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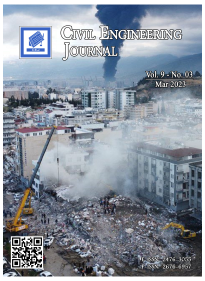

Design of Controlled Pre-Split Blasting in a Hydroelectric Construction Project

Younes Tahir [1*], Imad Kadiri [1], Saïf Ed-dîn Fertahi [2], Mohammed El Youbi [1], Rachid Bouferra [3], Rachid Agounoun [1], M. Dlimi [1]

[1] *Ecole Supérieure de Technologie de Meknès, Laboratoire d'Etude des Matériaux Avancés et Applications (LEM2A), Moulay Ismail University of Meknes, Meknes, Morocco.*

[2] *Energy Research Center, Physics Department, Faculty of Science, Mohammed V University in Rabat, Rabat 1014, Morocco.*

[3] *Geosciences, Geo-environment and Civil Engineering Laboratory, Cadi-Ayyad University, Marrakesh, Morocco.*

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Abstract

Geologic conditions and design requirements around upstream Nachtigal Falls, in Cameroon, for the hydroelectric construction project on the Sanaga River dictated close control of blasting procedures with very precise geometry to obtain safe and economical excavation lines. Various techniques of pre-split blasting were used in the initial stage of all major excavations. Hole diameters for pre-splitting were 89 mm, and hole spacing ranged from 0.8 to 1m. Explosive charges varied from 1 to 7 kg per hole, and the detonating cord linear charge ranged from 12 to 60g. The contour blasting technique is aimed at controlling overbreak and improving remaining slope stability. Over-break or over-excavation needs to be controlled since its occurrence compromises the operations in terms of safety (instability in the remaining slope; loosening rocks that increase the risk for operational people; an irregular free face for subsequent blasting); and costs (need for reinforcement of the remaining rock structure through costly sustainment systems; increase in concrete volumes in civil works). This paper discusses in detail the design and field implementation of pre-split blasts successfully carried out to achieve clean vertical walls in moderately dipping, though complexly sheared and jointed gneiss. Based on the results of the experiments, we were able to design a pre-splitting pattern both experimentally and in a very cost-effective manner. It is felt that the methods developed on this project could have useful applications on other major construction projects.

Keywords: GNSS Network; Controlled Blasting; Pre-Splitting; Back-Break Control; Fracture Propagation.

1. Introduction

The pre-split blasting technique was initially developed in 1962 at the Lewiston Power Plant [1]. The main objective of this technique is to create a continuous surface of separation between the blasted and remaining rock masses [2]. Pre-splitting techniques have various applications in civil works, such as preventing/controlling back-breaking, controlling excessive ground vibrations [3, 4], and filtering the effects of explosive gases from production blasting [5].

The pre-split holes should be aligned along the excavation outline. These holes can be blasted before (pre-splitting) or at the same time (post-splitting or smooth blasting) as the production shot [6, 7]. In both cases, the holes have generally small diameters and are less loaded than the holes drilled for primary production [8]. In addition, the explosives loaded in the holes must be decoupled from the sides of the borehole. That way, the gas could be able to vent to the air inside the borehole instead of infiltrating the fracture network of the rock mass [9]. This consequently decreases the gas pressure and avoids damage to the final wall [10].

* Corresponding author: yo.tahir@edu.umi.ac.ma

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The design of blast experiments is a method to define the optimal pattern of pre-splitting [11, 12]. It should be noted that the fragmentation of the rock depends on many factors. Some of these factors are uncontrollable and out of the reach of the blast engineer. Hence, in some cases, the solution seems to be difficult [13].

Domestic and foreign scholars use mathematical methods, numerical simulation, field tests, similar simulation tests, theoretical analysis, and other methods to study the blasting parameters, including the blasting effect, damage degree, blasting safety, pre-cracking, and other aspects [14, 15].

Several techniques can be implemented to control blasting and reduce the size of the blasting induced by the production holes. These techniques include buffer blasting [16]. Buffer blasting holes are in the last row between the production and pre-split holes. They are loaded with no more than 50% of the explosives that are used in the production holes. It is also important that these explosives be well distributed within the borehole to improve the fragmentation of the rock mass without over-breaking [17].

The borehole pressure can be calculated more precisely using numerical models and equations of state for the detonation products and rock mass. The numerical simulation method has become one of the major techniques to investigate the rock damage process under blasting loads [18]. Nevertheless, the elastoplastic behavior of the rock with hardening and damage requires several mechanical parameters that are not well defined during the usual projects [19]. The widely used method in real projects to adjust the blast parameters is to perform a pre-splitting trial vicinity of the project. By doing this, the final excavation line is fully visible and it becomes easy to assess visually the damage induced around the borehole and to perform adjustments to the design of the pre-splitting [20].

The purpose of this study is to enrich the database of case studies for establishing a general methodology to design pre-splitting. In this case, the pre-splitting was tested in a hydroelectric construction project on the Sanaga River, in Cameroon. The case study is introduced, and the results of three sets of pre-splitting experiments are discussed, aiming to select the best configuration.

2. Project Location

The explosion area is located on the Sanaga River at Nachtigal, approximately 65km NE of Yaoundé, Cameroon, at 700 m above sea level, with a variety of geological formations as shown in Figure 1. The Sanaga River is the largest in Cameroon and obtains its waters from the Adamawa Plateau. The geology of the project area is mainly made up of Precambrian basement rocks consisting of variable deposits of metamorphic rocks such as mica schist and schists [21]. Shallow soils consist mainly of red-brown ferrous clayey laterite, which is created from alterations of the underlying metamorphic rocks. Due to their clayey nature, the shallow soils are locally mined for construction [22].

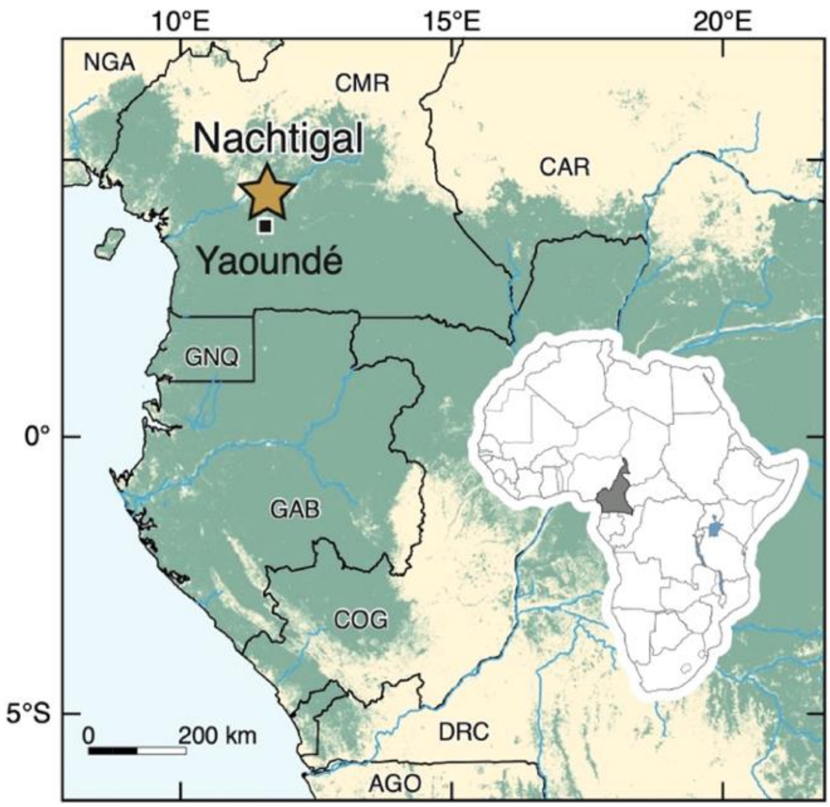

Figure 1. Location of Nachtigal in Cameroon

Groundwater is typically present in fractured, crystalline metamorphic basement rocks. The aquiferous formations are overlain by relatively impermeable and clayey laterite formations.

3. Study Case

The penstocks of the Nachtigal project were initially planned to be constructed in concrete. However, to optimize the cost of the project and to reduce the construction time, it was decided that the penstocks would be cut into the rock with very precise geometry. Concrete will be applied thereafter only as a surface coating. Therefore, this is not a classic pre-splitting aiming to create a given slope but to shape the rock to create a surface structure with very specific slopes on the sides and the base of each pipe. The dimensions of the penstocks, their proximity, and the slope failures at their base require ensuring that the pre-cutting and the production firing will not cause damage within the reserved rock.

4. Mechanical Properties of Rocks

The geological site is composed of a few meters of lateritic materials and weathered gneiss G_0, which are supported by gneiss, of good to excellent quality ranging from G_1 to G_3. For pre-splitting studies with the objective of back-break control, as it is aimed in this research work, rock mechanical properties tests were performed. Rock samples were collected and tested in the rock mechanics laboratory. The mechanical characteristics of rocks have been evaluated as the mean value for each rock type, as shown in Table 1. Major joint sets' characteristics are summarized in Table 2. As the variability is considerable for those samples, it can be assumed that in situ conditions change frequently and play a major role, which must be taken into consideration.

Table 1. Mechanical characteristics of different geological formations

Rock	Base side (NGC)	Thicknes s (m)	Dry density (kN/m^3)	Cohesio n (kPa)	Friction angle (°)	Uniaxial Compression Strength (MPa)	Slope stability factors
Topsoil	490 - 497	0,20	-	-	-	-	
Laterites and gores	482 - 491	6 à 8	15,3	8	32	0,13	2H/1V
Gneiss G0	483 - 489	1 à 2	23,5	70	45	0,5 à 15	1H/1V
Gneiss G1	480 - 488	3 à 8	26,9	146	57	19	1H/2V
Gneiss G2	440 - 485	35 à 45	26,9	349	64	45	1H/10V
Gneiss G3	< 440	-	26,9	349	64	66	1H/10V

Table 2. Directions and dips of discontinuities

	Dip	Dip Direction
Foliation S1	50°	300°
Foliation S2	0°	-
Diaclase J1	90°	255°
Diaclase J2	90°	90°
Diaclase J3	90°	230°
Diaclase J4	80°	340°

5. Borehole Pressure Calculation for Pre-Split Blast Holes

The pre-split holes spacing is calculated by the following empirical formula (Equation 1) [23]:

$$L \le \frac{P_b + f_t}{f_t} D \tag{1}$$

where L is the spacing between the adjacent boreholes; P_b is the blasting pressure o the borehole wall f_t is the tensile strength of rock, and D is the diameter's hole.

The borehole pressure can be calculated by (Equation 2) [24]:

$$P_b = 228 \times 10^{-6} \rho_e \times \frac{V_d^2}{1+0.8\,\rho_e} = 228 \times 10^{-6} \times 1.2 \times \frac{4000^2}{(1+(0.8 \times 1.2))} = 2233.47 \text{ MPa} \tag{2}$$

$$(P_b)^* = P_b \left[\frac{d}{D}\right]^{2.4} = 23.97 \ \frac{\text{MPa}}{\text{m}} = 2233.47 \times \left[\frac{32}{89}\right]^{2.4} = 191.78 \text{ MPa} \tag{3}$$

where Pb is the borehole pressure in MPa, ρ_e is the explosive density, V_d is the detonation velocity of the explosives in m/s, d is the diameter of explosives charge in mm, D is the diameter of the borehole in mm, L_d is the borehole length and Pb* is the effective pressure.

Spacing for decoupled charges is calculated as follows:

$$S = \text{D} \times \frac{(P_b^* + R_t)}{R_t} = 0.089 \times \frac{(191.78+17.4)}{17.4} = 1.07 \text{ m} \tag{4}$$

The borehole pressure must be equal to or less than the dynamic compressive strength of the rock. It should be noted that pre-split blast holes are generally left unstemmed.

Chiappetta (2001) suggested a good rule of thumb for hole spacing in feet to be equal to the hole diameter in inches. The explosive diameter should be 1/2 to 1/3 of the hole diameter, and the load should be distributed all along the length of the hole except 2–3 m near the collar [25]. These holes are charged lightly with 32 mm cartridges suspended into them and axially tied with a detonating fuse without stemming.

6. Design of Experiments

6.1. Test No. 1

6.1.1. Drilling, Charging, and Stemming

The technique used in the first test is to detonate the pre-splitting line and buffer row in one shot (Figure 2). The characteristics of this test are summarized in Table 3. The holes in the pre-split row were drilled with 1m spacing and 85° tilt angle, corresponding to the slope stability factor (1H/10V). Pre-splitting holes were charged with decoupled cartridges with a diameter of 32 mm, spaced 1m apart along a 12 g/m detonating cord. Pre-split holes were fully charged without stemming. A line of buffer holes was drilled with 3 m spacing and 85° tilt angle. The stem length for buffer holes was 1.5m (Figure 3-a).

Figure 2. Drilling pre-split and buffer holes

Table 3. Characteristics of pre-split and buffer blast for test no. 1

Materials	G2-type gneiss
Hole diameter/mm	89
Hole length/m	7
Spacing/m	1
Hole inclination	85°
Sub-drilling/m	0.5
Buffer row's Powder Factor/ $kg.m^{-3}$	0.5
Mass of charge in buffer row hole/kg	15 with detonating cord of 12 g/m
Mass of charge in the pre-split hole/kg	7 with detonating cord of 12 g/m
Buffer row's stemming	crushed rock (between the main charges)
Delay/ms	42 ms between pre-split and buffer row blast

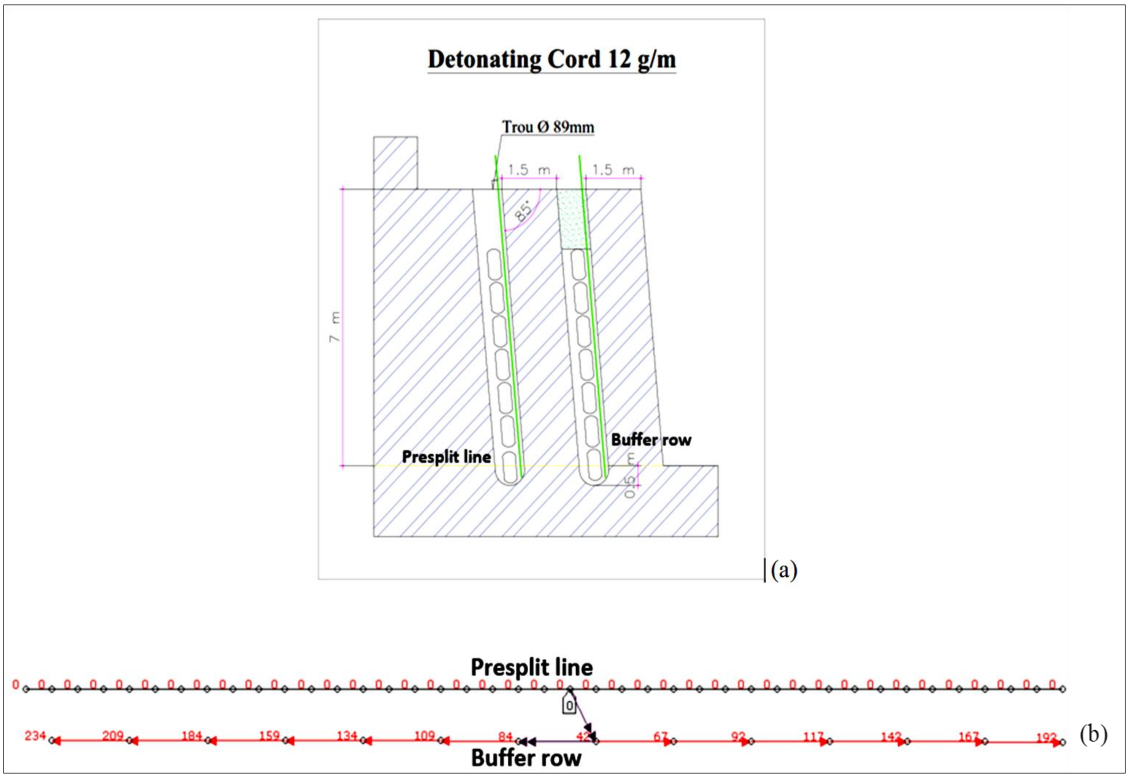

Figure 3. a -Blast patterns for test no. 1. b- Initiation sequence (delay of 42 ms between pre-split and Buffer holes)

In each hole, the detonation is delayed by 500 ms after initiation to allow achieving the sequence in complete safety. The pre-splitting line is initiated with a delay of 42 ms respecting the buffer line. The time delay between detonations in the buffer holes is 25 ms (Figure 3-b).

6.1.2. Results of Test No. 1

In test no. 1, the hypothesis of the excessive power of blasting has been assessed. In the calculation of hole pressure, the effects of faults, sets of joints, and foliation planes are not considered. The pressure of gas generated from cartridges in pre-slit holes acting on the surface of pre-existing fractures and undesirable results encountered will therefore be attributed to the directions of geological structures rather than rock mass strength features. The test was conducted in poor geologic conditions, with joints and bedding. Hence, the pre-split generates an over-break for the entire region and causes joints and bedding planes to open due to gas penetration (Figure 4).

Figure 4. Test no. 1: crack propagated beyond pre-splitting row

By considering such conditions, the required blast power must be reduced. Meanwhile, the unbroken rock at the bottom of the final wall (Figure 5) is due to the increased confinement in the rock around the ends of the vertical boreholes and the dissipation of energy through the foliation planes.

Figure 5. Test no. 1: view of final wall after blasting

6.2. Test No. 2

6.2.1. Drilling, Charging, and Stemming

Given the geological characteristics of the rock, gneiss with sub-horizontal decimetric foliation planes, the conditions of test no. 2 can be presented below (Figure 6):

- The pre-splitting blast will be s dissociated from the buffer row blast to prevent the reactivation of plane fractures, which leads to the rupture of the column of explosives in the buffer holes.
- The pre-split hole's spacing was reduced to 0.8 m for a drilling diameter of 89mm to consider the effect of vertical fractures.
- Few unloaded holes were drilled in the horizontal extension of the pre-splitting line with a spacing of 30 cm to 40 cm on each side of the pre-splitting line to prevent relay splitting from being activated beyond the pre-split line after firing.

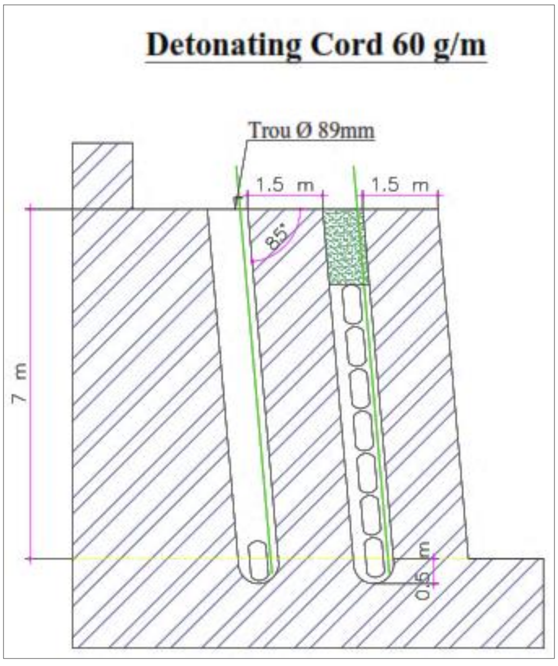

Figure 6. Test no. 2: blast patterns

In this second experiment, the pre-splitting row and buffer holes were drilled, charged, and blasted separately. Holes in a pre-split row were drilled with 0.8m spacing and an 85° tilt angle. Buffer row holes were drilled with an inclination of 85° and in 3 m spacing as in Test no. 1. The pattern specifications for this test are shown in Table 4. In this test, a dual objective was achieved:

- Reduce the damage of the rock beyond the limit of the pre-split.
- Ensure the fragmentation of the rock at the base of the holes.

Table 4. Data from test no. 2

Materials	G2-type gneiss
Hole diameter/mm	89
Hole length/m	7
Spacing/m	0.8
Hole inclination	85°
Sub-drilling/m	0.5
Buffer row's Powder Factor/ kg m^{-3}	0.5
Mass of charge in buffer row hole/kg	15 with detonating cord of 12 g/m
Mass of charge in the pre-split hole/kg	1 with detonating cord of 60 g/m
Buffer row's stemming	Crushed rock (between the main charges)
Delay/ms	Blasted separately

To achieve the first aim, the blasting power of the explosives used in the pre-splitting row was reduced. Hence, it was proposed to eliminate cartridges, which are a fast alternative, easy to implement, and cost-effective. This allows perfect decoupling of the borehole to prevent excessive breakage while allowing the gas pressure to be released quickly. To ensure the second aim, the bottom cartridge was conserved, but a detonating cord of 60g/m instead of 12 g/m was used. This helps to increase the charge load and ensures the fragmentation of the confined mass rock at the bottom of the hole.

6.2.2. Results of Test No. 2

By reducing the strength of the explosive in the pre-split row, a considerable decrease in the back-break phenomenon was achieved. The main advantage of using only detonating cord in the pre-splitting row is a remarkable reduction in back-break, an improvement in fragmentation, and a reduction in explosive mass. In this case, the back-break is restricted to a smaller and more localized region (Figure 7). The bottom of the final wall was well fragmented; nevertheless, the upper part of the wall still suffers from excessive displacements (a few centimeters) (Figure 8). Pre-split explosives still produce more energy than necessary. To improve these areas, a third experiment was designed.

Figure 7. Test no. 2: pre-splitting blast with excessive displacement

Figure 8. Test no. 2: view of final wall after blasting

6.3. Test No. 3

6.3.1. Drilling, Charging, and Stemming

The drilling and charging parameters of Test no. 3 have been specified based on the results of previous tests. The geometry of blasting patterns for buffer holes is 1.5 m of burden and 3 m of spacing. All pre-split holes were fired at the same time using an instantaneous delay, and the charging method of buffer holes was modified (discrete charging). The linear charge of the pre-splitting holes was reduced to 48 g/m of detonating cord, as well as the mass charge of the buffer row was decreased to 12 kg/hole (Table 5). The main charge in the buffer holes was partitioned (powder factor reduction, Table 5), and all other effective parameters were kept fixed.

Table 5. Data from test no. 3

Materials	G2-type gneiss
Hole diameter/mm	89
Hole length/m	7
Spacing/m	0.8
Hole inclination	85°
Sub-drilling/m	0.5
Buffer row's Powder Factor/ kg m^{-3}	0.4
Mass of charge in Buffer row/kg	12 with detonating cord of 12 g/m
Mass of charge in the pre-split hole/kg	1 with detonating cord of 48 g/m
Buffer row' stemming	Crushed rock (between the main charges)
Delay/ms	Blasted separately

6.3.2. Results of Test No. 3

In this experiment, no back-break was observed. There was no displacement on the face of the pre-split line but just local crushing around the hole (Figure 8). The shape and stability of the final wall surface and slope seem very satisfactory (Figure 9).

Figure 9. Test no. 3: pre-splitting blast without back-break behind a pre-splitting row

Figure 10. The final wall shows clear traces of holes in the pre-splitting row after the blasting

7. Conclusions

In this paper, a model has been presented to produce an artificial surface of separation between the blasted and remaining rock masses on the final wall, which leads to a smooth remaining wall with a minimum back-break. This was completed using previous studies and empirical data to define explosive loading and spacing between boreholes to develop pre-split blasts in gneiss rock and hole alignment conditions.

Three experiments were performed. The result of the first one was not satisfactory, as the full-length charging of the holes resulted in severe back-break and disturbance. In the second test, with only the main charge of the detonating cord as well as leaving the top part of the pre-splitting holes without charging or stemming, back-break was controlled locally. In the third test, the spacing of the pre-splitting holes has been reduced, and the main charge in the buffer holes has been partitioned. Thereafter, the perfect result was achieved.

Through this work, the main conclusions to achieve the desired result can be drawn as follows:

- Using the linear charge of pre-splitting holes without cartridges or stemming;
- Calibrating the linear load to the mechanical conditions of the rock;
- Firing buffer holes separately (discrete charging with a reduced powder factor);
- Make additional drilling at the ends of the pre-split zone to absorb the shock.

Rock mechanical properties, the design of the perforation, the choice of explosives, and the detonation order are decisive for an efficient blasting design using the pre-split technique. Each rock type deserves a specific design; however, the present proposal leads and indicates that success lies in the study of binomial rock-blasting.

8. Declarations

8.1. Author Contributions

Conceptualization, Y.T.; methodology, Y.T., I.K., and S.F.; validation, I.K., E.M., and R.A.; writing—original draft preparation, Y.T., I.K., R.B., E.M., and S.F.; writing—review and editing, I.K., M.D., and S.F. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

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8.4. Acknowledgements

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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