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Analysis of optimal three-port workspace for in-utero robotic fetoscopic repair of open spina bifida

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Objective

To determine optimal port locations and configurations for 3-port robotic-assisted in-utero spina bifida repair.

Methods

3-dimensional mathematical analysis was conducted on the port position and tool orientation of 3 surgical ports (1 endoscope and 2 tools). The optimality of port locations was determined by assessing 3 parameters: the approach distance (the minimum distance between the port remote centre of motion (RCM) and the center point of the lesion), the approach angle (the angle between the lesion surface normal and the central axis of the tool when pointed at the lesion center) and the entry angle (the angle between the uterine surface normal and the axis of the tool). The uterus surface was approximated as a hemisphere of diameter 30 cm. A fetal model with open spina bifida of average size for 22-week gestational age was placed in cephalic presentation at the center of the hemisphere with the midline of the fetus aligned with the mother's midline. The placenta was assumed to be posterior and the entire anterior surface of the uterus accessible. A central axis was defined along the midline of the uterus surface representing potential scope insertion points at discrete intervals of 1cm. A transverse axis was defined on the surface of the uterus intersecting the center point of the lesion as it would appear in a frontal view. A grid representing potential tool insertion points equidistant from the scope in a linear transverse configuration was derived from these two axes, with increasing lateral offset values in 1cm intervals. The range of the entire grid covered a 30cmx20cm area aligned with the length of the fetus. Tilting of the fetus ranging from 0 to 30 degrees were investigated in increments of 5 degrees. A script iterated through all potential linear transverse port configurations and fetal tilt angles (n=2170), calculating the approach distance, approach angle, and entry angle for each configuration. Gradient plots were obtained that describe the optimal port placements for each of the 3 parameters individually. Additionally, a gradient plot that considered all 3 parameters in combination was constructed using a cost function with a 1: 2: 1 weighting. This weighting distribution was based on clinical expertise (where approach angle was valued equivalently to approach distance and entry angle combined), the parameter value distributions were intersected to determine regions where all 3 parameters were optimized. These regions were plotted using a color gradation to enable visual identification of optimized regions.

Results

Optimal scope placement along the midline should be 5cm superior to the transverse centerline, with ideal fetal tilt angle between 0 to 15 degrees. For fetal tilt angles above 15 degrees up to 30 degrees, the scope should be positioned slightly lower at 2.5cm superior to the transverse centerline. Considering optimal lateral tool port offset relative to the central scope position, offset should be minimized in all cases. For a high fetal tilt angles (up to 30 degrees), this is more critical, where the tool offset should be 1-2cm from the central scope. For a lower fetal tilt angle (closer to 0 degrees), the tool offset can be up to 4cm from the central scope while maintaining optimality.

Conclusion

We here propose a model for determining optimal 3-port configurations based on workspace parameters for in-utero robotic fetoscopic OSB repair. These findings are equally extensible to traditional fetoscopic intervention. To apply these results, the fetal position and orientation is set during by pre-handling by the surgeon and the fetal tilt is assessed via ultrasound. The surgeon should establish a central point on the uterus corresponding to the center of the lesion as viewed frontally. From this central point, the surgeon shall measure the desired scope position along the midline and insert the scope port. From this port, the surgeon shall measure the desired lateral tool offset positions equidistant on either side and insert the two instrument ports. Future extensions of this model include scaling down the uterus size to model the impact of earlier gestational periods on optimal tool placement, and investigating optimal non-transversal, non-linear, and/or asymmetric port configurations (eg. triangular configuration). Additionally, future extensions of this analysis will consider the 30 degree endoscope since only the 0 degree endoscope was considered in the modelling.