Interventional Pain Medicine 3 (2024) 100429

Contents lists available at ScienceDirect

Interventional Pain Medicine

journal homepage: www.journals.elsevier.com/interventional-pain-medicine

Comparison of curved and straight tip radiofrequency cannula deflection in a ballistic model

Allen Chen [a,*], Udai Nanda [b], Joseph Solberg [a], Ethan Rand [c], George Christolias [d], Jaspal Ricky Singh [e]

[a] *Department of Orthopaedic Surgery, University of California – Los Angeles, Los Angeles, CA, USA*
[b] *Department of Physical Medicine and Rehabilitation, Veterans Health Administration, Los Angeles, CA, USA*
[c] *Kaiser Permanente Los Angeles Medical Center, Los Angeles, CA, USA*
[d] *Department of Rehabilitation and Regenerative Medicine, Columbia University Medical Center, USA*
[e] *Department of Rehabilitation Medicine, Cornell University Medical Center, USA*

ARTICLE INFO

Keywords:
Interventional pain
Radiofrequency ablation
Cannula
Spinal needle
Needle deflection
Ballistic gel

ABSTRACT

Background: Percutaneous pain and spine procedures play an important diagnostic and therapeutic role in the treatment of various pain diagnoses. Accurate placement of needles or cannulae during these procedures is paramount to the success of these procedures.
Objective: The purpose of this study is to examine and quantify the amount of deflection of radiofrequency cannulae based on curved tip versus no curved tip, using a ballistic gel tissue simulant.
Materials and methods: Six different types of cannulae commonly used for spinal and peripheral nerve ablations were selected, including 18, 20, and 22 gauge curved and straight radiofrequency cannulae. Ballistic gel samples were made in molds of 40 mm and 80 mm. Each cannula was mounted in a drill press to ensure accurate trajectory.
Results: Curved RFA cannula had increased deflection when compared to straight cannula for 18-, 20-, and 22-gauge cannulae at a depth of 40 mm. Curved RFA cannula had increased deflection when compared to straight cannula for 20- and 22-gauge cannulae at a depth of 80 mm. Overall, the mean deflection for a curved cannula increased 1.9x for 20-gauge cannulae and 2.5x for 22-gauge cannulae when compared to a straight cannula.
Conclusions: For interventionalists, understanding the effects of needle or cannula shape is crucial for accurate placement. When a procedure requires additional steerability, additional deflection up to 2.5x obtained by placing a bend in the needle or cannula tip should be considered.

1. Introduction

Minimally invasive, percutaneous pain and spine procedures play an essential role in the diagnosis and treatment of various conditions and diagnoses. While the injectate (local anesthetic, steroids, and/or regenerative substances) and technology used to guide the injection (i.e. fluoroscopy, ultrasound, CT) continue to develop over time, the foundation of percutaneous interventions remains the same. A needle (or needle-like instrument) is introduced superficially and advanced to provide access to a deeper structure of interest. Along this trajectory, the instrument encounters multiple layers of non-homogenous soft tissue, including subcutaneous fat, fascia, muscle, tendons, and ligaments. These tissue properties, in addition to various instrument characteristics, contribute to the amount of deflection and tissue deformation. Deflection impacts the accuracy of instrument placement and the effectiveness of the procedure [1]. Given the wide range of available needle and cannula types, it is crucial to recognize the impact that certain characteristics have on maneuverability or steerability. The interventionalist must understand and apply these concepts to maneuver the instrument precisely and optimize safety. Mastery of instrument manipulation and careful pre-procedural planning allows a percutaneous approach to be used to reach a target not only when there is an unobstructed trajectory but also when vital structures or anatomic barriers must be circumvented.

Although most spine procedures are performed under image guidance, and fluoroscopy is available to adjust needle position regardless of

* Corresponding author.
E-mail address: allenschen@mednet.ucla.edu (A. Chen).

https://doi.org/10.1016/j.inpm.2024.100429
Received 8 June 2024; Received in revised form 1 July 2024; Accepted 16 July 2024
Available online 31 July 2024

deflection, this study aims to quantify the amount of needle deflection depending on whether the tip is straight or bent. Having this knowledge may help the practitioner in better understanding needle trajectory based on depth, gauge, and bend to minimize needle manipulation, resulting in increased patient comfort and decreased procedural time. Needle and cannula types and characteristics contribute significantly to the amount of steerability. Needle tip design (i.e., pencil point vs. beveled), tip bend, needle or cannula gauge, depth of insertion, and use of an introducer all impact deflection [2]. Pencil point needles have been reported in one study to deflect in the direction of the distal injection orifice and in another study to deflect independently of the distal injection orifice [3,4]. Beveled needles tend to deflect away from the bevel opening unless there is a curved tip, in which case deflection is usually in the direction of the curve. Larger gauge (smaller diameter) needles tend to deflect more than smaller gauge (larger diameter) needles, and deflection tends to increase with depth of insertion, but this has not been shown consistently for all types of needles [4]. The impact of an introducer differs based on needle type, enhancing or reducing deflection in different circumstances.

The tissue medium impacts needle deflection through tissue deformation and needle-tissue interaction [5]. Although it is challenging to mimic all of the relevant layers of human tissue, such as skin, adipose, fascia, and muscle, multiple tissue simulants have been studied. Polystyrene foam, plastisol, porcine, and ballistic gel have all been used as tissue simulants. Ballistic gel, made of collagen extracted from animal tissue, is often used to simulate the effects of a projectile on human tissue [6,7]. The benefits of ballistic gel include its relatively low cost and similar physical properties to human muscle tissue. However, limitations include difficulty replicating the heterogeneity of human soft tissue, including the skin layer and fascial planes within the muscle layer, which are potential sites of needle deflection.

Needle characteristics and steerability have been investigated for application in various medical fields, such as brachytherapy in radiation oncology and lung biopsy in pulmonology [8,9]. Likewise, specific needle types commonly used in percutaneous pain and spine interventions have been studied. The relative deflection of six spinal needle types (Quincke, Short Bevel, Chiba, Tuohy, Hustead, Whitacre) was described in 2016 by Rand et al. at various depths in a ballistic gel model [4]. This study, which includes several of the authors of the original 2016 Rand study, aims to further elucidate the effect of instrument shape on deflection and steerability. Additional modifications can be applied to a needle or cannula during manufacturing or afterward by the practitioner. One such modification is the tip bend or curve. While practices vary, needle bending has been described as a method to more effectively “steer” a needle to the target location [10]. The purpose of this study is to expand on the prior Rand study and evaluate the effect of a curve on the deflection of a needle or cannula by comparing curved vs. straight radiofrequency cannula deflection in a ballistic gel tissue simulant.

2. Objectives

The purpose of this study is to evaluate and quantify the deflection of commonly used radiofrequency cannulae based on gauge, and whether the cannula has a straight or bent tip.

3. Materials and Methods

As this study does not involve human subjects, it is IRB exempt. For the purposes of the study, manufactured straight and bent cannulae were obtained. In order to ensure consistent tip bends, we selected radiofrequency cannulae (Avanos Medical) which are manufactured with either straight or curved tips. We chose to use manufactured curved tip cannulae in order to maximize consistency and minimize curved tip variability. We chose Avanos Medical cannulae because they are commonly used at our institutions, and were readily available. We also examined Medtronic cannulae and found the curved tips to be at a similar angle at 7.5–8°. In order to maximize consistency, we performed this experiment with a single manufacturer. To evaluate for changes based on diameter, 18-gauge, 20 gauge, and 22-gauge 100 mm curved and straight cannulae were used. To maintain additional consistency, each cannula had a 10 mm active radiofrequency tip. The bend of the curved cannula was at 10 mm, which correlated with the length of the active tip Each cannula tip was measured using a digital protractor. The angle of bend for each curved cannula remained consistent, measured digitally at 8°. In addition, the angle of the bevel remained consistent at 14° in all tested cannula, regardless of gauge.

3.1. Needles

Number: 4 of each type (24 total)
Length: 100 mm.
18 Gauge Curved Tip.
18 Gauge Straight Tip.
20 Gauge Curved Tip.
20 Gauge Straight Tip.
22 Gauge Curved Tip.
22 Gauge Straight Tip.

3.2. Gel preparation

Ballistic gel was made by mixing eight ounces of 250 Bloom Knox Gel (Kraft Foods Group, Northfield, Il) and 64 ounces of 40 °C filtered water. This yielded a uniform consistency of all gel samples that was then poured into cylindrical aluminum molds. A total of 30 gel molds were made (15 with 40 mm depth and 15 with 80 mm depth) from a single batch of gel mixture. To maintain consistency, this solution was poured into the molds in a slow and deliberate manner. The ballistic gel was then stored at 10 °C for 24 h prior to experimental use. The gel specimens were made one day prior to the experiment trials to avoid any dehydration or change in density with time. The gel production process was identical to that of the original Rand study. A total of 30 molds were made, 15 with mold depths of 40 mm and 15 molds with a depth of 80 mm. These depths were chosen for two reasons – first, they were the same depths used in the original Rand study, and second, these depths approximate the halfway point and endpoint (needle “hubbed to skin”) of either a 3.5 inch spinal needle (88.9 mm) or a 100 mm radiofrequency cannula. The 40 mm molds had volume of 82 mL and radius of 26.8 mm, and the 80 mm molds had a volume of 164 mL, also with a radius of 26.8 mm.

3.3. Drill press mount

The drill press, also known as a pedestal or bench drill, was used to ensure consistent cannula placement and uniform downwards pressure. This consists of a case, column, and spindle with a movable grip controlled by a rotating handle. A 13” Bilt Hard (City of Industry, CA) floor drill press (Fig. 1) with 3–1/8 inch spindle travel was used. The angle of entry was fixed relative to the table.

3.4. Cannula placement

Each cannula was mounted in the drill press and measured using a bubble level to confirm true vertical, in order to ensure accurate and consistent initial trajectory into the ballistic gel. Each cannula was secured to the grip and driven down to circular graph paper (Fig. 2), piercing it in the direct center. Then, the gel mold was positioned underneath the cannula and the grip was again lowered, driving the cannula through the ballistic gel and again piercing the graph paper. This was repeated using both 40 mm and 80 mm gel molds, and four times for each cannula.

Fig. 1. Drill Press
Photo: Amazon.com.

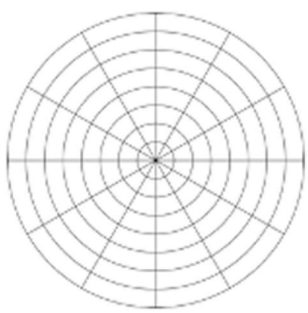

Fig. 2. Circular graph measurement.

3.5. *Data collection and analysis*

The point at which the cannula entered the gel was equivalent to the initial center point of the graph, as there was no deflection. Once all four passes were completed, the distance of deflection from the center was measured with a digital caliper. We then calculated the mean distance between these points and the center, resulting in a mean deflection distance at that particular depth. These were then compared using the ANOVA test.

4. Results

We performed 4 passes of each cannula type through both gel depths, 40 mm (Table 1) and 80 mm (Table 2). Deflection was measured by determining the distance of cannula exit from the location of initial puncture in the center of the gel. Mean and standard deviation were calculated for each cannula type at both depths. Using ANOVA, we analyzed mean deflection differences between curved and straight cannula of each gauge. When comparing straight and curved cannula, there was a statistically significant difference in deflection ($p < 0.001$) in both 20g and 22g cannula at both gel depths (40 mm and 80 mm), as well as with the 18g needle at 40 mm gel depth ($P < 0.01$); however no statistical difference in deflection was noted between the curved and straight 18g cannula at 80 mm gel depth ($P = 0.741$).

Table 1
Deflection of cannulae in 40 mm depth gel.

Pass	18 Gauge		20 Gauge		22 Gauge	
	Straight	Curved	Straight	Curved	Straight	Curved
1	3.8	5.7	4.6	7	4	8
2	3.9	5.8	4.5	6.9	3.9	8.1
3	3.5	6.1	3.9	7	3.9	8.2
4	3.6	6.2	3.8	7.1	4	8.3
Mean	3.70	5.95	4.20	7.00	3.95	8.15
SD	0.18	0.24	0.41	0.08	0.06	0.13
P-Value	**<0.01**		**<0.001**		**<0.001**	

Table 2
Deflection of cannulae in 80 mm depth gel.

Pass	18 Gauge		20 Gauge		22 Gauge	
	Straight	Curved	Straight	Curved	Straight	Curved
1	7.4	8.1	6.4	13.2	5.5	15.6
2	7.5	6.8	6.9	12.8	4.9	13.9
3	6.3	6.7	7.1	13	5.8	13.6
4	6.5	5.5	6.5	12.3	6.1	13.7
Mean	6.93	6.78	6.73	12.83	5.58	14.20
SD	0.61	1.06	0.33	0.39	0.51	0.94
P-Value	0.741		**<0.001**		**<0.001**	

There was more deflection noted among both straight and curved cannulae with increased gel depth. Among all curved cannulae, there was a clear pattern of increased deflection with higher (thinner) gauge (Fig. 3), which was not seen among straight cannulae (Fig. 4). At the 80 mm gel depth, the mean deflection for curved cannulae was 6.78 mm ± 1.06, 12.83 mm ± 0.39, 14.2 mm ± 0.94 for 18g, 20g and 22g cannulae respectively. Whereas mean deflection for straight cannulae was 6.93 mm ± 0.61, 6.73 mm ± 0.33, 5.58 mm ± 0.51 or 18g, 20gf, and 22g cannulae respectively. Regardless of gauge, there was similar deflection among all straight cannulae. Overall, when compared to straight cannulae, the average deflection of curved cannulae was similar with 18-gauge cannula, 1.9 times as much with 20-gauge cannula, and 2.5 times as much with 22-gauge cannula.

5. Discussion

Spinal needle deflection has been demonstrated to be a seemingly predictable phenomenon dependent on type and gauge through varying depths [4]. By evaluating the true amount of deflection between straight and curved RF cannulas, we were able to quantify the effect curved tips have on movement dynamics, and reconsider the postulates made by the original Rand study.

Our results from the multiple passes of straight cannulas showed that regardless of gauge, there was similar deflection among all straight cannulae. This contrasts with the earlier study by Rand et al. which demonstrated increased deflection with increased needle gauge [4].

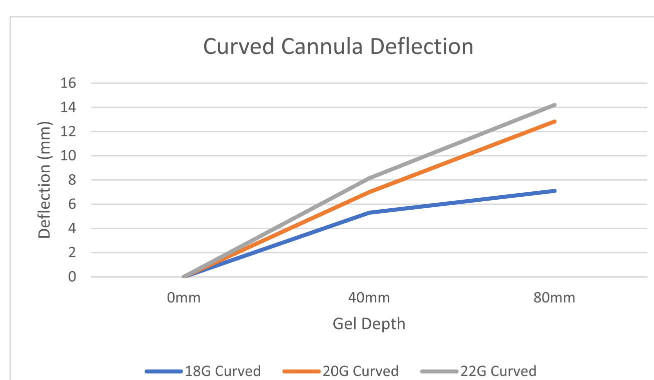

Fig. 3. Curved cannula deflection.

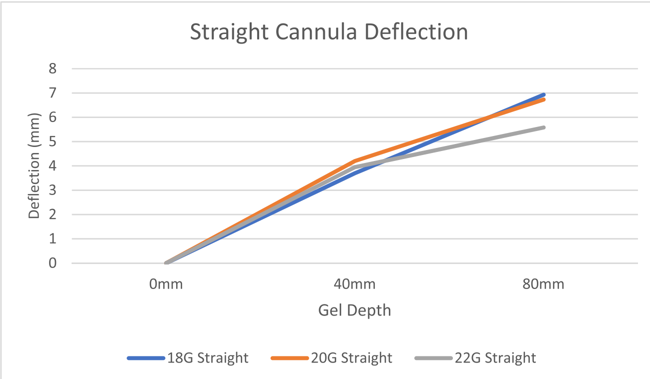

Fig. 4. Straight cannula deflection.

Rand postulated that tissue force perpendicular to the bevel of the needle directed needle movement and that the degree of movement was dependent on resistance from the elastic coefficient of the needle, consistent with Hook's law. In our study, we postulate that construction of the cannulae with insulation resulted in similar elastic coefficients regardless of gauge. This resulted in an expected and demonstrable deflection away from the bevel, but one without significant variations secondary to needle gauge.

When evaluating all curved tip cannulae, a clear pattern of increased deflection with higher gauge emerged, not seen amongst the straight cannulae. Given the similar construction characteristics and likely similar elastic coefficients noted on the straight cannulae, these deflections are likely more related to the biomechanics associated with the bent tip rather than Hook's Law. Needle deflection observed with the curved tip cannulae are likely influenced by beam mechanics as they relate to a variety of needle/cannula factors including shear forces, bending moments, support reactions, and couple forces. In beam mechanics, a point of contraflexure occurs when the bending moment curve changes sign, causing the beam to bend in the opposite direction.

The Euler-Bernoulli beam theory, commonly used in structural engineering, describes the relationship between the bending of a beam and the applied loads, material properties, and geometry of the beam [11]. Although typically applied to straight beams, the theory can be adapted to analyze the deflection of curved beams, such as needles as they pass through tissue. This theory has several assumptions: small deflections compared to the length of the beam, linear elastic behavior following Hooke's law as described above, and that cross-sections of the beam that are plane before deformation remain plane after deformation. While the calculations needed to apply the Euler-Bernoulli bean theory are beyond the scope of this manuscript, the needle's interaction with tissue can be modeled such that the tissue provides boundary conditions such as applied forces, or moments. Thus, as the needle penetrates tissue, the tissue exerts distributed loads along the needle's length, influencing deflection.

As straight-tip cannula gauge increased, we observed a progressive decrease in the net deflection when comparing the differences at 40 and 80 mm depths (Fig. 4). At the 40 mm depth, the 18-gauge cannula exhibited the least deflection, whereas at 80 mm depth with 18-gauge cannula exhibited the most deflection. This suggests that thinner cannulas were more likely to have contraflexion occur at a shallower depth, limiting and possibly reversing the extent of deflection as depth increased. An increase in deflection was observed between the 20-gauge cannula compared to the 18-gauge cannula at 4 cm, but then a decrease for the 22-gauge needle, likely due to the development of contraflexion in the 22-gauge needle.

There was a statistically significant difference in both curved and straight cannulae at the same gauge and at different depths, with one exception. There was no statistical difference in deflection between the curved and straight 18g cannulas at 80 mm gel depth. We hypothesize that the 18G cannula are simply thicker and as such stiffer, and thus less impacted by a curved tip. However, the true explanation is likely much more complex, especially without further measurements at different depths, and likely secondary to a combination of beam mechanics, force vectors, variations in axial loads, and a variety of other factors.

There are several limitations to this follow-up needle mechanics study, most of which are similar to the limitations outlined in the initial Rand study [4]. First, the ballistics gel model by nature is homogeneous and does not account for tissue heterogeneity with tissues of varying density, or for heterogeneity in degrees of orientation with relation to the axis of advancement. As an unfunded project, this study was small in terms of the number of cannula available, passes generated, and with regard to the depths at which measures were obtained. Additional depths of measure may have provided support for the contraflexure hypothesis above. Lack of true consistency and subtle control of velocity and acceleration of cannula advancement may have led to variations in needle deflection properties. Lastly, to maintain consistency in bend angle, we chose Avanos radiofrequency cannulae with a manufactured bend at 8°. However, radiofrequency cannulae have an insulation around most of the needle, and as such this changes the beam mechanics and force vectors, and resistance of the RFA cannula as opposed to a non-insulated spinal needle. In addition, the angle of the Avanos curve cannula, although similar, may not be the exact angle of other manufactured cannula, and may not be the tip angle achieved when bending a spinal needle manually. Bevel angle, while also consistent within cannula tested, may also have slight deviations and as such may affect needle deflection. While we believe that the overall results help guide any bent needle or cannula movement dynamics, the findings in this study may not completely translate to non-insulated spinal needles. From a practical and clinically relevant perspective, there was a clear pattern of increased deflection with higher (thinner) gauge cannulas suggesting that bent/curved needles and cannulas are less subjected to contraflexure, as simple beam mechanics alone can no longer describe their behavior.

6. Conclusion

Curved needles/cannulas behave predictably with increased deflection up to 2.5 fold when compared to straight needles/cannulas, particularly with increased gauge and increased depth. This finding, however was not observed with thicker 18-gauge cannulae. Therefore, for 22- and 20-gauge needles, practitioners should consider bending/curving needle tips to enhance steerability and when enhanced deflection is needed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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