.23
IV-NICu	**Max**	**0.74**	**0.84**	**-8**	**0.000**	**0.95**
IV-NICu rate	Max	0.10	0.15	-26.723	0.016	0.59
IV-NICu product	**Max**	**0.40**	**0.55**	**-17.677**	**0.000**	**0.83**
(+) : positive peak, (-): negative peak, Max: maximum peak						

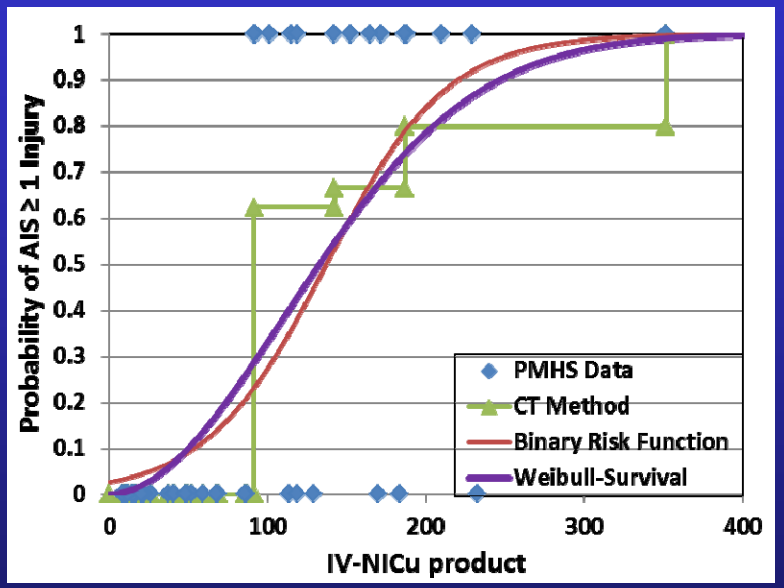
Peudo R^2 > 0.2, Nagelkerke R^2 > 0.4, P-value < 0.05 , Goodman-Kruskal Gamma > 0.6

Best correlation and prediction

Injury Analysis

Injury Risk Curves – IV-NIC parameters





- Each intervertebral level was normalized by physiological range of motions
  - IV-NICu : best correlation to injuries
    - IV-NICu product: also shows correlation
- 50 % chance of AIS 1+ injuries
  - IV-NICu : 1.12
  - IV-NICu product : 132.58

Current/Potential Injury Criteria

- **Correlation between IV-NIC values and existing injury criteria**

$IV - NIC_u$

$(IV - NIC_{u\ product})$

Correlation?

Yes

Potential PMHS IARVs

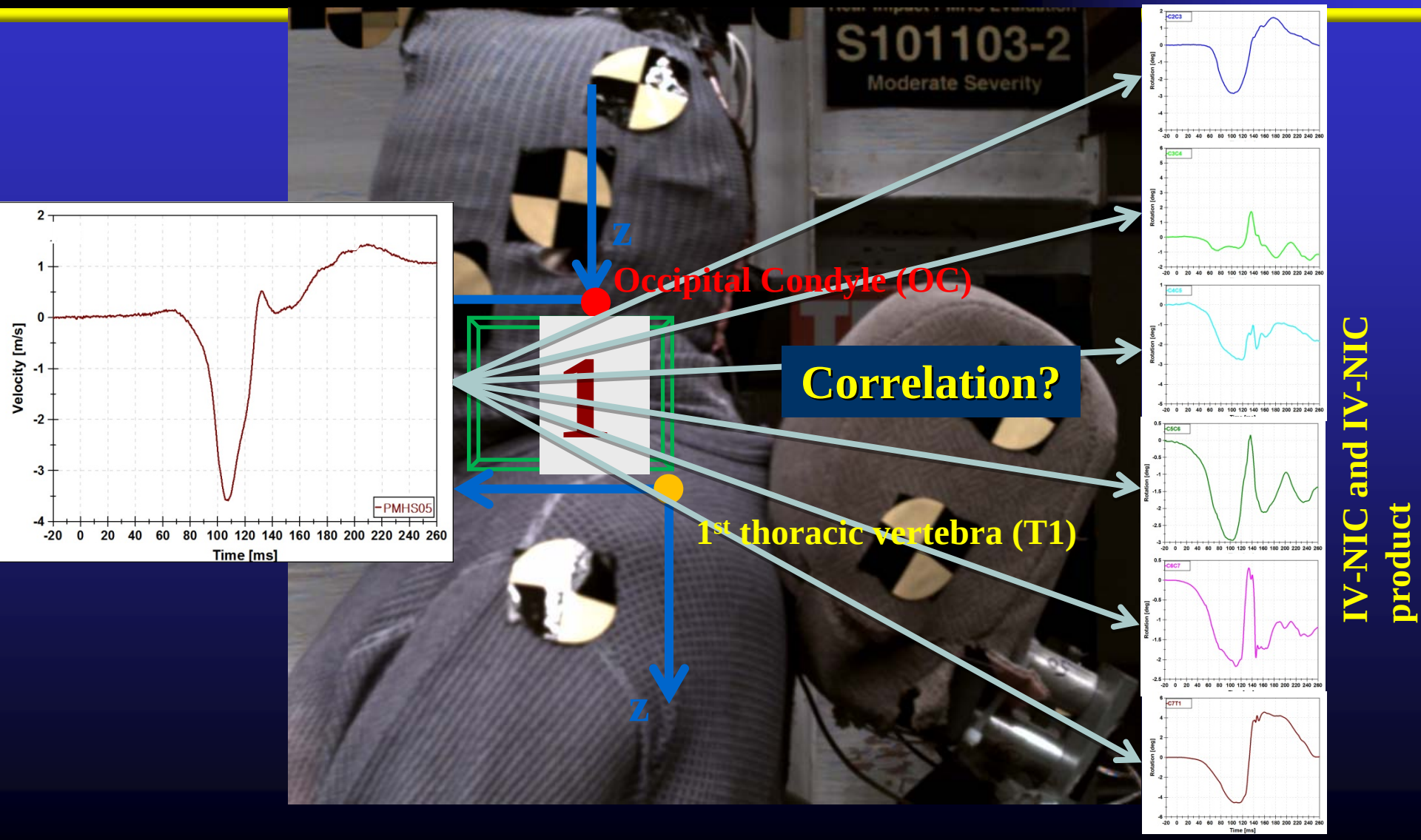
$$NIC = 0.2 \times a_{rel} + v_{rel}^{2}$$

$$N_{km} = \frac{F_x}{F_{\text{int}}} + \frac{M_y}{M_{\text{int}}}$$

NDC, Nij
Head-to-T1 Rotation
Upper/Lower Fx, Fz, My
T1G
Rebound V
Any physical parameters

$$LNL - index(t) = \left| \frac{\sqrt{My_{lower}(t)^2 + Mx_{lower}(t)^2}}{C_{moment}} \right| + \left| \frac{\sqrt{Fx_{lower}(t)^2 + Fy_{lower}(t)^2}}{C_{shear}} \right| + \left| \frac{Fz_{lower}(t)}{C_{tension}} \right|$$

Current/Potential Injury Criteria



Injury Analysis

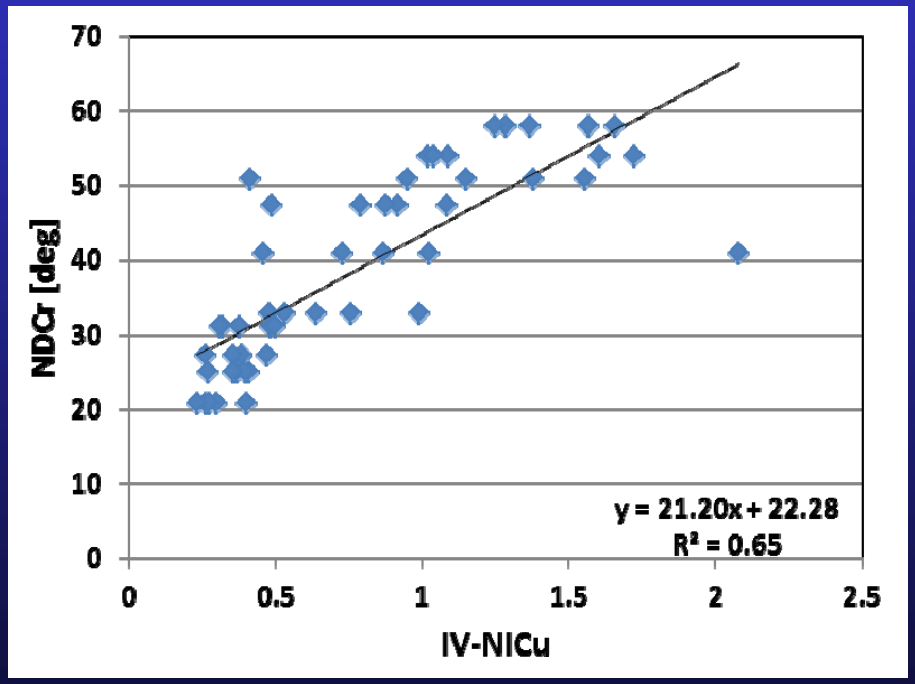
IV-NIC vs. Current/Potential Injury Criteria

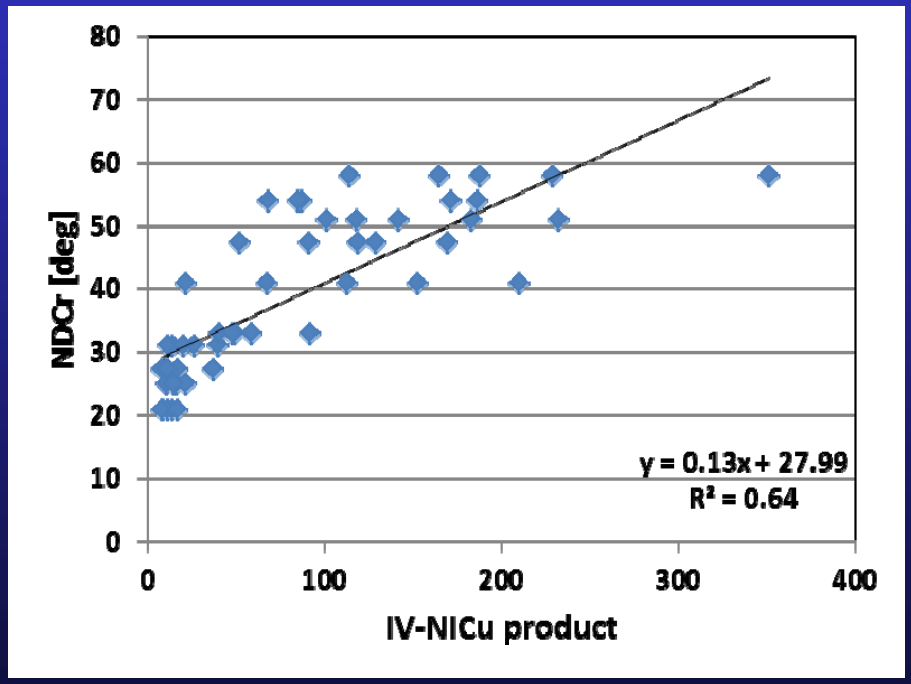
		IV-NICu		IV-NICu product	
		R - value	P - value	R - value	P - value
	NIC	0.685	0	**0.714**	**0**
Nij	**Nte**	0.356	0.011	0.419	0.002
	Ntf	0.68	0	0.659	0
	Nce	0.208	0.147	0.332	0.018
	Ncf	0.698	0	0.661	0
Nkm	**Nae**	0.25	0.08	0.353	0.012
	Naf	0.169	0.24	0.257	0.072
	Npe	0.018	0.899	0.121	0.402
	Npf	0.305	0.031	0.359	0.011
	LNL	0.285	0.045	0.349	0.013
NDC	**NDCx**	**0.72**	**0**	0.687	0
	NDCx rate	**0.799**	**0**	**0.776**	**0**
	NDCx product	**0.809**	**0**	**0.778**	**0**
	NDCz	0.694	0	**0.758**	**0**
	NDCz rate	0.604	0	**0.701**	**0**
	NDCz product	0.588	0	0.695	0
	NDCr	**0.805**	**0**	**0.801**	**0**
	NDCr rate	**0.818**	**0**	**0.801**	**0**
	NDCr product	**0.818**	**0**	**0.81**	**0**

Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCr**





Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

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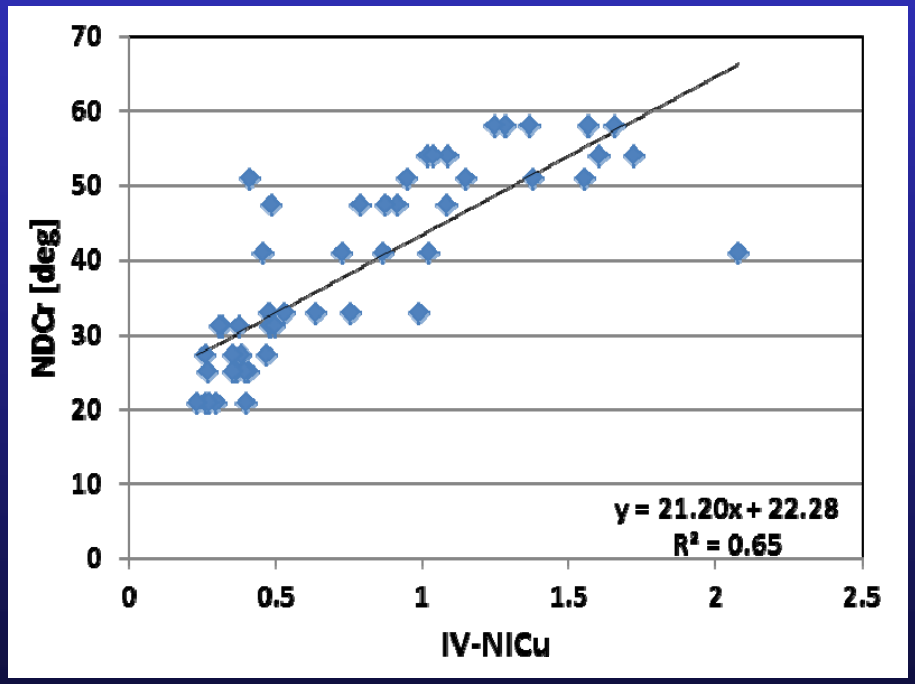
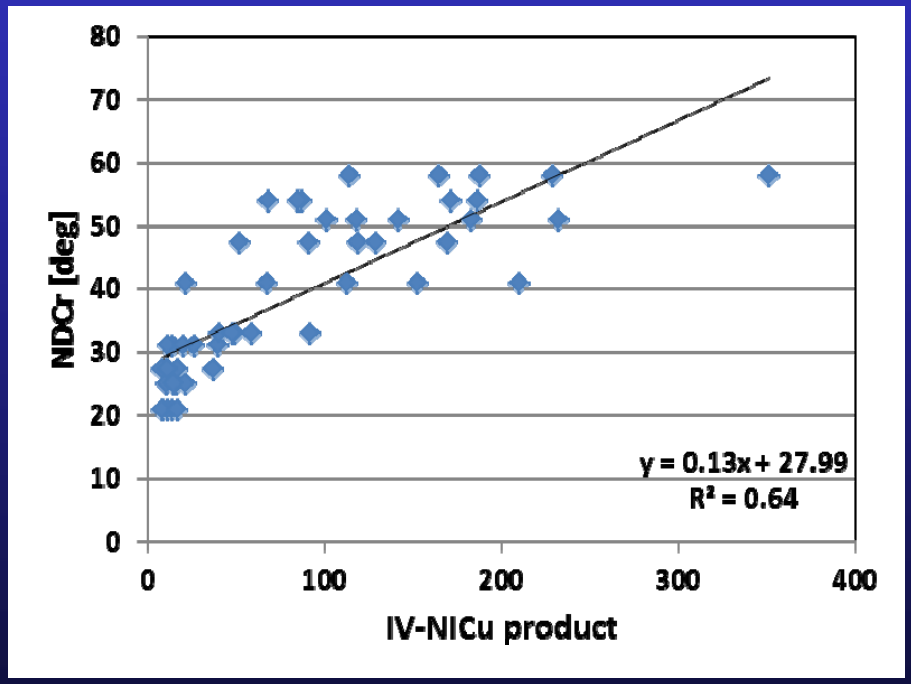
Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCr**





Injury Analysis
Summary

- **Best injury predictor**
  - IV-NIC
    - Rotation more correlated than displacements
  - IV-NIC product
  - Current Injury Criteria
    - NIC, NDC
      - NDCr more correlated than NDCx or NDCz
  - Potential Injury Criteria
    - NDCr rate and product; NDCx rate and product

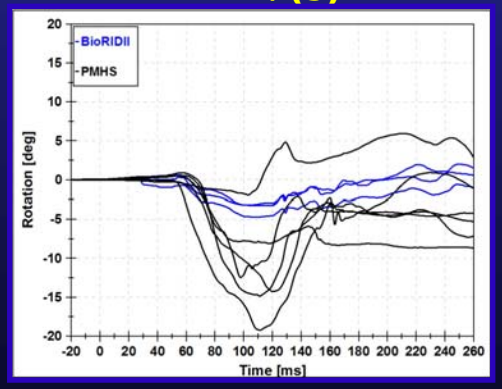
Injury Criteria Analysis Plan

PMHS and BioRID II in identical test conditions

<PMHS>

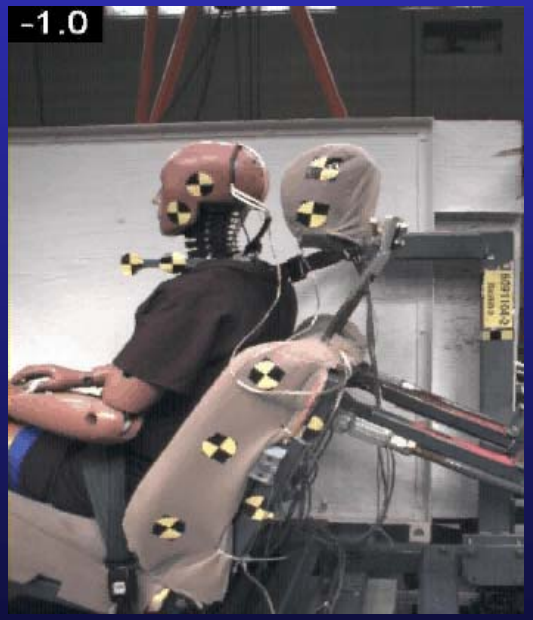
Scaling technique for IARV(s)

Transfer function for IARV(s)



<Intervertebral rotation @ C4/C5>

<BioRIDII>



Injury Criteria Analysis Plan

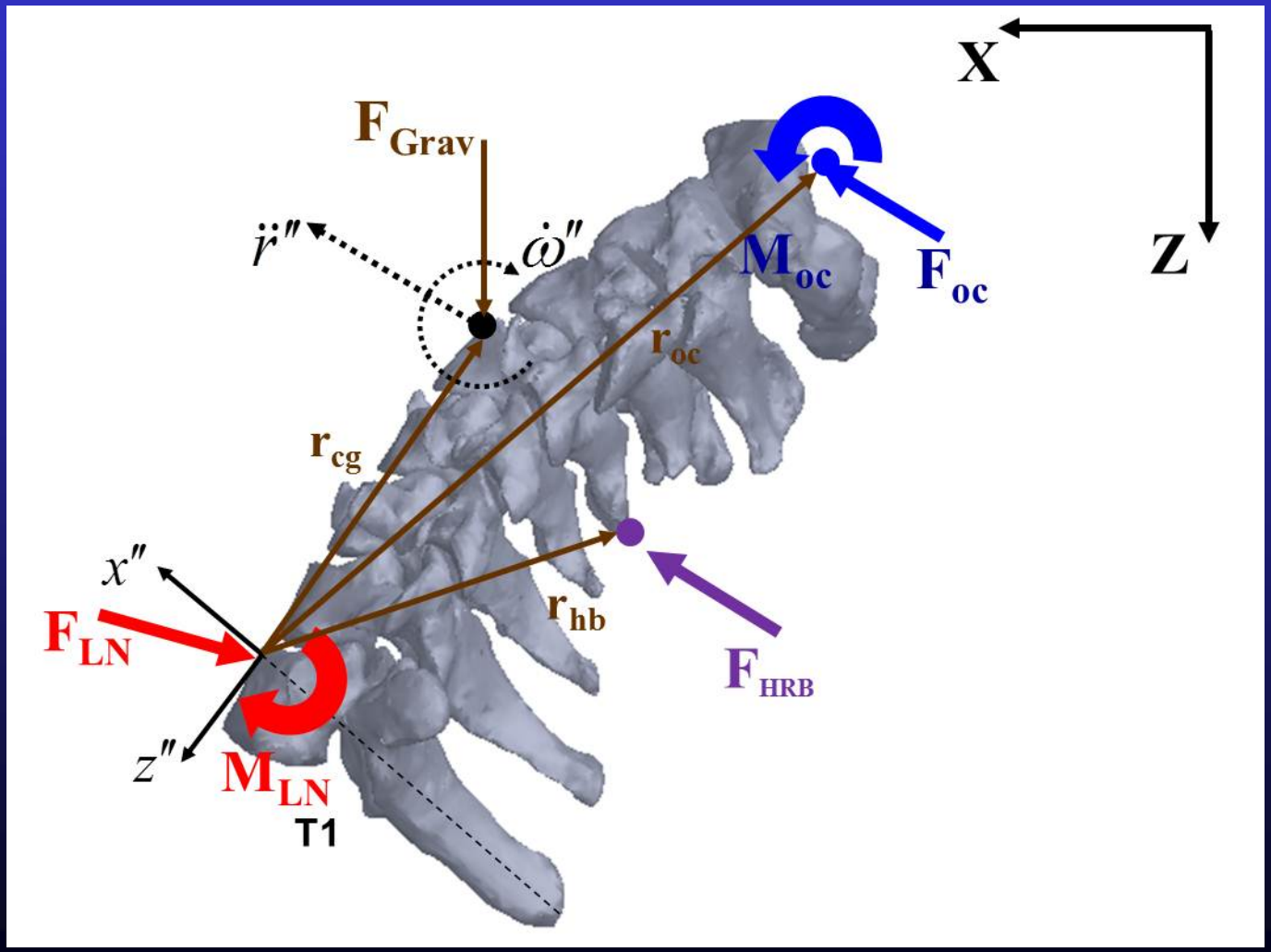
- **Plan for next meeting**
  - Calculate intervertebral strain and strain rate
    - Develop corresponding injury risk curves
  - Detailed discussion and collaboration with Japan
  - Develop most appropriate IARVs for PMHS
  - Develop most appropriate IARVs for BioRID II

Thanks for your attention

Questions?

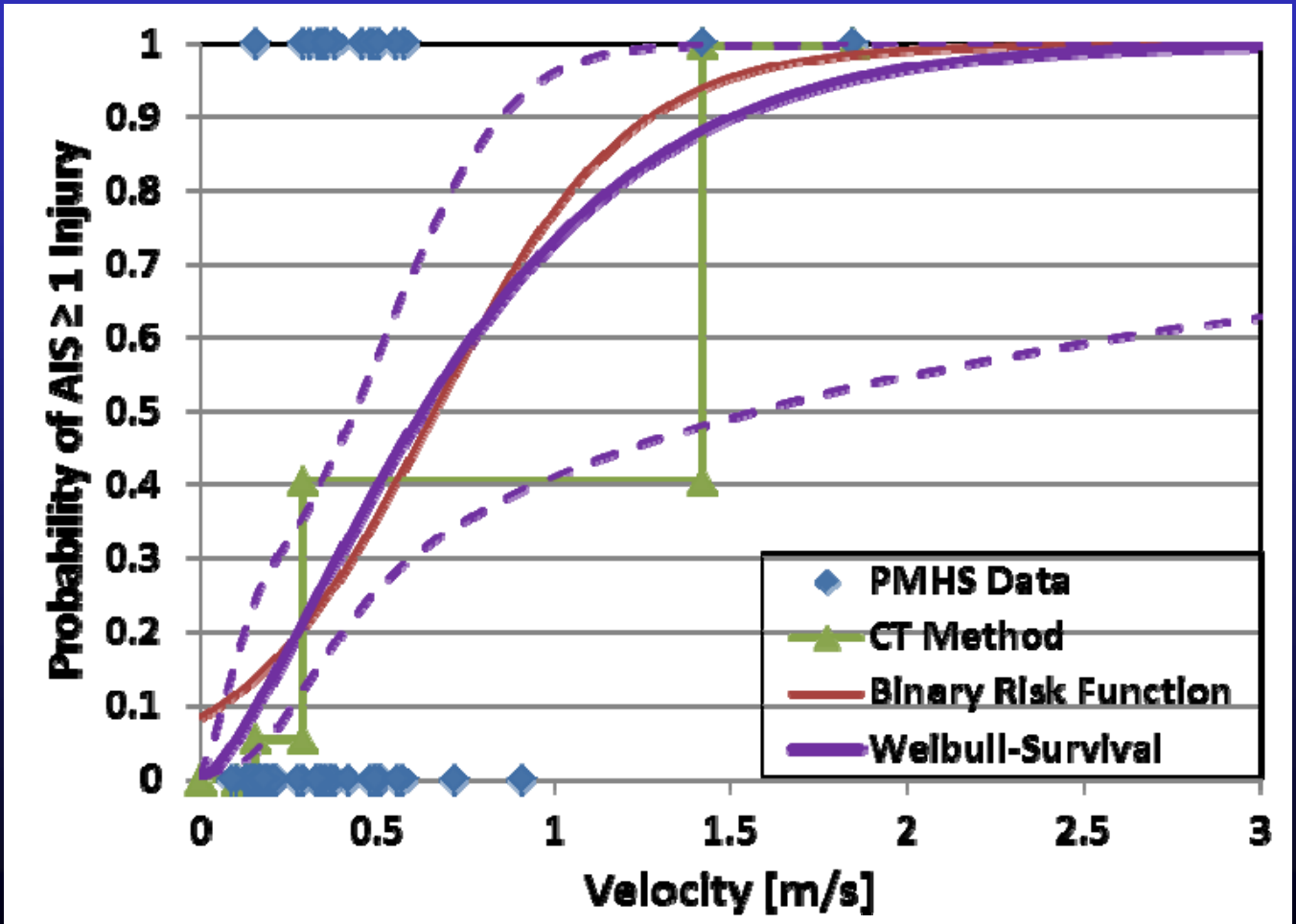
NHTSA
www.nhtsa.gov

FBD for Lower Neck Loads



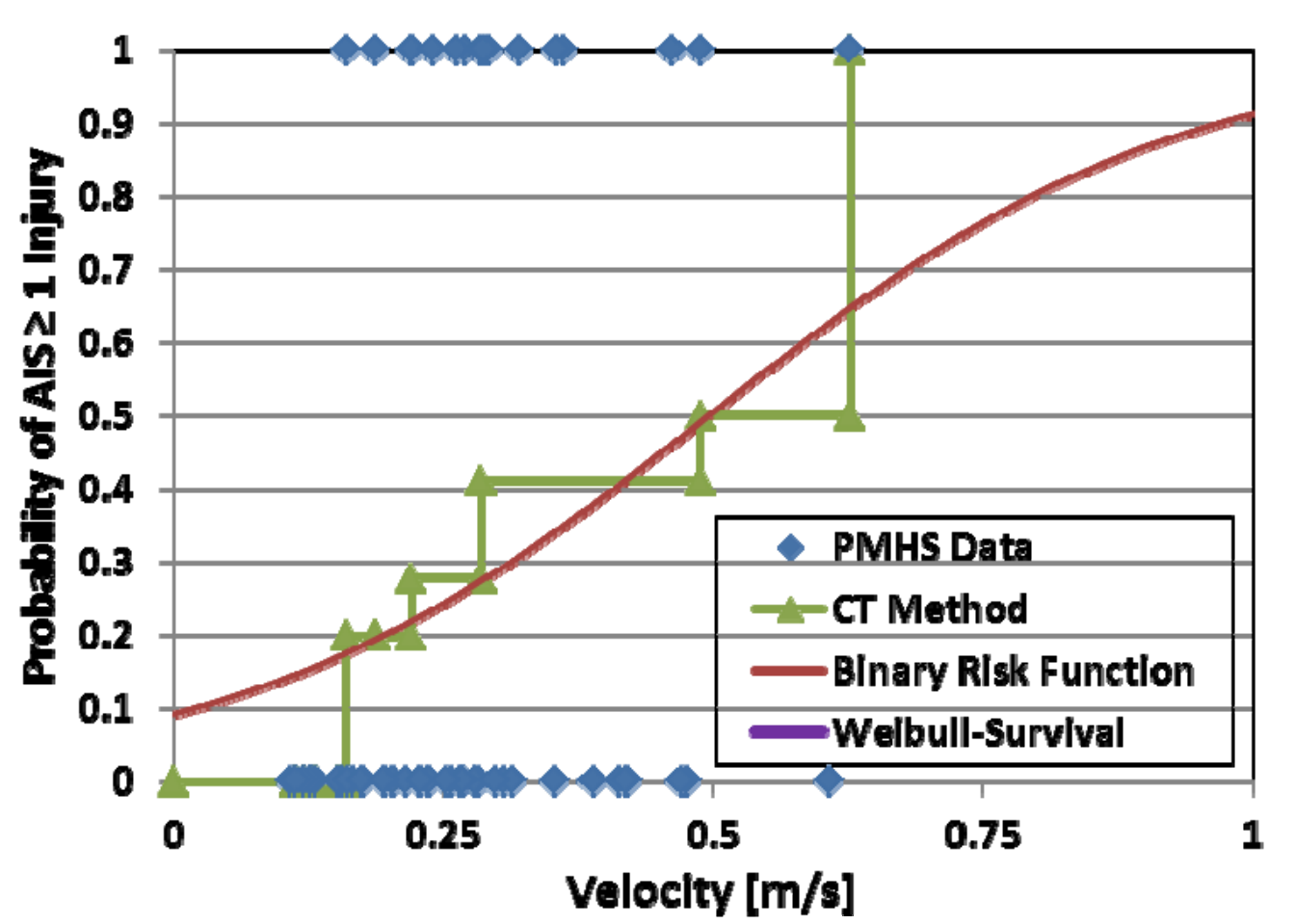
Additional Injury Risk Curves

- Intervertebral facet sliding rate (maximum peak)



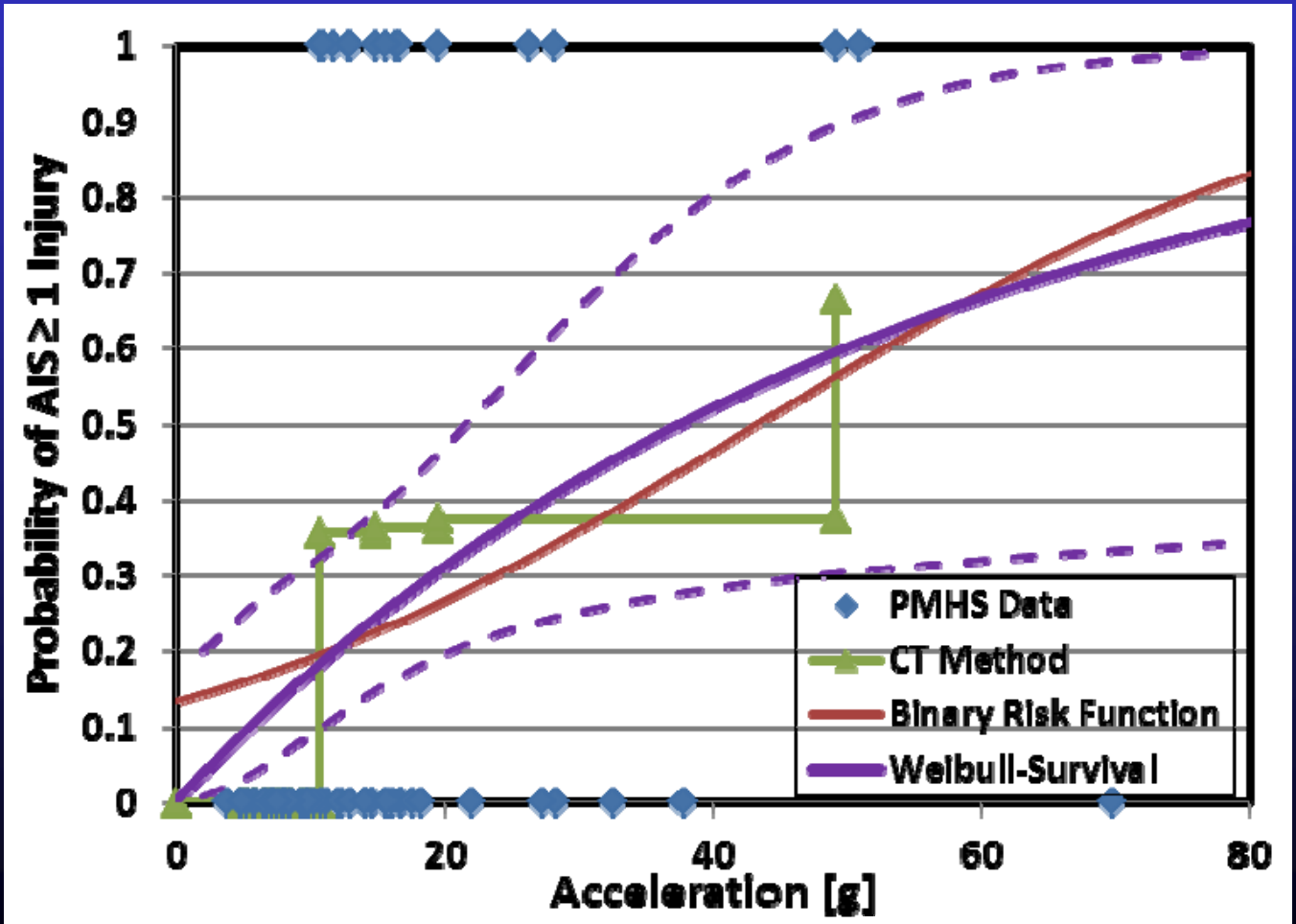
Additional Injury Risk Curves

- Intervertebral facet axial rate (maximum peak)



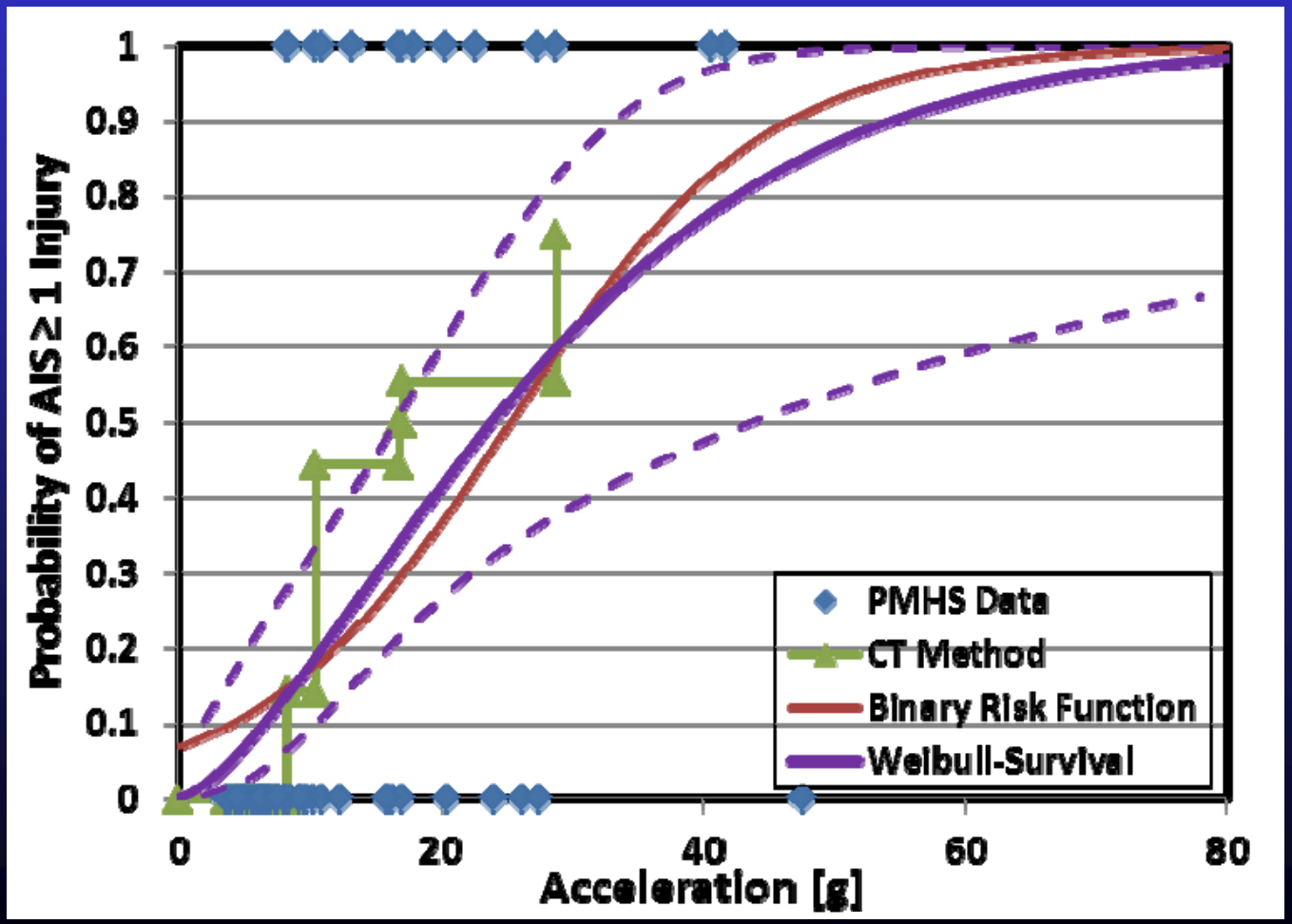
Additional Injury Risk Curves

- Intervertebral acceleration (positive peak x)



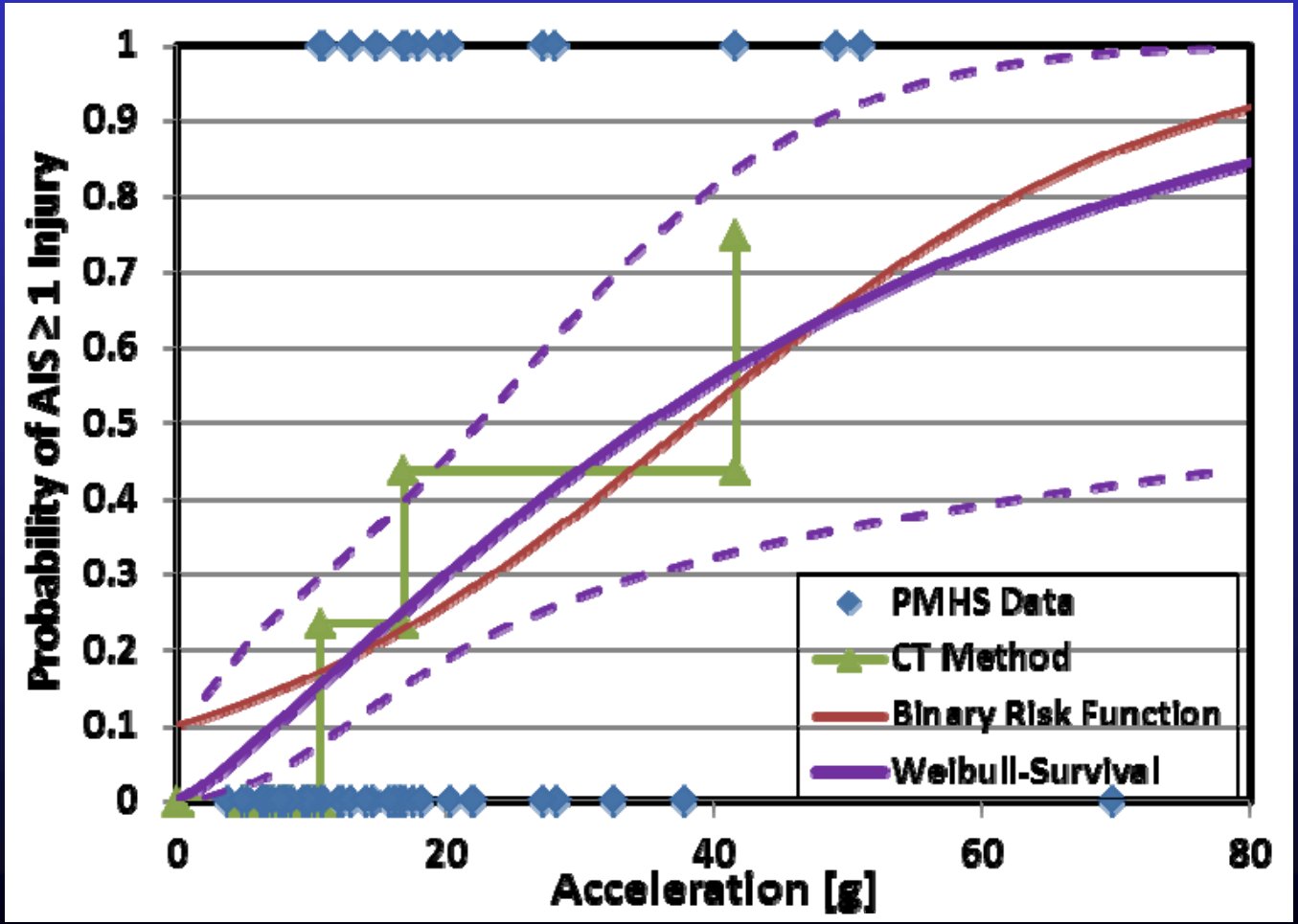
Additional Injury Risk Curves

- Intervertebral acceleration (negative peak x)



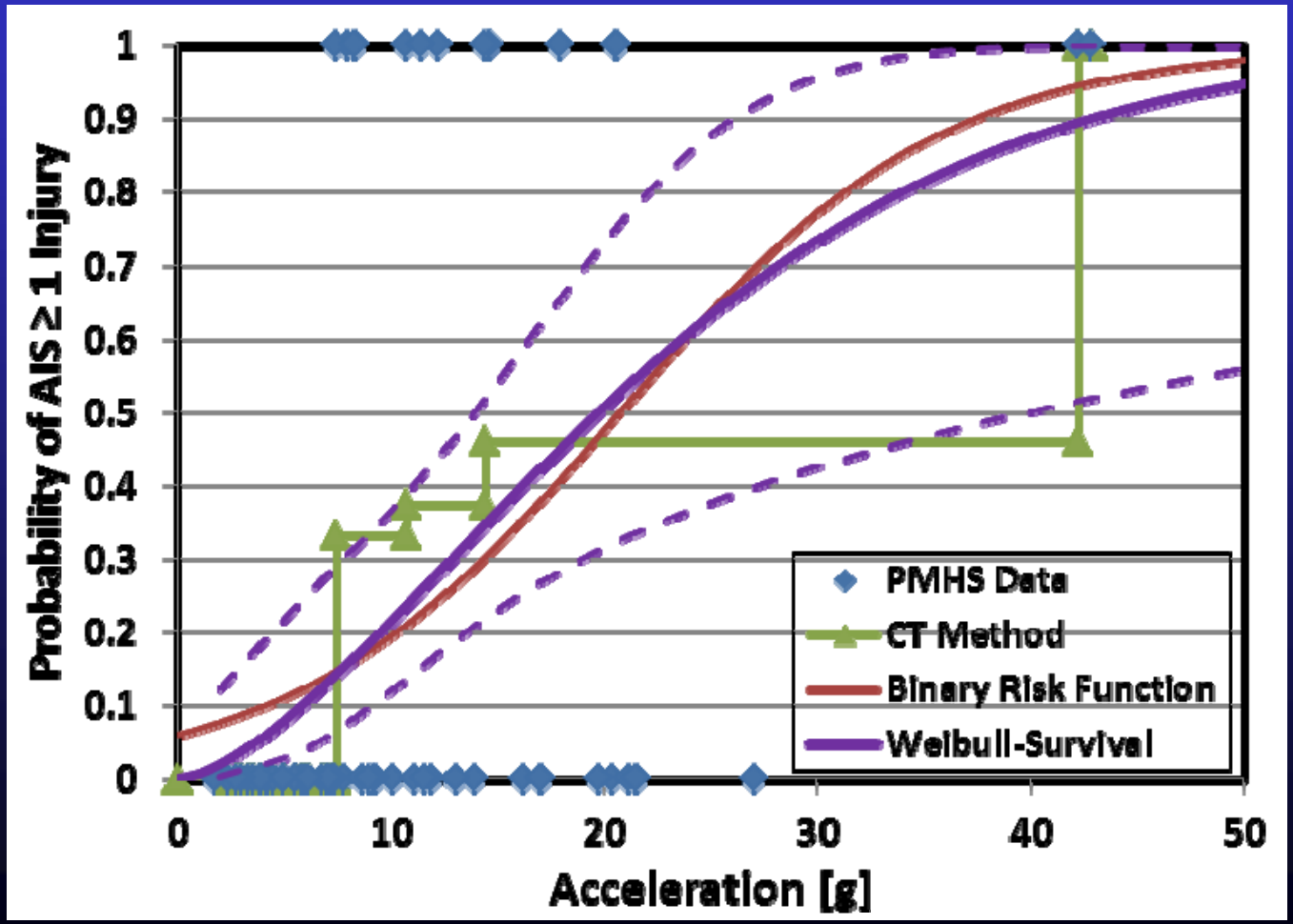
Additional Injury Risk Curves

- Intervertebral acceleration (maximum peak x)



Additional Injury Risk Curves

- Intervertebral acceleration (positive peak z)



Additional Injury Risk Curves

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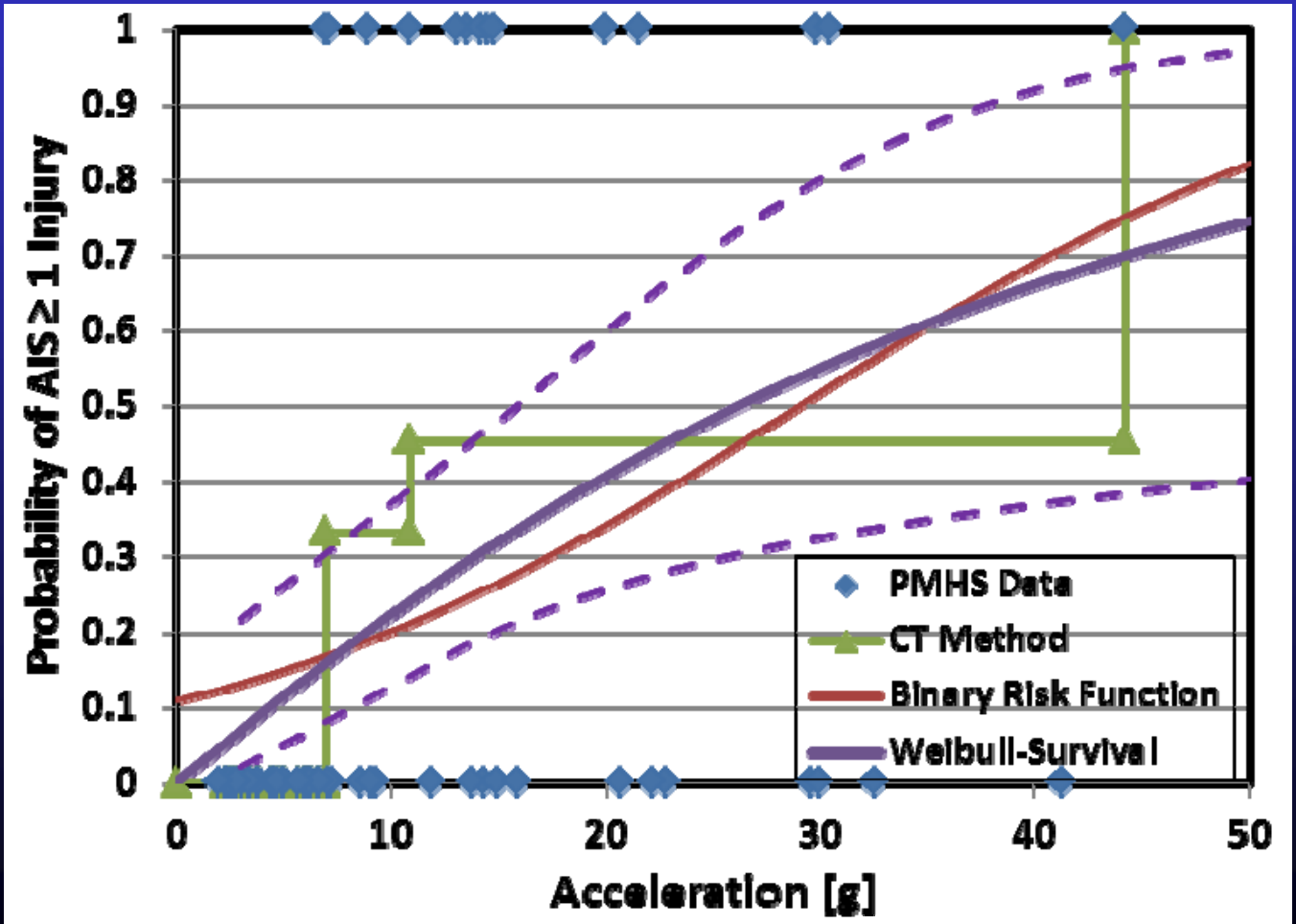

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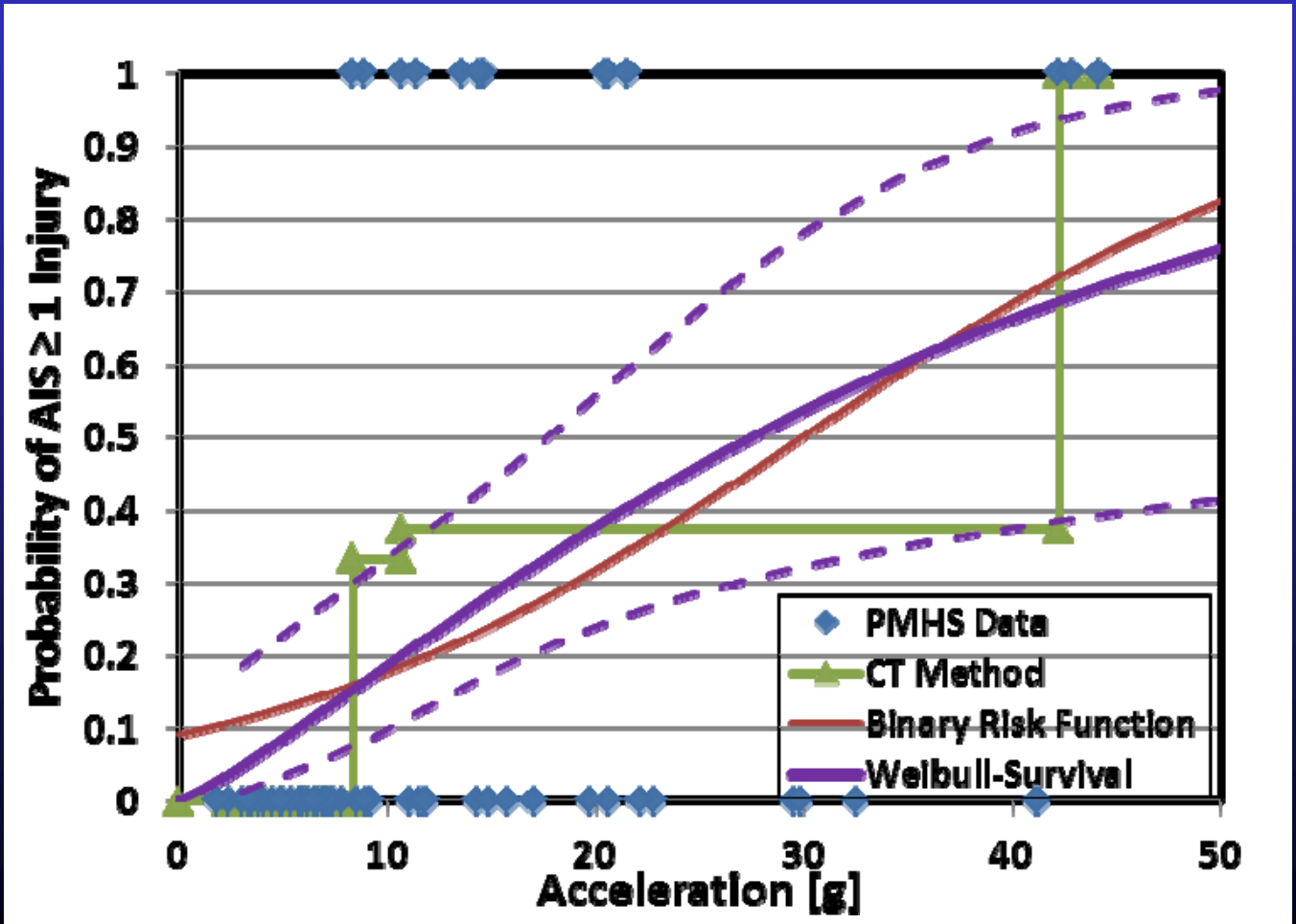
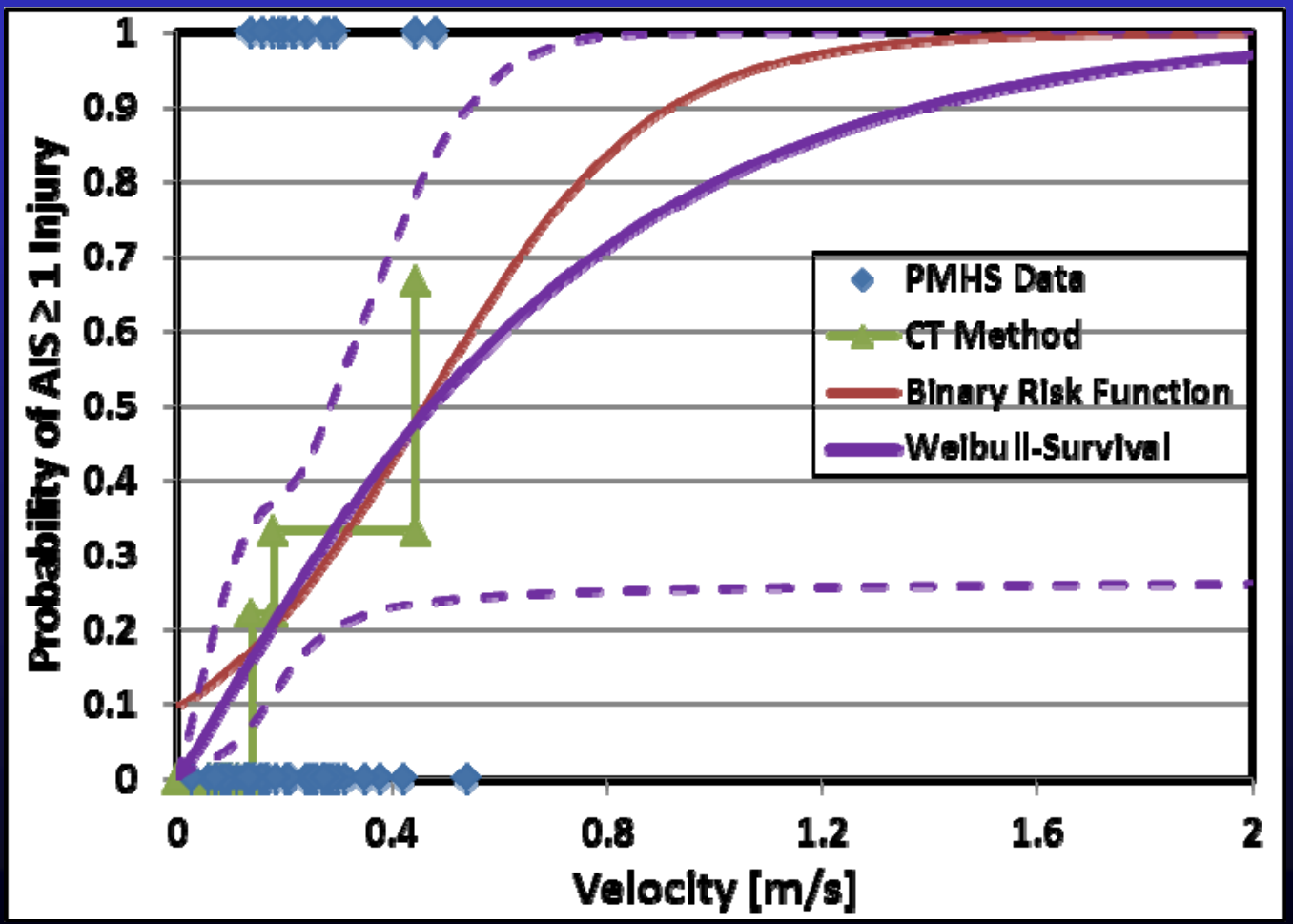


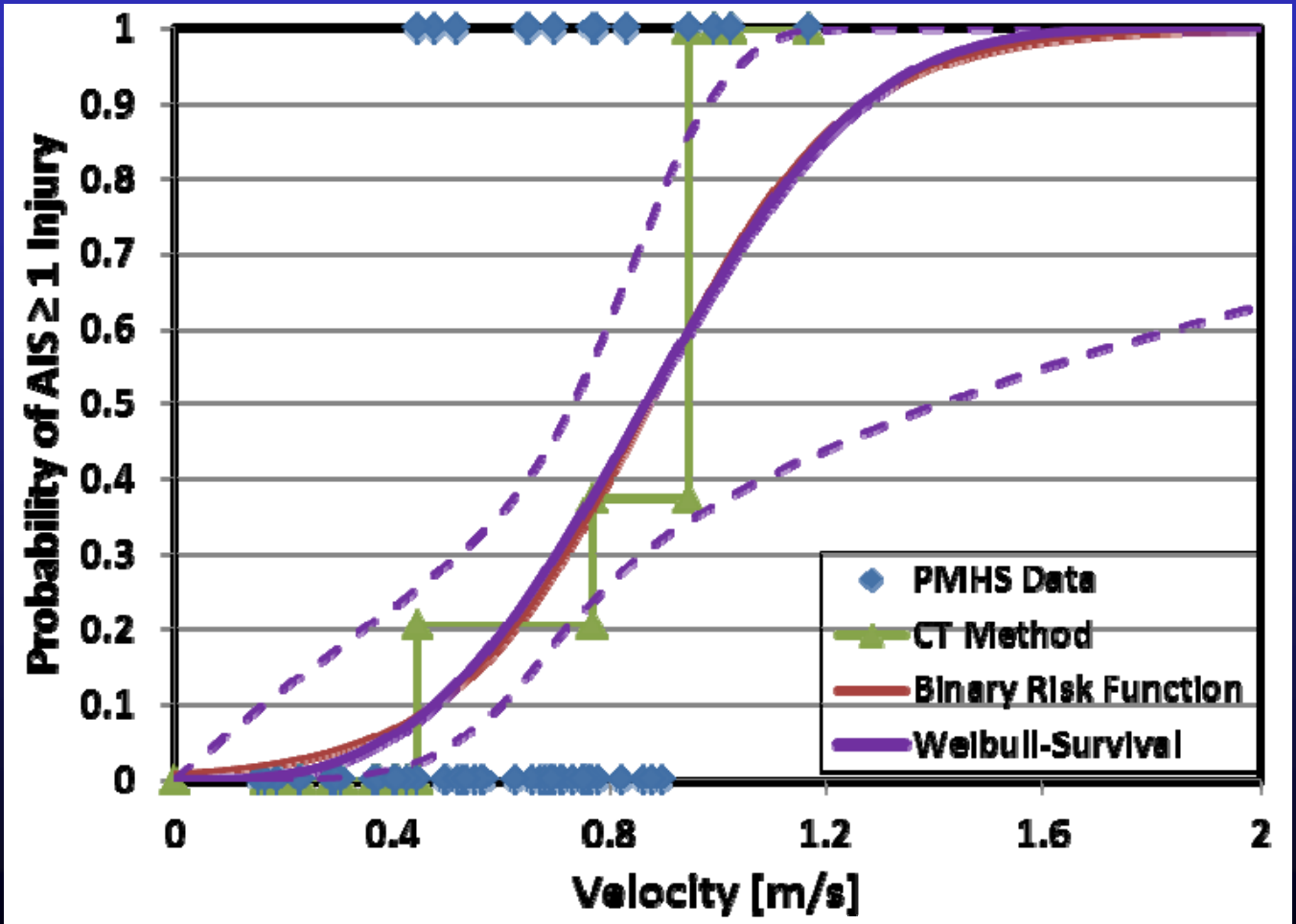
Additional Injury Risk Curves

- Intervertebral velocity (positive peak x)



Additional Injury Risk Curves

- Intervertebral velocity (negative peak x)



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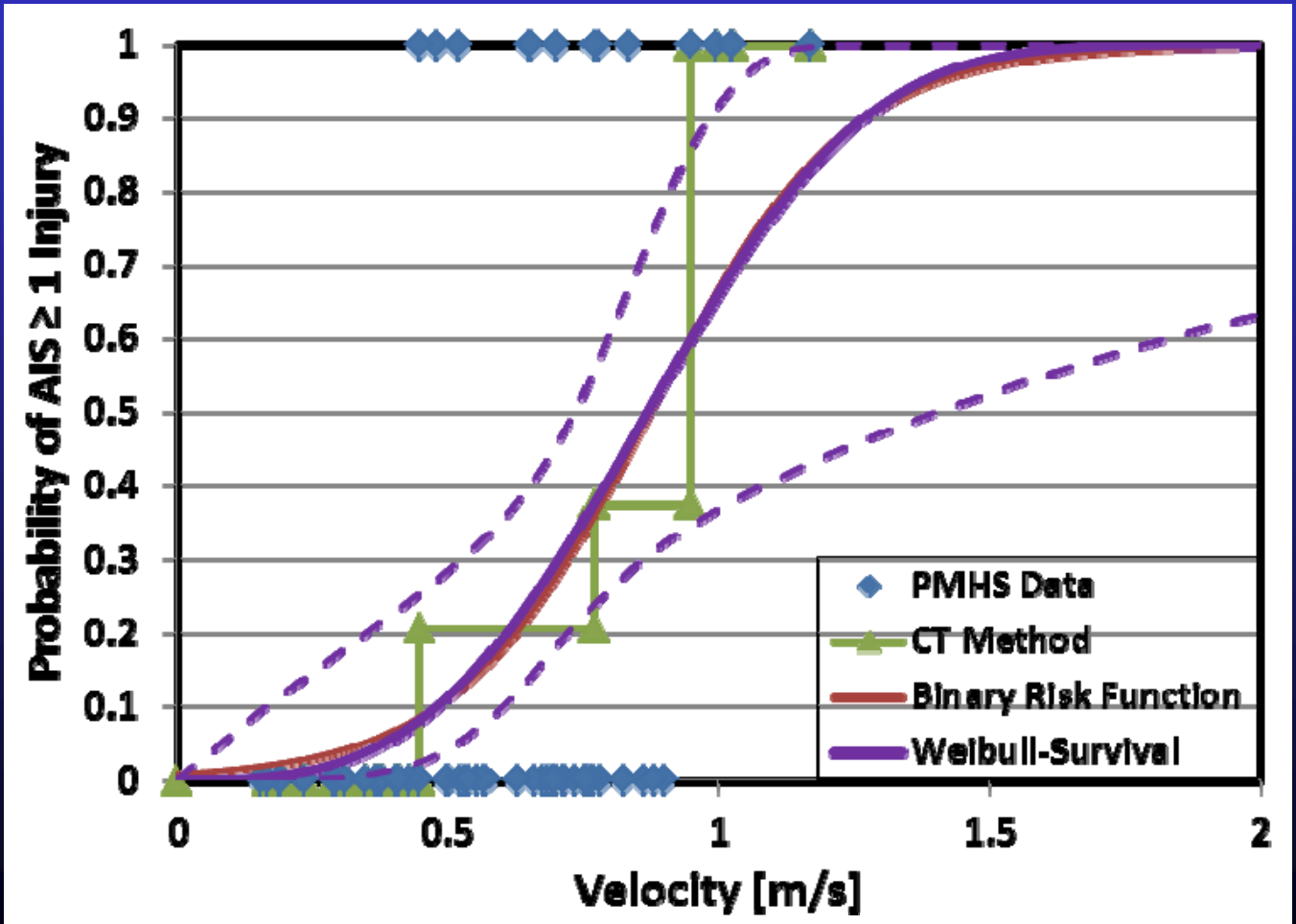

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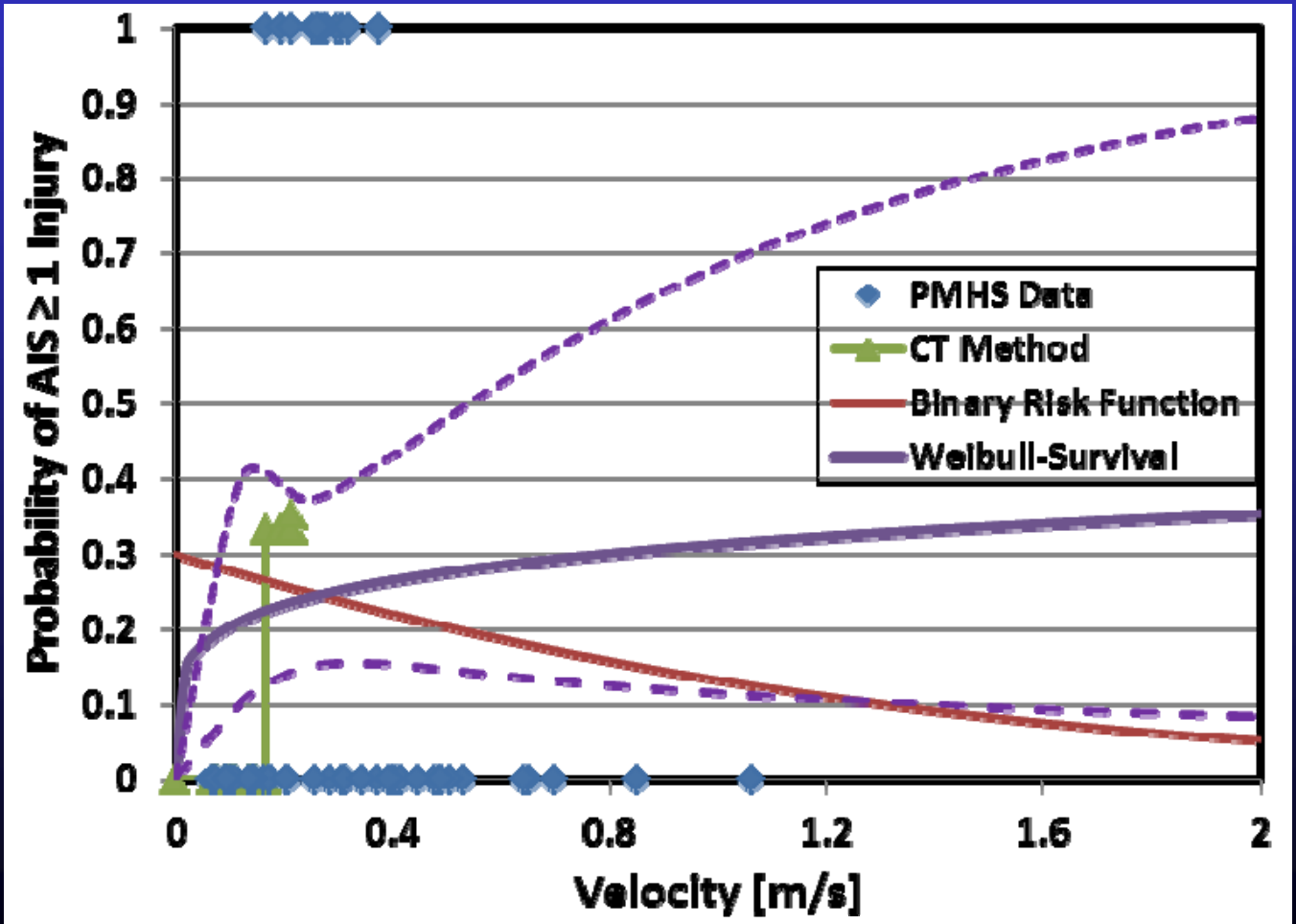
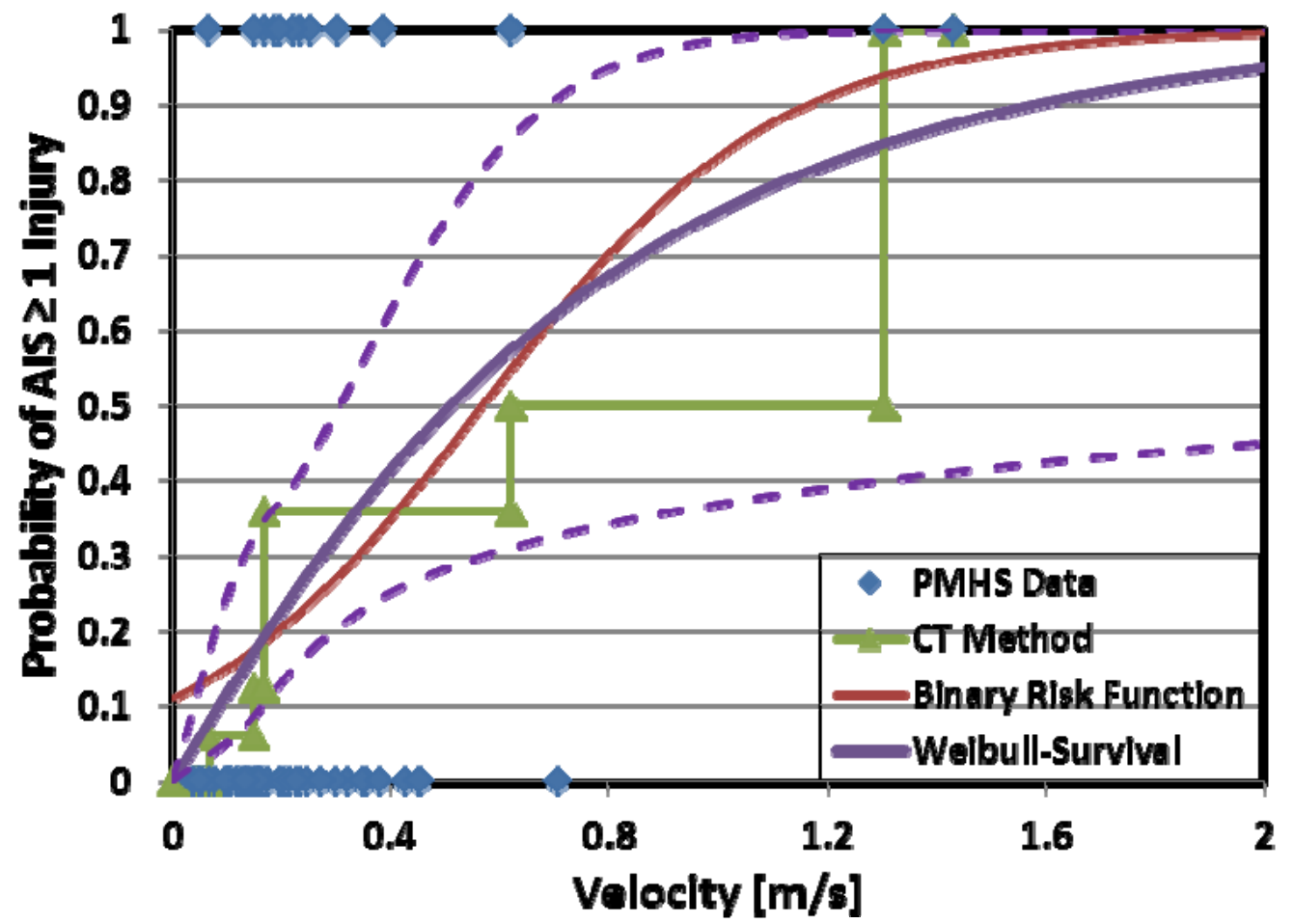


Additional Injury Risk Curves

- Intervertebral velocity (negative peak z)



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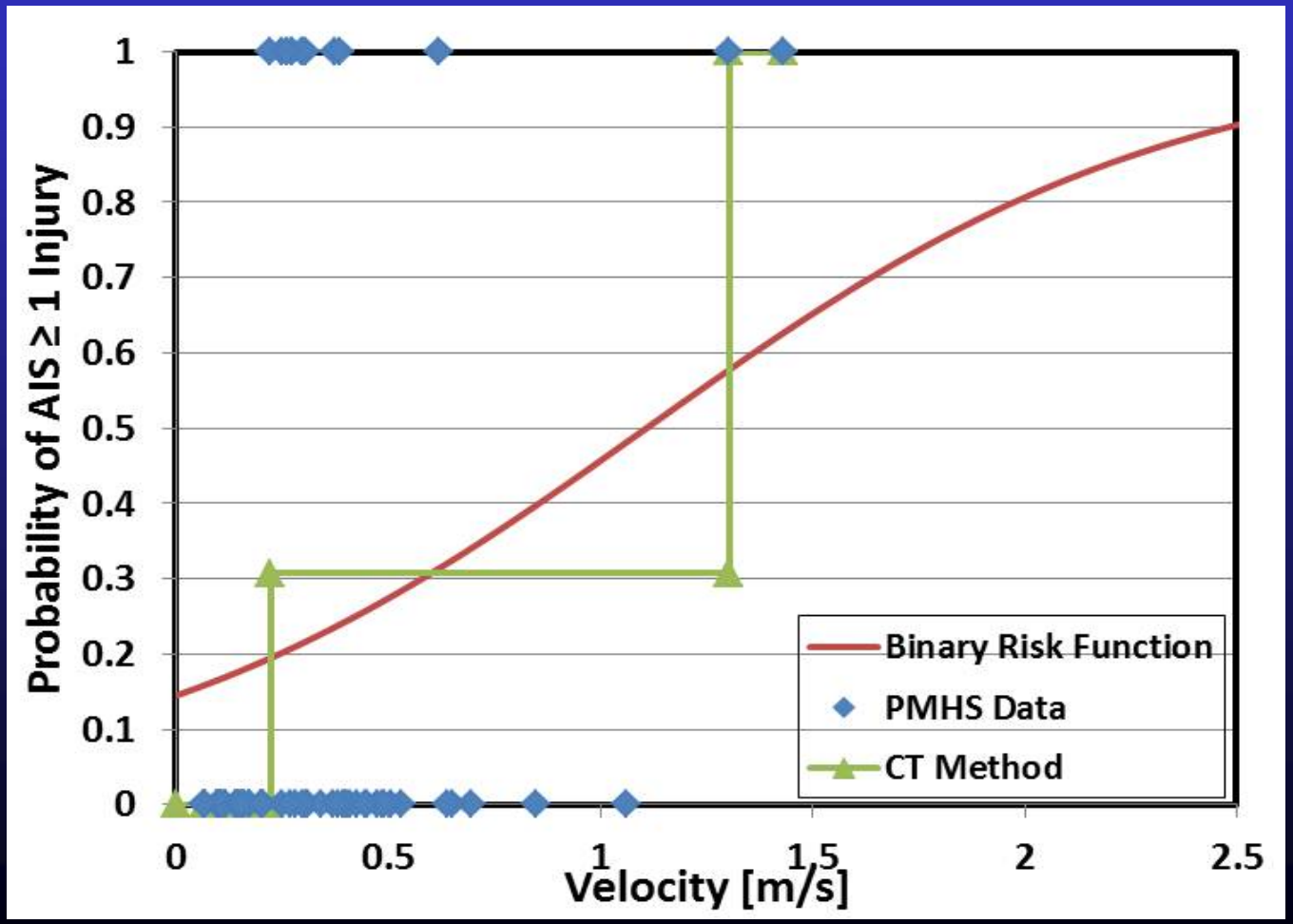
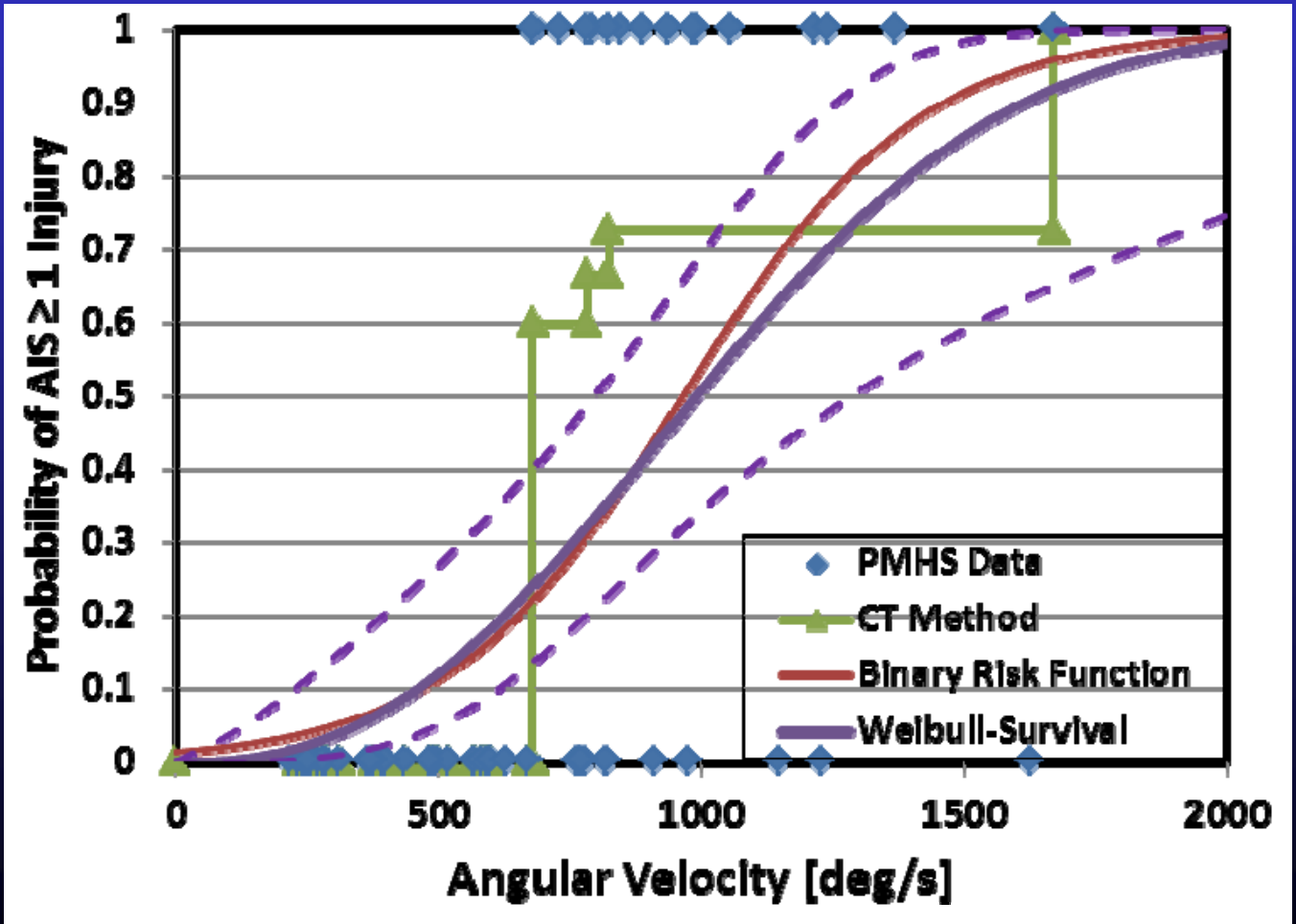


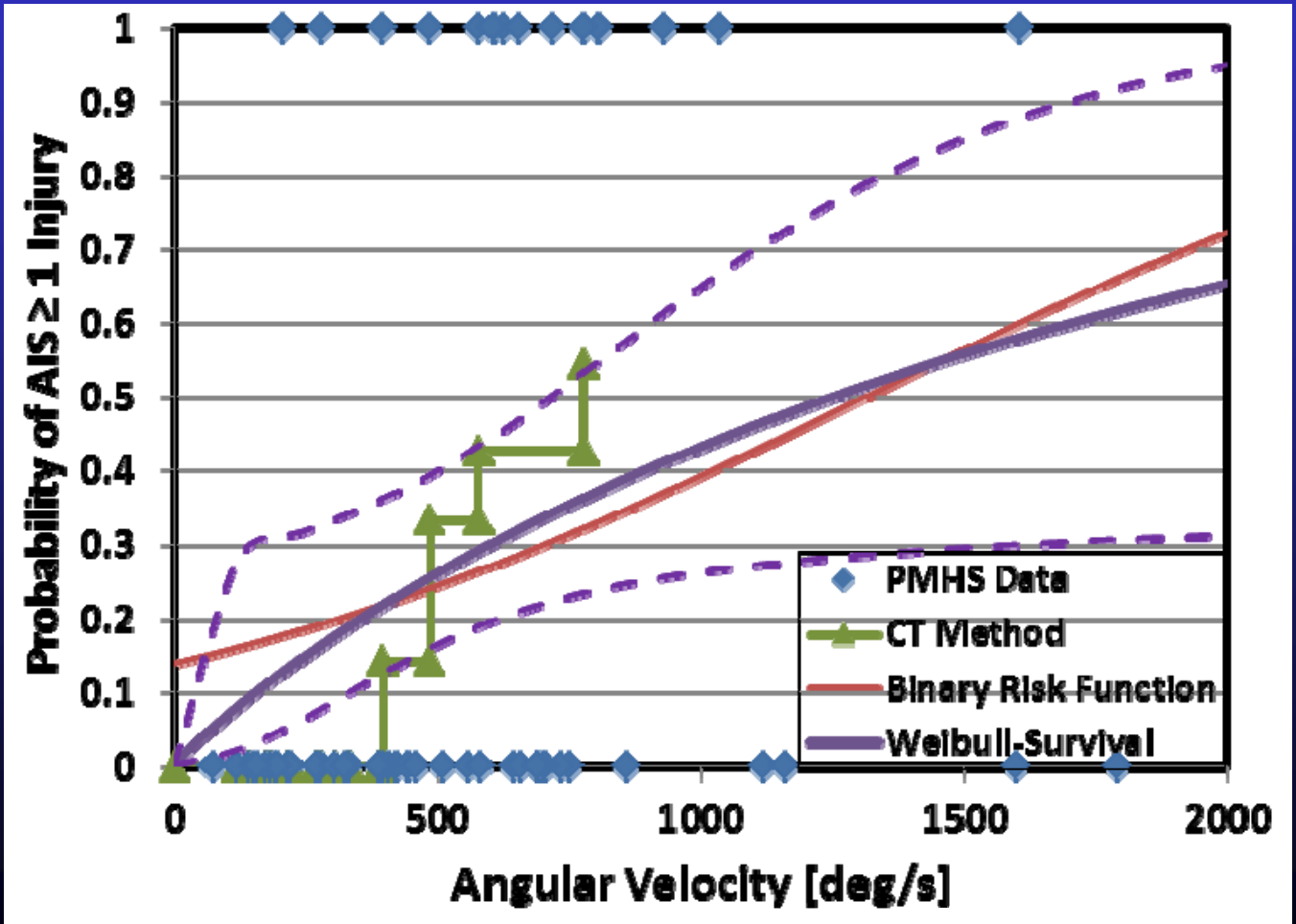
Additional Injury Risk Curves

- Intervertebral angular velocity (positive peak y)



Additional Injury Risk Curves

- Intervertebral angular velocity (negative peak y)



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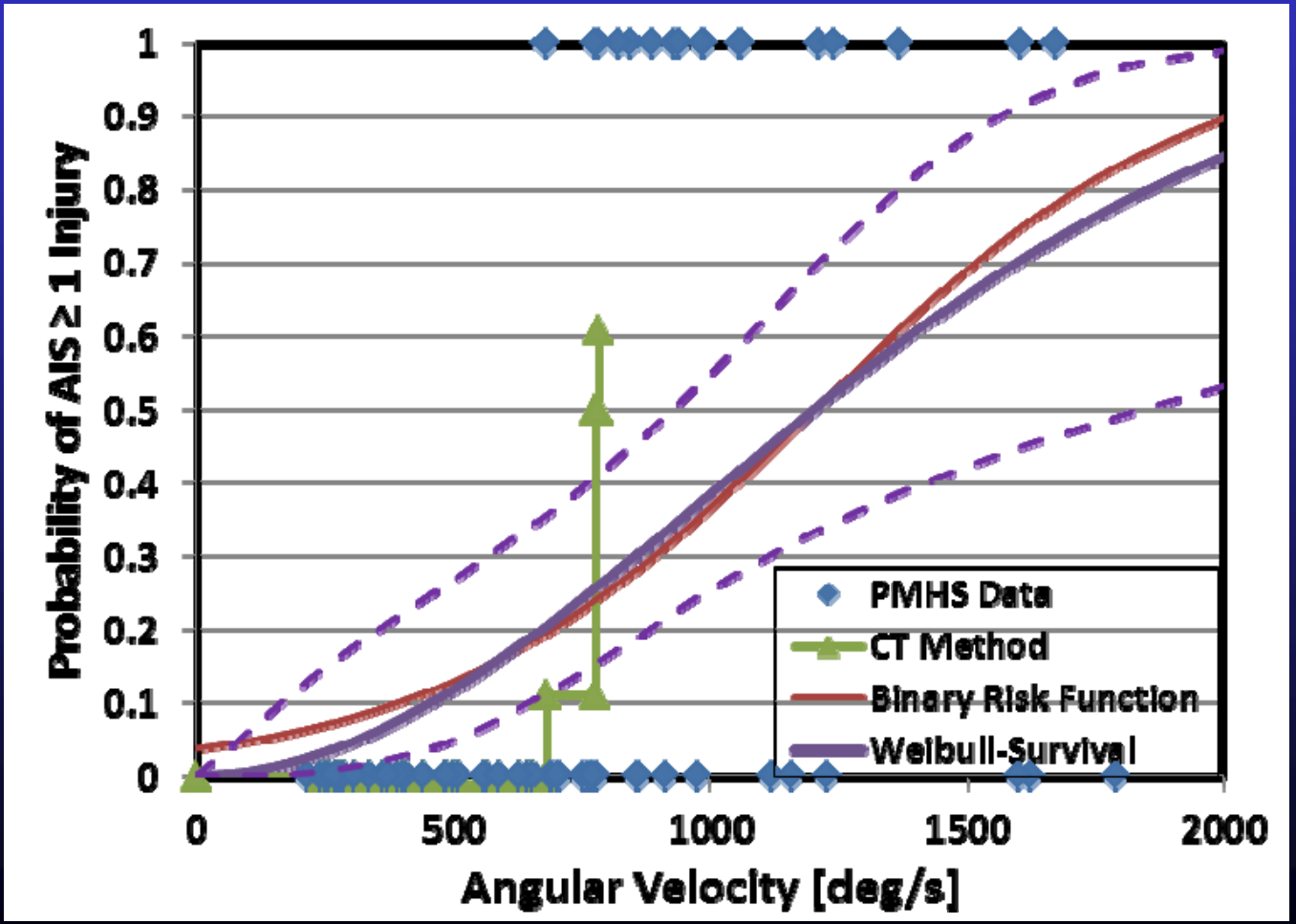
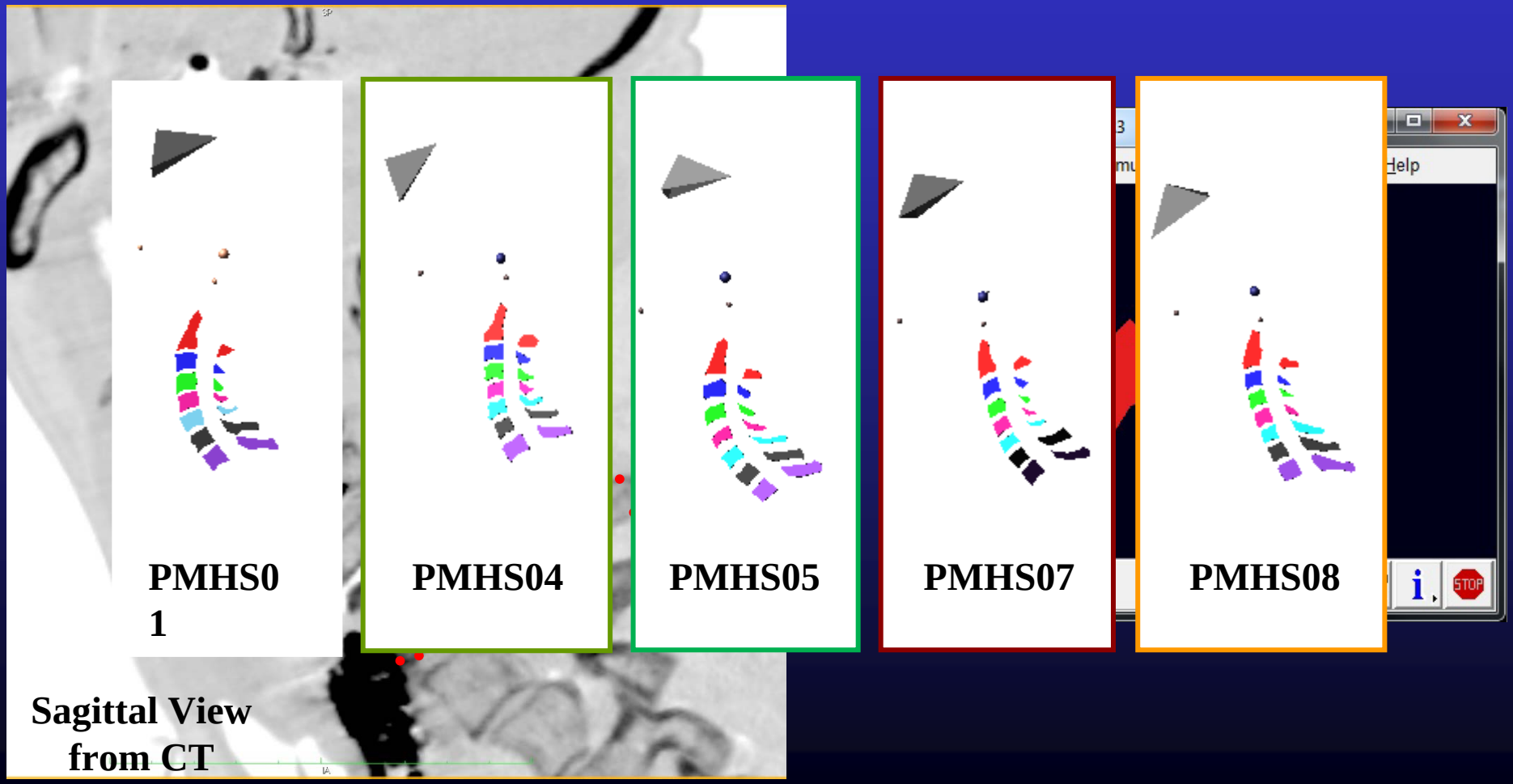


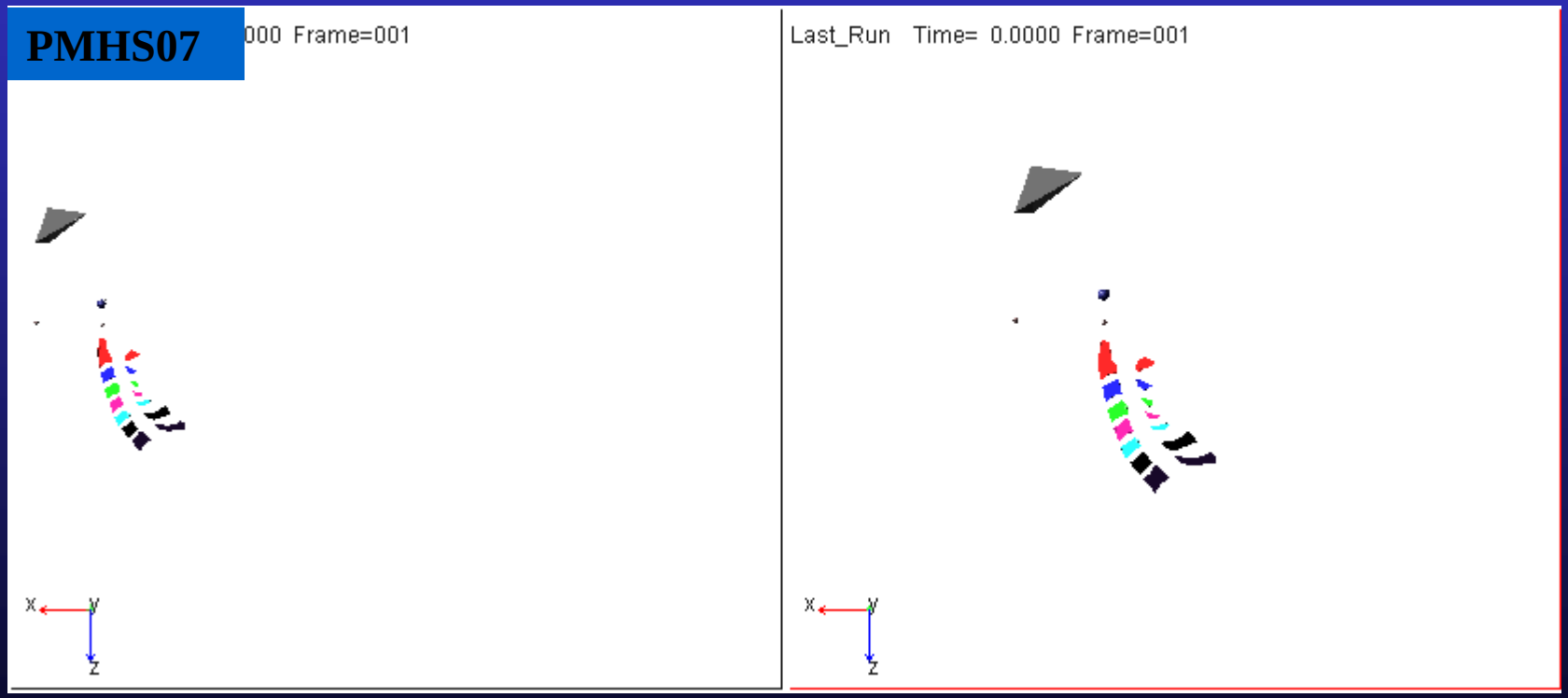
Cervical Kinematics (detailed geometry)

- **Detailed cervical model**



Cervical Kinematics (detailed geometry)

- **Detailed cervical model**
  - able to calculate strain and strain rate between vertebrae



correlation between strain/strain rate and injuries at each level

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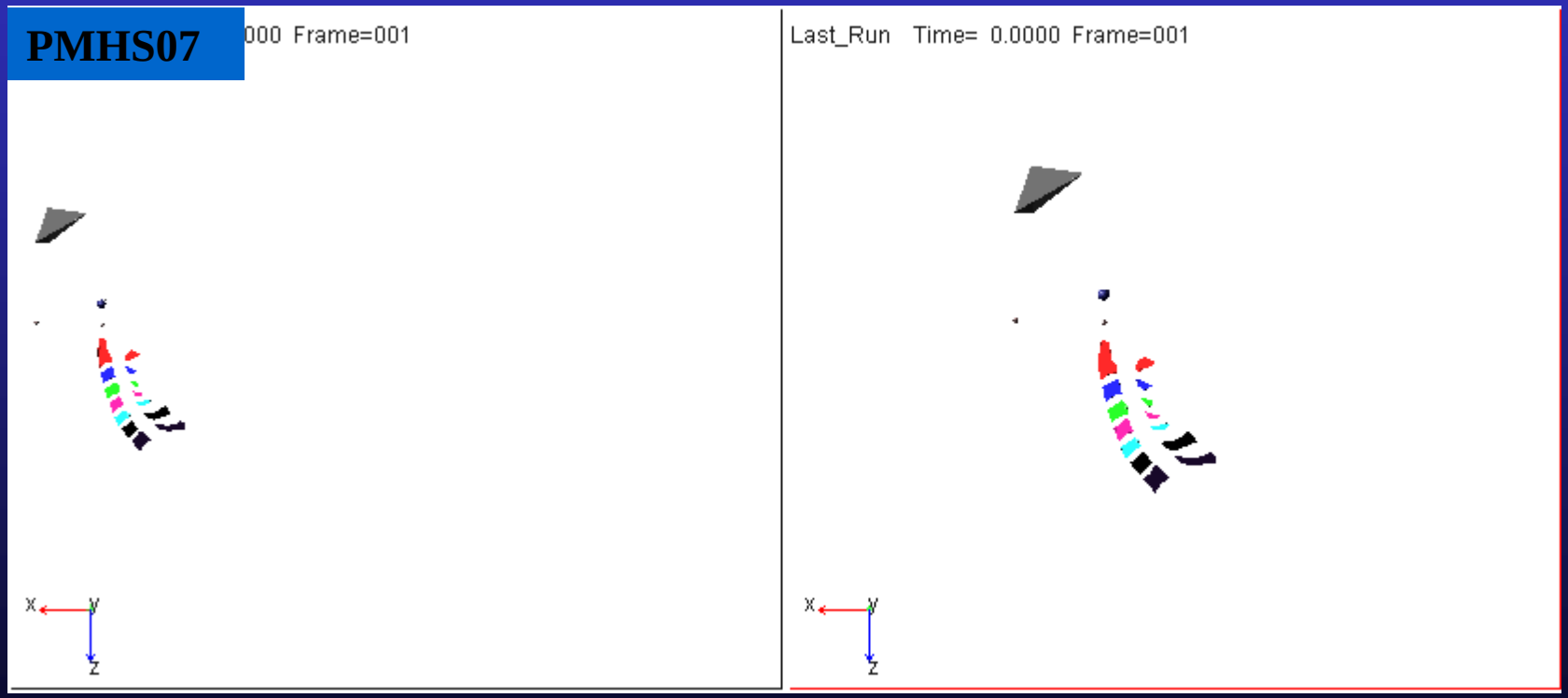
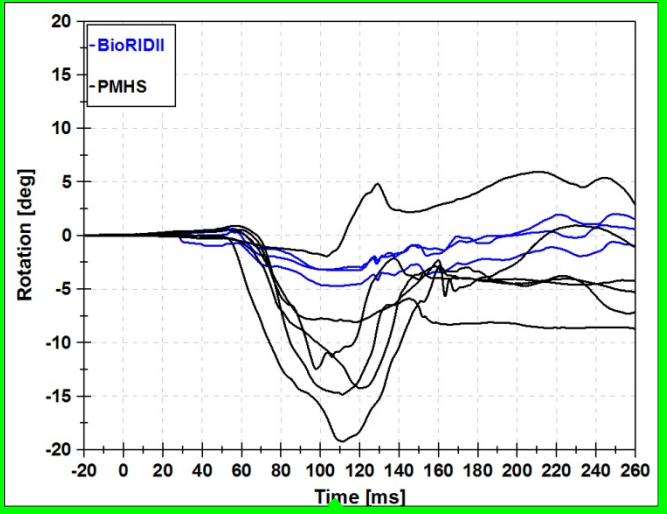


correlation between strain/strain rate and injuries at each level

IV-NIC Calculation

Physiological Relative Rotation (Panjabi, 2005)		
	Physiological Flexion(-)/Extension(+)	Max values Flexion/Extension
C2/C3	-5.4(2.3)/+3.6(1.8)	-7.7/+5.4
C3/C4	-5.7(2.7)/+4.2(1.9)	-8.4/+6.1
C4/C5	-7.6(2.7)/+6.7(2.9)	-10.3/+9.6
C5/C6	-7.7(4.5)/+6.5(3.5)	-12.2/+10.0
C6/C7	-8.0(1.6)/+7.1(2.2)	-9.6/+9.3
C7/T1	-3.7(1.6)/+3.1(1.1)	-5.3/+4.2

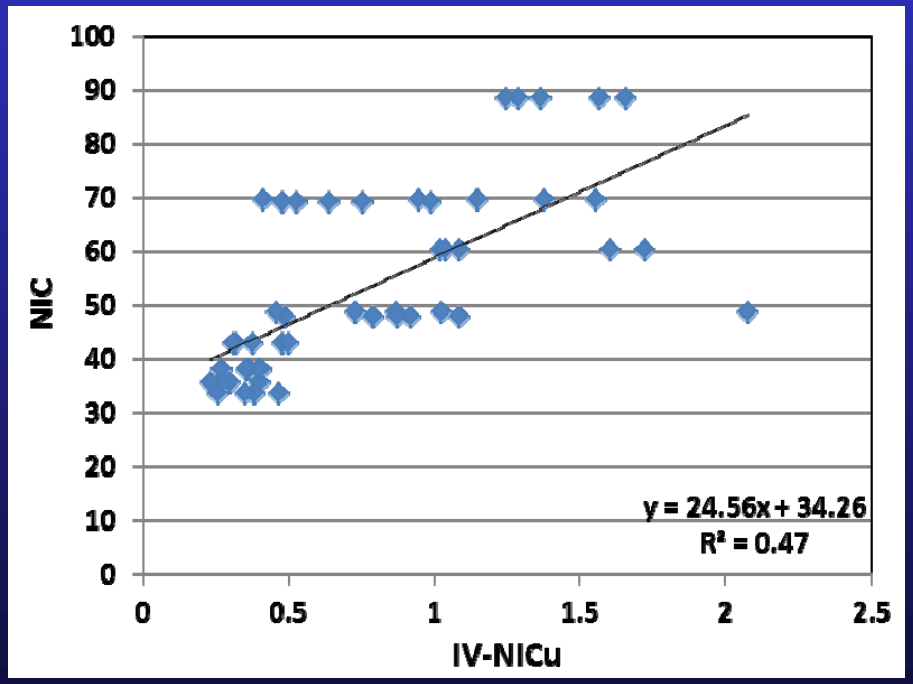


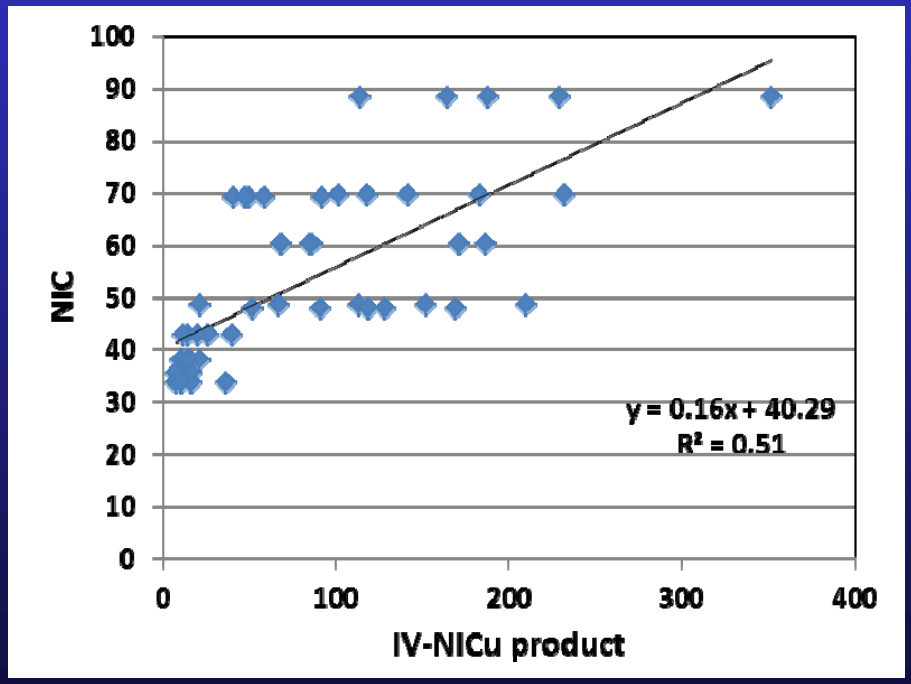
$$IV - NIC = \frac{\Theta_{trauma}}{\Theta_{physiological}}$$

Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NIC**

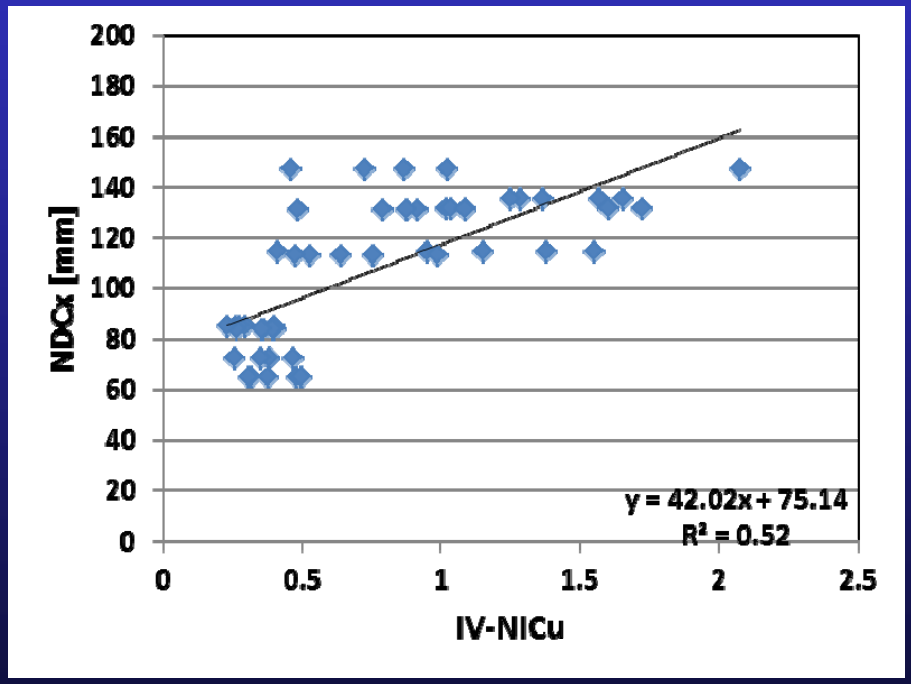


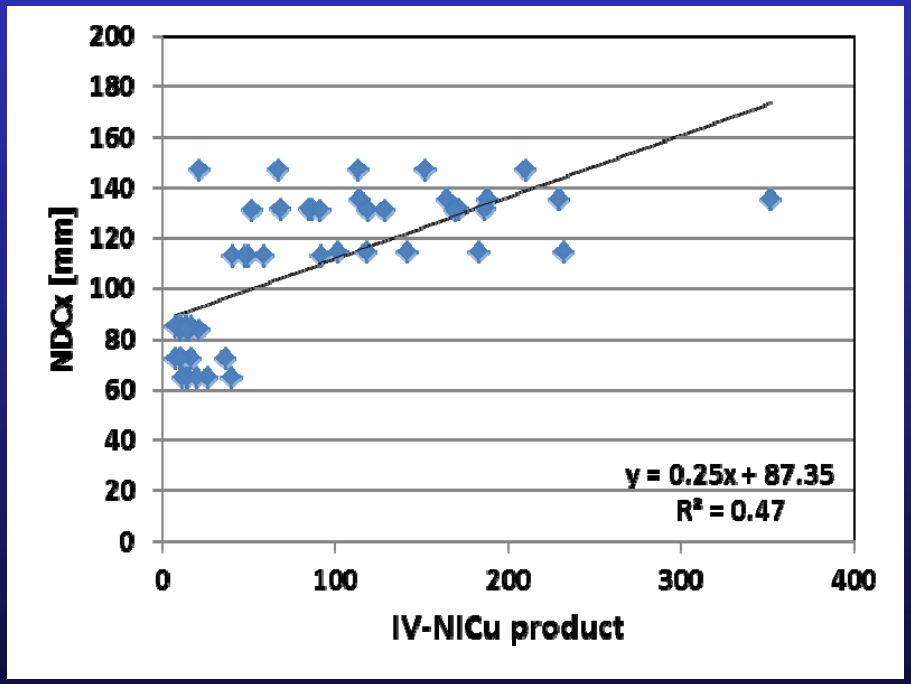


Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCx**

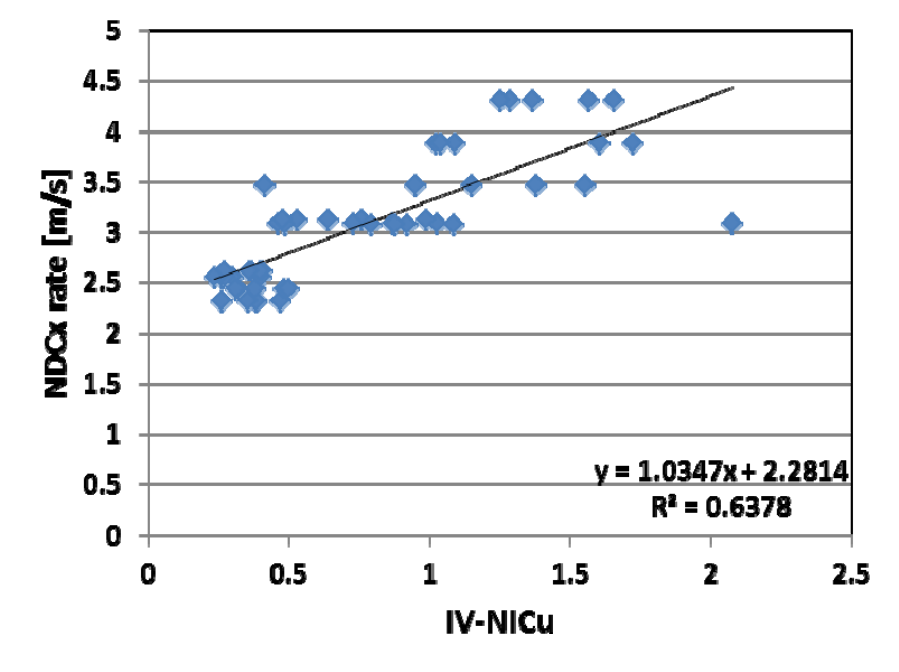


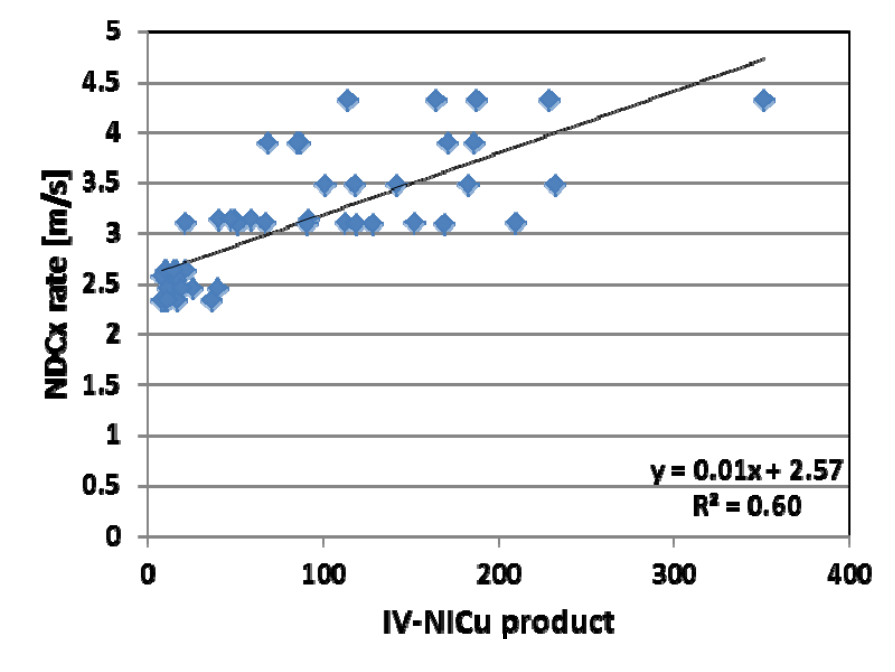


Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCx rate**

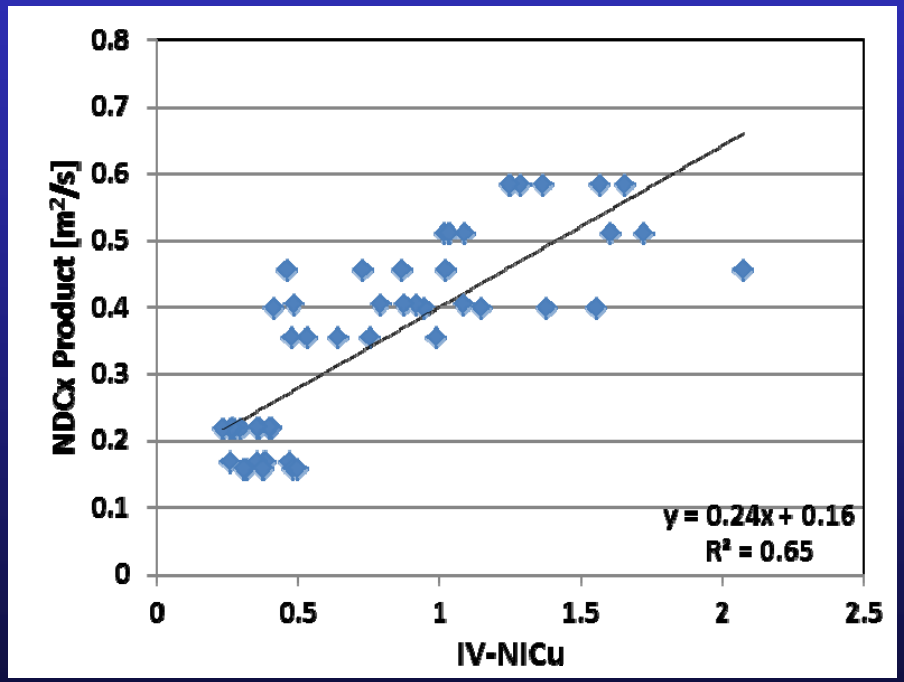


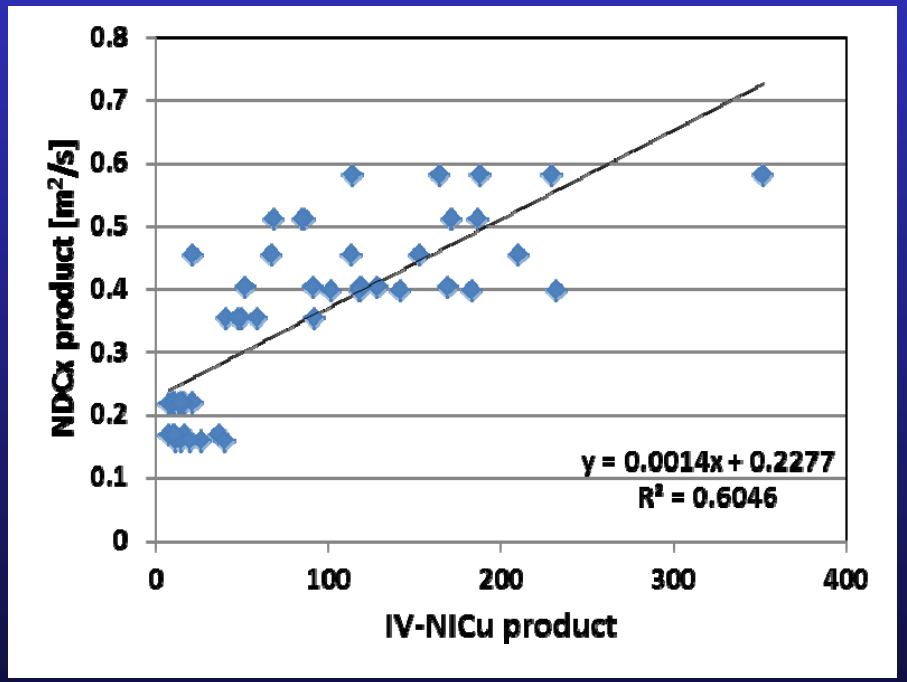


Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCx product**

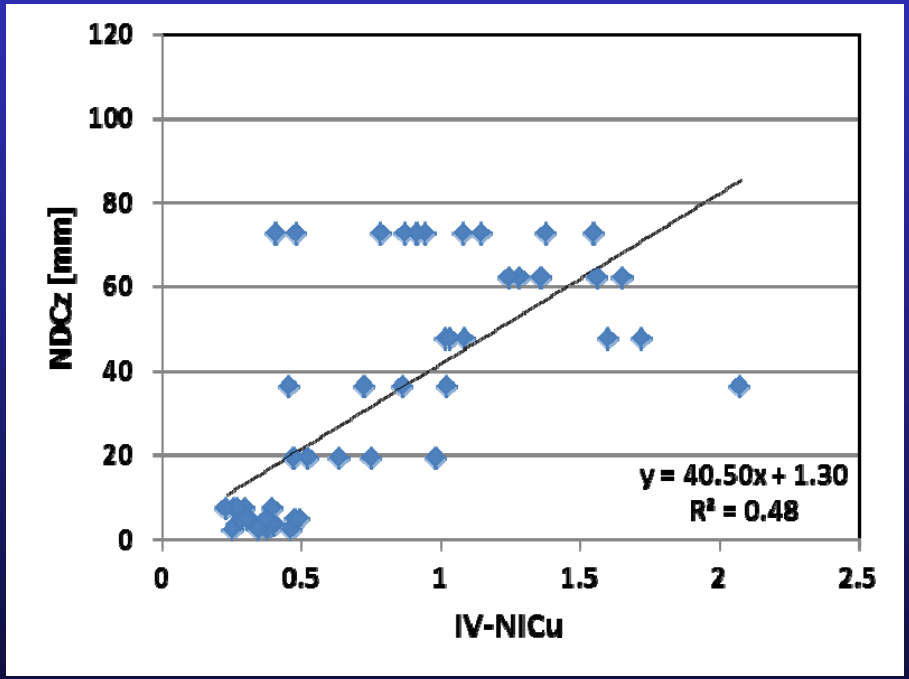


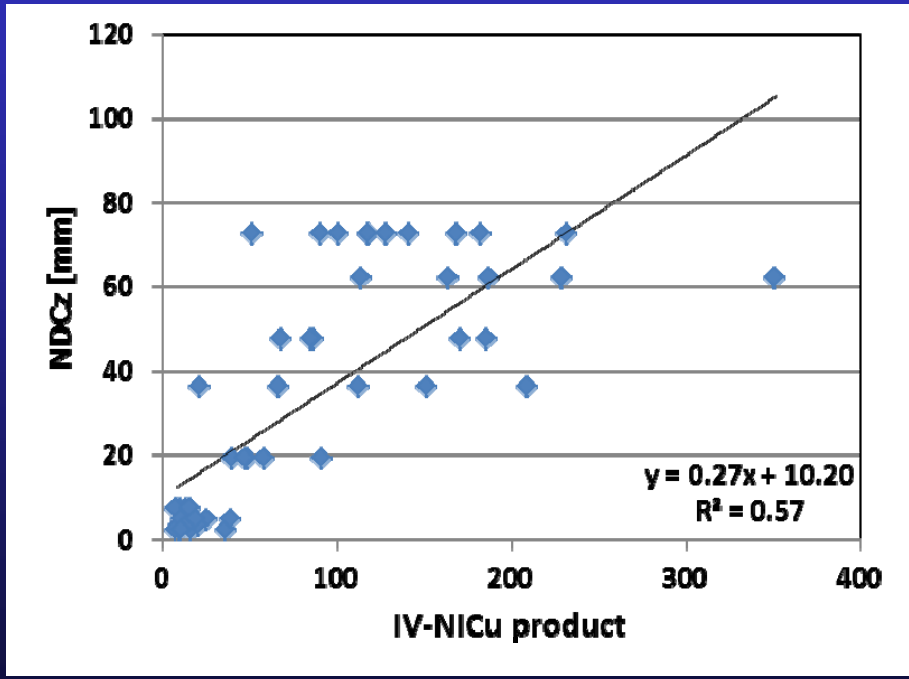


Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCz**

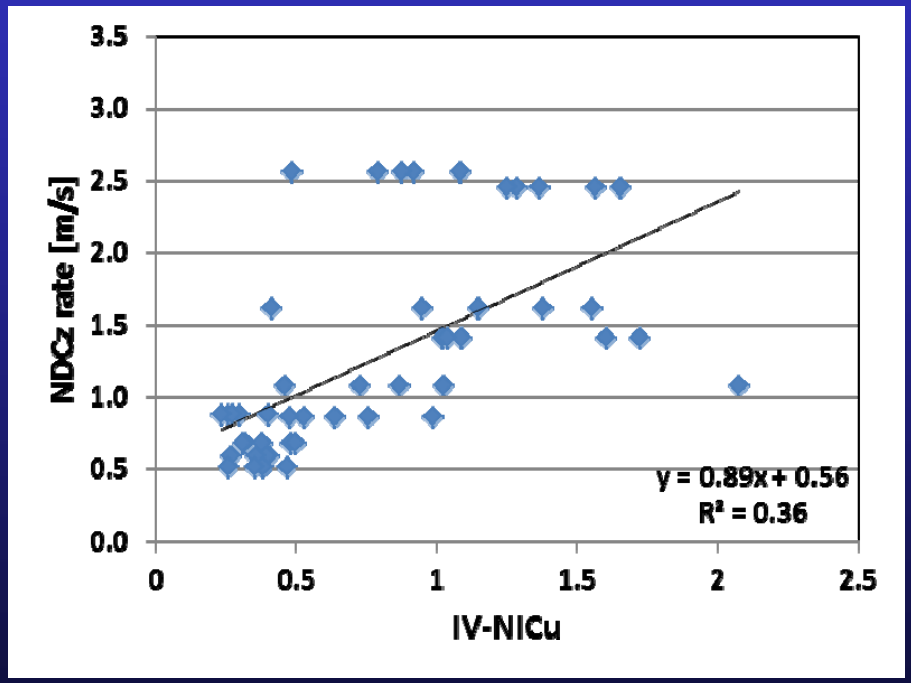


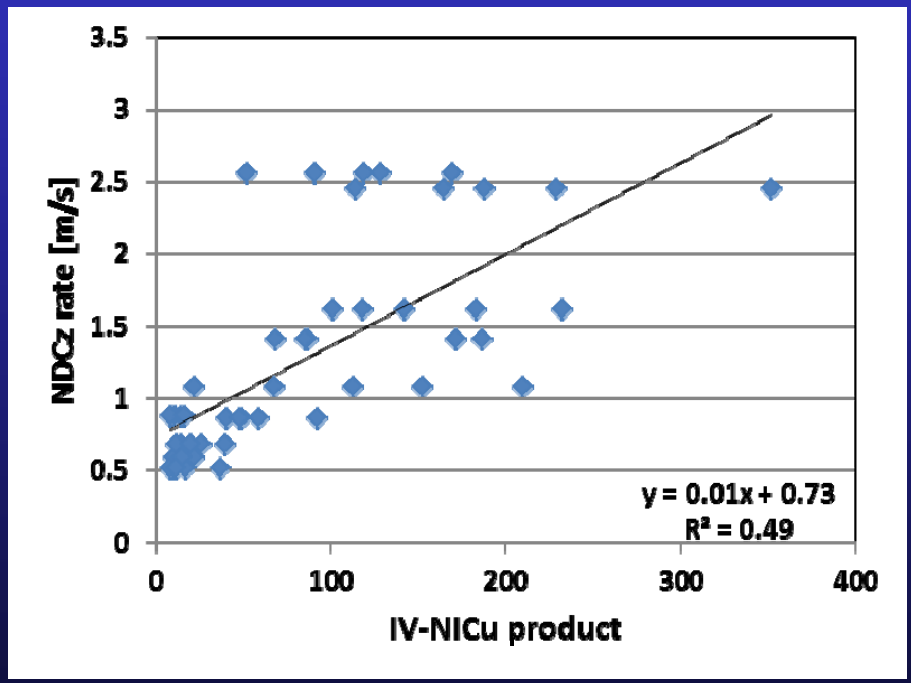


Injury Analysis

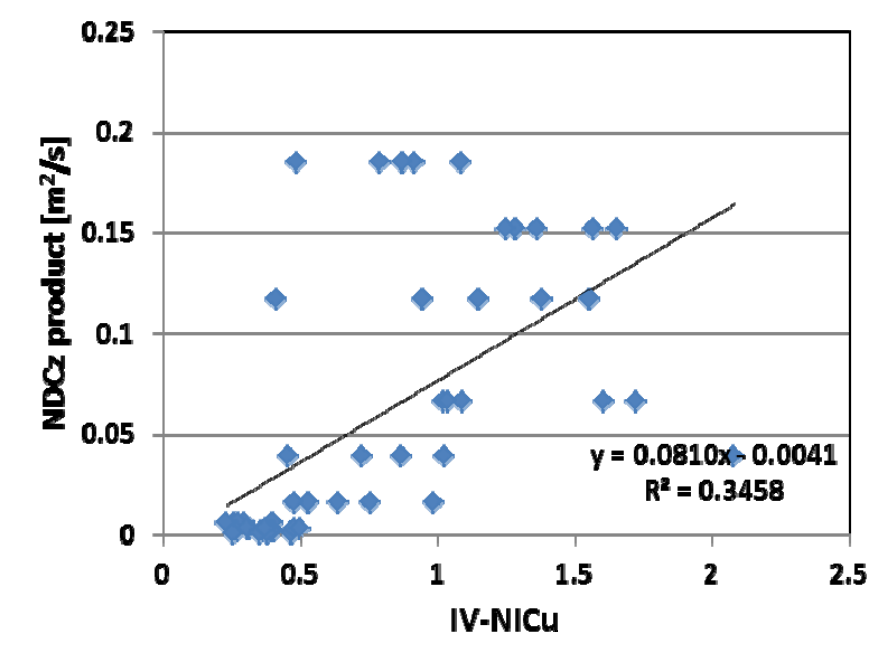
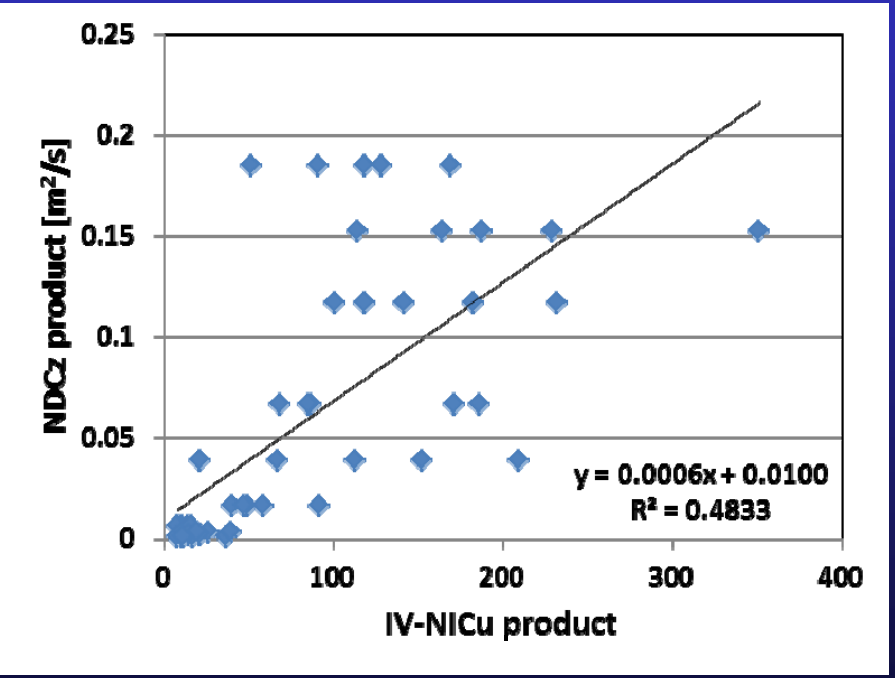
IV-NIC vs. Current/Potential Injury Criteria

- **NDCz rate**





Injury Analysis

IV-NIC vs. Current/Potential Injury Criteria

- **NDCz product**