The Role and Stress of Surge-Protective Devices in Sharing Lightning Current

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Significance
Part 2 – Development of standards — Reality checks
Part 4 – Propagation and coupling — Numerical simulations

Most simulations performed to investigate the sharing (dispersion) of lightning current for the case of a direct flash to a building have focused on the role and stress of surge-protective devices (SPDs) installed at the service entrance of a building and their involvement in that part of the lightning current that exits the building via the power supply connection to the energy supply.

The numerical simulations performed for this paper, based on a postulated waveform and amplitude suggested by current standards, include downstream SPDs, either incorporated in equipment or provided by the building occupant. The results show that a significant part of the exiting lightning current can involve those downstream SPDs with some likelihood that their surge withstand capability might be exceeded. Such a possibility then raises questions on the validity of the postulated amplitude in the face of the relatively rare occurrence of reported failures.

THE ROLE AND STRESS OF SURGE-PROTECTIVE DEVICES IN SHARING LIGHTNING CURRENT

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Abstract – This paper examines the sharing of lightning current associated with a direct flash to a building. This sharing involves not just those surge-protective devices (SPDs) that might be installed at the service entrance, but also all SPDs involved in the exit path of the lightning current. Such sharing might involve built-in SPDs of some equipment located close to the service entrance, but heretofore not included in numerical simulations performed by many researchers. From the numerical simulations reported in this paper, conclusions are offered that may influence the design and EMC testing of equipment, as well as the risk analysis associated with lightning protection.

I. BACKGROUND AND RATIONALE

This paper offers additional information to the body of knowledge accumulated on how the lightning current of a direct flash, injected into the earthing system of a building, is shared among the many available paths towards intended or opportunistic earthing electrodes.

Recent developments in the International Electrotechnical Commission (IEC) and the Surge-Protective Devices (SPD) Committee of the Institute of Electronics and Electrical Engineers (IEEE) have focused on the role of SPDs connected at the service entrance of a building in the case of a direct lightning flash to the building. This scenario is described in IEC 61312-3 (2000) [9], IEEE PC62.41.1 [12] and PC62.41.2 [13].

Prior to this new focus, most of the considerations on SPD applications were based on the scenario of surges impinging upon the service entrance of a building as they come from sources external to the building. The new (additional) focus addresses the scenario of the earth-seeking lightning current as it is shared among the many possible paths to earth, including the deliberate and opportunistic exit paths of the building earthing system, services other than the power system connection and, mostly, the power supply connection.

Quite independently from these lightning protection considerations, the IEC Subcommittee SC77B had developed a series of documents on the electromagnetic compatibility of equipment, IEC 61000-4-5, Surge withstand capability [8] in particular. These documents were primarily concerned with immunity against typical disturbances, the rare case of a direct lightning flash to a building containing electronic equipment not included.

Increasing recognition of the need to include the scenario of a direct flash to a building – rare as it might be – has motivated the formation of an IEC Joint Task Force TC81/SC77B for the purpose of considering surge stresses on equipment higher than those currently described in the IEC document 61000-4-5 on immunity testing [8].

The purpose of the paper is to examine in detail the sharing of lightning current, not just by the SPDs at the service entrance, but also by all SPDs that might be involved in the exit path of the lightning current. Such sharing might well involve SPDs incorporated in the equipment located close to the service entrance, but not always included in the numerical simulations that have been performed by many researchers (Altmaier et al., 1992) [1]; (Standler, 1992) [23]; (Rakotomalala, 1994) [20]; (Birkl et al., 1996) [3]; (Mansoor and Martzloff, 1998) [15]; (Mata et al., 2002) [19]. In its recent development of a Guide and a Recommended Practice on surges in low-voltage ac power circuits [13] the IEEE has refrained from identifying SPDs as being those that may be connected at the service entrance. Instead, it refers to "SPDs involved in the exit path" without reference to their point of installation.

Given the tendency of equipment manufacturers to include an SPD at the equipment power input port, the issue of "cascade coordination" arises. Several previous papers (Martzloff, 1980) [17]; (Goedde et al., 1990) [5]; (Lai and Martzloff, 1991) [14]; (Standler, 1991) [22]; (Hostfet et al., 1992) [7]; (Hasse et al., 1994) [6] have explored the concept of cascade coordination involving two or more SPDs connected on the same power supply but at some distance from each other.

The legitimate wish of the energy service providers to specify robust SPDs at the service entrance results in SPDs having a relatively high Maximum Continuous Operating Voltage (MCOV). On the other hand, some equipment manufacturers tend to select SPDs with a low MCOV under the misconception that lower is better (Martzloff and Leedy, 1989) [18]. This dichotomy can result in a situation where the low-MCOV SPDs included in equipment might well become involved in the "exit path" and thus become overstressed in the case of a direct flash to the building. This situation is made more complicated by the fact that commercial SPDs packages are assembled from typical distributors' supplies that can have an allowable tolerance band of ±10% on the voltage-limiting rating.

To explore the possibility and implications of a questionable coordination, numerical simulations were performed on a simplified model of a building featuring SPDs installed at the service entrance and SPDs that may be incorporated in equipment connected inside the building near the service entrance.

II. NUMERICAL SIMULATIONS

II.1 Basic circuit

Figure 1 shows a simplified building power system that includes the key elements of this scenario: the building earthing system and all earthing electrodes, with the corresponding exit paths via the service-entrance SPDs and a built-in SPD provided at the power port of a typical item of electronic equipment. In this example, these SPDs are metal-oxide varistors (MOVs) with typical voltage ratings (150 V at the service entrance and 130 V in the equipment) selected for a 120/240 V residential power system. (The conclusions obtained for this type of power system will also be applicable to 240/400 V systems.)

Numerical analysis of the circuit behavior by EMTP [4] allows inclusion of the SPD characteristics as well as the significant R and L elements of the wiring, with injection of a stroke current of 100 kA 10/350 µs at any selected point – the earthing system in this case. The selection of a 100 kA peak is consistent with the postulate made in many published simulations, but might be questioned on the basis of field experience and lightning detection statistics, as will be discussed later in this paper.

In Figure 1, the neutral is defined as part of a "multiple-grounded neutral" system (TN-C-S), with distributed R and L elements between its earthing electrode connections. The R and L values for the cables used in the numerical simulation, but not shown in the figure to avoid clutter, were selected to emulate the typical wire diameters used in low-voltage power distribution systems and building installations.

Previous studies (Birkl et al., 1996) [3]; (Mansoor and Martzloff, 1998) [15] have validated the intuitive expectation that the tail of the 10/350 µs waveform often postulated for simulations will be shared among the available paths simply according to the relative values of resistance in the paths leading to the earthing electrodes. This fact is apparent in the results of Figure 2, for example at the 350 µs time: when inductive effects have dwindled, the current I_H in the 10-Ω earthing resistance of the building is ten times smaller than the total current exiting the building $[I_N+I_{L1}+I_{L2}]$ toward the power distribution system in which multiple earthing electrodes offer an effective earthing resistance of only 1 Ω. It is also worthy to note that this sharing is controlled by the ***relative*** values of the resistances, so that any earth conductivity differences associated with local conditions will wash out.

The combination of the service-entrance 150-V MOV on Line 2 and the 130-V MOV incorporated at the power port of the equipment constitutes a so-called "cascade". When two such cascaded SPDs are to be coordinated, a decoupling impedance must be provided between the two SPDs so that the voltage drop caused by the current flowing in the decoupling impedance – in this example the impedance of the 2,5 mm^2 diameter wires – and added to the limiting voltage of the 130-V MOV, will cause enough of the current to flow through the 150-V MOV to reduce stress on the 130-V MOV.

The simulation was performed for three values of the impedance (length) of the connection, i.e., 0,1 m, 1 m, and 10 m to assess the effect of this impedance for practical situations. Figure 3 shows the results for these three cases and Table 1 shows the resulting energy deposition in the respective MOVs.

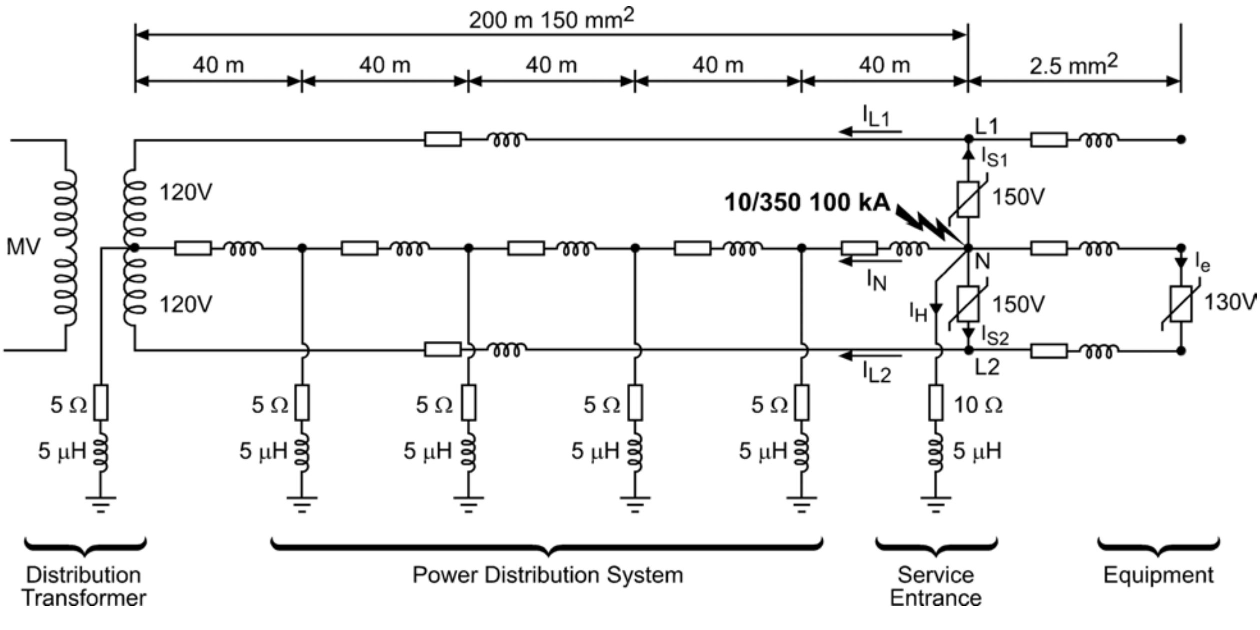
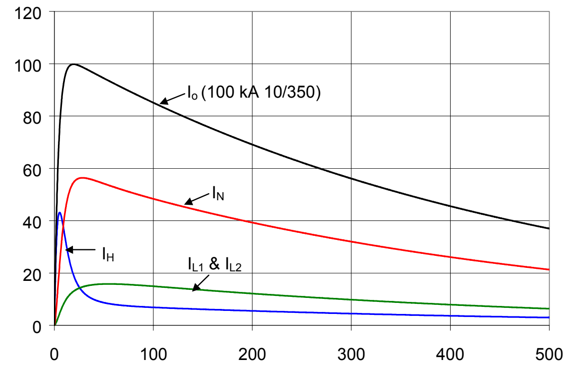


Figure 1 Simplified building schematic with service-entrance SPDs, one built-in equipment SPD, and multiple-grounded power distribution system in case of a direct lightning flash to the earthing system



Legend

I_O: 100 kA, 10/350 µs stroke to the building earthing system
I_N: current exiting via the neutral of the power supply
I_{L1}, I_{L2}: current exiting via the two lines of the power supply
I_H: current into the building earthing electrode(s)

Vertical scale: current in kA – Horizontal scale: time in µs

Figure 2 – Sharing of the lightning current among available paths to earth electrodes

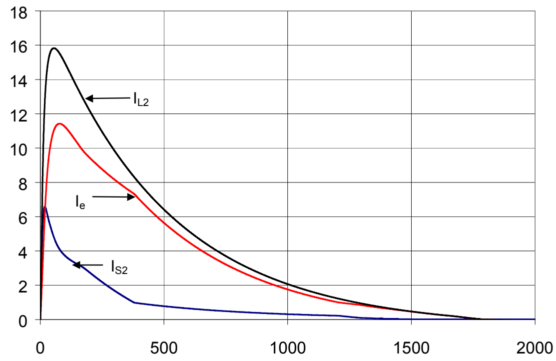
In the traces of Figure 3, the total current in Line 2 (sum of the two currents in the two MOVs) remains essentially unchanged for the three combinations, but the sharing of the current between the two MOVs is significantly affected.

Figure 3a, with only 0,1 m of separation, is not a practical example of connection of equipment that close to the service entrance – except perhaps an electronic residual current device incorporated in the service panel. The two other figures, 3b and 3c, show how the 130-V MOV that took the largest part of the current in the case of Figure 3a, now takes on less as separation length increases. An interesting situation develops as the current flowing in the 10-m line to the 130-V MOV stores energy that will cause a stretching of the current in the 130-V MOV long after the 150-V MOV current has decayed. This is significant because the total energy deposited in the MOVs is the criterion used for coordination, even though the current in the 130-V MOV could be lower than the current in the 150-V MOV. Table 1 shows how this energy sharing changes with the length of the decoupling connection, according to the integration of the varistor currents and voltages obtained from EMTP.

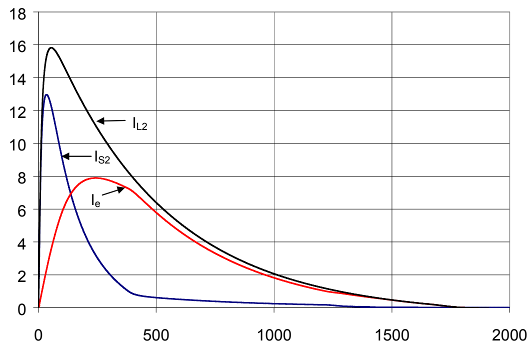
Table 1 – Sharing energy between MOVs for three different connection lengths

SPD	Energy deposition (joules)		
	0,1 m	1 m	10 m
150-V MOV	620	1090	2470
130-V MOV	2560	2030	890

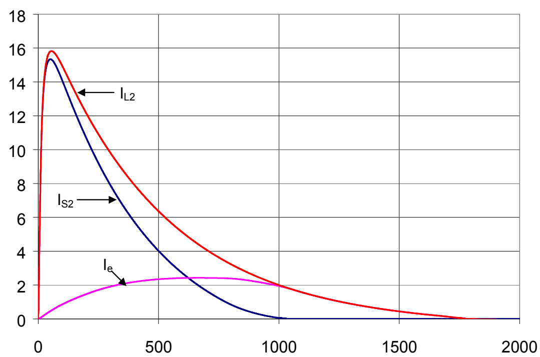
These energy levels might be acceptable for a 150-V MOV sized for service entrance duty, but the 890-joule deposition into the 130-V MOV incorporated in the equipment exceeds common-wisdom ratings for such



a) 0,1 m connection



b) 1 m connection



c) 10 m connection

Legend

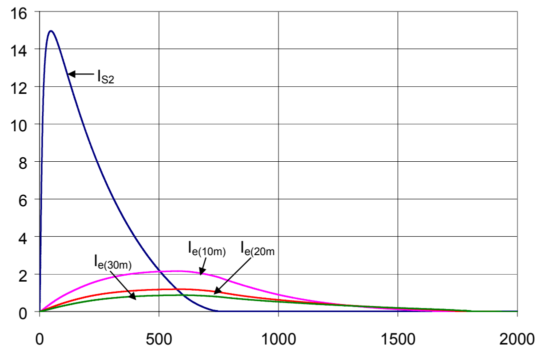
I_{L2}: current exiting via the power supply phase conductor
I_{S2}: current into the service entrance SPD
I_e: current into the equipment SPD

All vertical scales: current in kA
All horizontal scales: time in µs

Figure 3 – Sharing of lightning stroke current

devices. This finding then raises a question on the effectiveness of a cascade for the case of direct flash to the building. In an actual installation, there would be more than one piece of equipment, presumably each with a 130-V built-in MOV at the power port. One might expect that some sharing among these multiple SPDs would reduce the energy stress imposed on these devices.

To explore this situation, an additional simulation was performed for three branch circuits, respectively 10 m, 20 m, and 30 m, each of them supplying equipment incorporating a built-in 130-V MOV. Figure 4 shows the sharing of current among these three MOVs and the 150-V service entrance MOV, and Table 2 shows the energy deposition.



Legend

I_{S2}: current into the service entrance SPD
I_e: currents in the three SPDs at end of 10, 20, and 30 m lines

Vertical scale: current in kA – Horizontal scale: time in µs

Figure 4 – Sharing of current among MOVs

Table 2 – Energy sharing among MOVs

Branch circuit length and energy deposition into three 130-V MOVs			Service entrance 150-V MOV
10 m	20 m	30 m	
620 J	370 J	280 J	1930 J

II.2 Effect of manufacturing tolerances on commercial-grade metal-oxide varistors

The simulations discussed so far were performed by postulating that both the 150-V MOV and the 130-V MOV had their measured voltage limiting at the nominal value as specified by typical manufacturer specifications. Such a postulate is of course difficult to ensure in the reality of commercial-grade devices. For instance, the nominal voltage-limiting value of MOVs rated 130 V rms is 200 V, with lower limit of 184 V and upper limit of 220 V. To check that aspect of the problem, an arbitrary lot of 300 devices rated 130 V rms was purchased from a distributor and the actual measured voltage-limiting value at 1 mA dc was determined in accordance with IEEE Std 62.33-1994 [11]. For this lot, the standard deviation (sigma) was found to be 8 V.

On the basis on these measurements and to give an indication of the significance of tolerance effects, the computations reported for Figure 3c (10 m separation) were repeated, still with a 150 V MOV at the service entrance, but with varistors at ±1 sigma of the 130 V rms rating, that is, 122 V and 138 V rms. The results are shown in Table 3.

Table 3 Energy sharing for three values of the equipment built-in MOV (10 m separation)

Equipment MOV rating (V rms)	Energy deposited (J)	
	Equipment MOV	150-V service entrance MOV
122	915	2320
130	890	2890
138	750	2650

These results illustrate the significance of tolerances in a situation where the difference between the two SPDs of the cascade is not large, because of the de facto situation of low values of MCOV that the industry has unfortunately adopted. Of course, if tolerances were also taken into consideration for the service entrance MOV, the extremes of distributions for both MOV would make an effective coordination between a nominal 150-V MOV and a nominal 130-V MOV even more problematic.

II. 3 Nonlinearity of circuit elements

Most of the reported simulations, as cited above, have been performed with a conservative postulate of a 100 kA 10/350 lightning discharge. The median of the current peaks compiled in the seminal Berger et al. paper [2] is only 20 kA. Occasional reservations have been voiced on the validity of these data collected with technology dating back to the 1970's. A recent (July 2000) actual case history was communicated to the authors by a colleague for two major lightning storms recorded in the area of Tampa in Florida by means of the Lightning Detection System [24], during which over 30 000 flashes were detected in a period of less than 12 hours, with only one at the 150 kA level, and a median of 20 kA, confirming the Berger at al. data.

One could expect that the dispersion of the lightning current that results from the combined action of linear elements (resistance and inductance) with nonlinear components (MOVs) might produce a different sharing of the current as the decoupling element is linear but the SPDs are nonlinear. To explore this hypothesis, the computations for the case of Figure 4 and Table 2 were repeated, for peak currents of 100 kA (the original value of the computation), 50 kA, and 25 kA (about the median of the statistics). Table 4 shows the results of these computations. It is interesting to note that as the applied stroke is decreased 4 to 1 (from 100 to 25), the total energy deposited in the varistors is decreased by a factor of 3200/610 = 5.2. This relative greater decrease is caused by the larger portion of the current exiting via the linear-path neutral, further relief for all the SPDs involved in the exit path.

Table 4 Nonlinear effects on current sharing

10/350 stroke (kA)	Branch circuit length and energy deposited into three 130-V MOVs			Energy into service entrance 150-MOV	Total energy in the MOVs
	10 m	20 m	30 m		
100	620 J	370 J	280 J	1930 J	3200 J
50	329 J	215 J	179 J	700 J	1423 J
25	170 J	120 J	90 J	230 J	610 J

III. DISCUSSION

We have made all these computations based on postulating that the insulation levels are sufficient to prevent a flashover that would drastically affect the continuing energy deposition in the downstream SPDs. We have not included the limits of energy handling of the devices, which of course should be compared with computed deposited energy levels in a practical case.

Another set of readings from the EMTP computations confirmed that the presence of SPDs at the critical points prevents such overvoltages from occurring (as long as the SPDs can carry the resulting currents)

Not surprisingly, the results of the simulation confirm that the sharing of the lightning current occurs in inverse ratio of the resistances leading to the earthing electrodes after the initial phase of the 10/350 μs stroke. Likewise, one can expect that inductances will limit the current flow so that low-inductive paths, such as intended and opportunistic earth electrodes of the building itself, compared to the longer lines of the power supply, will carry a larger share of the total current during the initial phase of the current. This effect is clearly visible on the I_H of Figure 2, for the relatively slow rise time of 10 μs of a first stroke. One may expect that for the subsequent strokes, or the flashes associated with triggered lightning experiments that have shorter rise times (Rakov et al., 2001) [21], this effect will be even more apparent.

An important finding – predictable on a qualitative basis but heretofore not quantified for the case of a direct lightning flash to buildings containing electronic equipment – concerns the cascade coordination of built-in SPDs in the equipment. From the simple examples presented, it appears that a cascade of a robust service-entrance SPD and a built-in SPD sized for limited energy-handling capability, according to the common-wisdom practice, might well be a delusion.

A solution to the difficult coordination could be to replace the all-MOV SPD at the service entrance with a combined series gap-varistor device (Mansoor et al., 1998) [16]. Such a device would also alleviate the concerns about the temporary overvoltage problems associated with MOV-only SPDs. Sparkover of the gap during the initial rise of the lightning current (when the coordination by means of the decoupling inductance occurs) will invite the remainder (continuing rise and tail) of the surge current exiting via SPDs to use the service entrance SPD rather than the simple and less robust built-in MOVs downstream.

Last but not least, the practical question remains open on the need to provide surge protection against worst cases – the combined worst case of a direct flash to the building and the high-level 100 kA stroke, which is only at the 4% probability, according to the Berger et al. data [2] and even lower in the yet-anecdotal case of the Tampa Bay lightning storm [24]. The nonlinearity effect presented in II.3 adds further credibility to the overall need to make reasonable risk assessments of cost-effectiveness before specifying high surge level requirements, both for the service entrance SPDs and for built-in SPDs in connected equipment.

IV. CONCLUSIONS

1. When accepting the postulate that the reference parameter of a direct lightning flash to a building should be a 10/350 μs current with a peak of 100 kA, the numerical simulations performed for a simplified system with one surge- protective device installed at the service entrance, and one or more built-in SPD in downstream equipment indicate that the downstream SPD is very likely to be overstressed and fail, most likely catastrophically.

2. There are several possible explanations for the apparent contradiction between a prediction of down-stream equipment failures based on this postulated lightning parameters, and equipment field experience that does not report such frequent failures, although of course anecdotes abound.

- The occurrence of a direct flash to a building can cause such extensive damage that a post-mortem for investigating the specifics of a prevailing ineffective coordination is not performed at that time and the issue is ignored.
- Enough uncontrolled clearance flashovers occur in the installation to provide significant relief for any at-risk SPDs incorporated in downstream equipment.
- In an installation where many built-in or plug-in SPDs are present, the sharing illustrated by Figure 4, combined with a low probability of a 100 kA stroke, might reduce the stress on downstream devices to a value within their capability. In particular, many commercial plug-in SPDs advertise capabilities of hundreds of joules, unlike the 20 joules of a single MOV, which might be provided at the input port of electronic equipment.
- Insufficient field failure data have been obtained, compiled, shared, and published to enable realistic assessment of frequency and severity of occurrences involving an unsuccessful cascade coordination.

3. It is impractical at this point to mandate high energy handling capability for built-in SPDs. Such a move might meet with strong objections from manufacturers whose products have satisfactory field experience, and a risk analysis might show it to be not cost-effective.

4. Economic and political realities related to the type and mission of the installations to be protected should be kept in mind. Clearly, mass-market applications such as cost-conscious consumers, in a framework of regulated or unregulated installations, are different from bottom-line-conscious industrial applications, and even more so in the case of national assets – be they cultural or military.

5. Another approach for manufacturers might be to avoid placing low MCOV varistors at the input port of their equipment. Rather, they should select an SPD with an MCOV and resulting surge-protective level as high as their equipment can inherently stand. This is a "selfish" approach which is mentioned here half-seriously, half-facetiously: there are enough low MCOV SPDs installed by users or included in other equipment in a typical system that those unfortunate low-MCOV devices will take up the stress, leaving unscathed the equipment wisely provided with high MCOV SPDs!

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Note: The citations that appear in the text are listed here by alphabetical order of the lead author, not by chronological order of appearance in the text.

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